3D PRINTING OF PADS ON LASTS UTILIZED IN THE PRODUCTION OF CUSTOM-MADE COMFORTABLE FOOTWEAR

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ABSTRACT. The study investigated the process of adjusting the shape of the footwear last using solid modeling elements (individual pads) manufactured through 3D printing. Based on a comparative analysis of the results of anthropometric foot studies with the parameters of existing footwear lasts available on the Ukrainian market, the rationale for improving the method of correction lasts using individual pads in mismatched anthropometric zones to achieve consumer foot comfort is substantiated. A schematic diagram of the transverse cross-section of the foot-lasts-pads-footwear system is provided. The study obtained dependencies of the calculated radius of the outer contour of the pad on the thickness of the upper material of the footwear. The anthropometric regions of the foot that most commonly require adjustment in existing lasts to achieve the production of custom-made comfortable footwear have been identified. The method of adjusting the shape of the last has been improved based on the individual parameters of the customer's foot, using pads manufactured using 3D printing technology. The interdependencies between stress and deformation under tension have been established, and the strength limit of polymer material samples for corrective pads obtained through 3D printing has been determined. The rational technological parameters of the 3D printing process using elastane material for corrective pads on lasts have been determined and implemented in the production of custom-made footwear.

KEY WORDS: shoes, materials, modulus of elasticity, shoe last, 3D printing

IMPRIMAREA 3D A INSERȚIILOR PE CALAPOADE UTILIZATE ÎN PRODUCȚIA DE ÎNCĂLȚĂMINTE CONFORTABILĂ PERSONALIZATĂ

REZUMAT. Studiul a investigat procesul de ajustare a formei calapodului pentru încălțăminte folosind elemente de modelare solide (inserții individuale) fabricate prin imprimare 3D. Pe baza unei analize comparative a rezultatelor studiilor antropometrice ale piciorului cu parametrii calapoadelor pentru încălțăminte existente pe piața ucraineană, se justifică raționamentul pentru îmbunătățirea metodei de corecție a calapoadelor pentru încălțăminte cu ajutorul inserțiilor individuale în zonele antropometrice unde este necesar pentru a obține confort la nivelul piciorului consumatorului. Se prezintă o diagramă schematică a secțiunii transversale a sistemului picior-calapod-inserție-încălțăminte. Studiul a condus la determinarea unor variații ale razei calculate a conturului exterior al inserției în funcție de grosimea materialului din care este confecționată fața încălțămintei. S-au identificat regiunile antropometrice ale piciorului care necesită cel mai frecvent ajustări pe calapoadele existente pentru a realiza producția de încălțăminte confortabilă la comandă. Metoda de reglare a formei calapodului a fost îmbunătățită pe baza parametrilor individuali ai piciorului clientului, folosind inserții realizate cu ajutorul tehnologiei de imprimare 3D. S-au stabilit interdependențele dintre tensiune și deformarea sub tensiune și s-a determinat limita de rezistență a probelor de material polimeric pentru inserțiile de corecție obținute prin imprimare 3D. S-au determinat și implementat parametrii tehnologici raționali ai procesului de imprimare 3D care utilizează material elastan pentru inserțiile corectoare de pe calapoadele pentru încălțăminte în cadrul producției de încălțăminte personalizată.

CUVINTE CHEIE: pantofi, materiale, modul de elasticitate, calapod pentru încălțăminte, imprimare 3D

IMPRESSION 3D D'INSERTS SUR LES MOULES DE CHAUSSURE UTILISÉS DANS LA PRODUCTION DE CHAUSSURES CONFORTABLES SUR MESURE

RÉSUMÉ. L'article étudie le processus d'ajustement de la forme du moule de chaussure à l'aide d'éléments de moulage solides (inserts individuels) fabriqués par impression 3D. Sur la base d'une analyse comparative des résultats des études anthropométriques du pied avec les paramètres des moules de chaussures existant sur le marché ukrainien, le raisonnement est justifié pour l'amélioration de la méthode de correction des moules de chaussures à l'aide d'inserts individuels dans les zones anthropométriques où il est nécessaire d'obtenir un confort au niveau du pied du consommateur. Un diagramme schématique de la section transversale du système pied-moule-insert-chaussure est présenté. L'étude a permis de déterminer des variations du rayon calculé du contour extérieur de l'insert en fonction de l'épaisseur du matériau constituant la tige de la chaussure. On a identifié les régions anthropométriques du pied qui nécessitent le plus souvent des ajustements sur les moules existantes pour obtenir une production de chaussures personnalisées confortables. La méthode d'ajustement de la forme de la moule a été améliorée en fonction des paramètres individuels du pied du client, à l'aide d'inserts réalisés par la technologie d'impression 3D. Les interdépendances entre contrainte et déformation sous contrainte ont été établies et la limite d'élasticité des échantillons de matériau polymère a été déterminée pour les inserts de correction obtenus par impression 3D. On a déterminé et mis en œuvre des paramètres technologiques rationnels du processus d'impression 3D utilisant un matériau élasthanne pour les inserts correcteurs sur les moules de chaussures dans la fabrication de chaussures sur mesure.

MOTS CLÉS : chaussures, matériaux, module d'élasticité, moule de chaussure, impression 3D

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INTRODUCTION

Today, it is hard to imagine an industry that has not been touched by 3D printing technology. The application of additive technologies in footwear production is not just a fashionable trend but also a justified modernization of the manufacturing process. Additive technology, or layered synthesis technology, 3D printing — today is one of the most dynamic areas of the digital production [1]. The implementation of additive technologies in modern light industry production enables the manufacturing of polymer products of practically any complexity and configuration [2]. The whole idea of 3D printing is to produce affordable products in an efficient and effective manner, ensuring they are strong, lightweight, and have minimal waste. The primary focus is on high quality, efficiency, and low-volume production. Computer-generated designs will help reduce costs and improve the utilization of energy and resources by aiding in the development and early stages of production of new products in the light industry. They also eliminate the need for storing physical products. Custom-made footwear production offers opportunities for adjusting or creating footwear lasts based on the anthropometric parameters of the customer's foot. This allows for an ideal fit of the footwear to the foot, ensuring maximum comfort during its usage.

EXPERIMENTAL

Materials and Methods

In the study, the three-dimensional graphic environment Delcam Crispin was utilized, employing modules such as ShoeMaker, LastMaker, and PowerShape, which provide a comprehensive cycle of design processes in footwear production. These modules cover tasks ranging from foot scan processing and upper construction modeling to last design. The Ultimaker Cura slicer was used to configure the printing of experimental samples using various polymer materials. The study investigated printed samples made from the following materials: polylactic acid (PLA), high-temperature melting point ABS plastic, Elastan, polycyclohexanedimethylene terephthalate glycol (PCTG), and glycol-modified polyethylene terephthalate (PETG).

For the investigation of footwear last correction using a printed pad, the Fused Deposition Modeling (FDM) method was utilized for 3D printing in the study. The study proposes an improved method for correcting existing lasts using printed pads manufactured through 3D printing technology in anthropometric zones of the foot that require adjustments in volume for individual consumers. The correction of lasts using printed pads made from polymer materials will significantly reduce production time, lower costs, and facilitate the implementation of custom-made footwear lasts.

Analysis of Previous Research and Sources of Investigation

Analysis of theory and practice in footwear production indicates that manufacturing products at a high level of quality is the primary goal of footwear manufacturers. The sportswear industry has long relied on technologies to optimize the characteristics of their products, and thanks to digital workflows, they have numerous opportunities to create limited edition collections [3].

3D printers with 3D printing technology are gradually gaining significance in the footwear design field. Additionally, 3D printing technology allows for the use of multiple different polymer materials in the production of a single product in the lightweight industry [4]. Such an approach allows for addressing issues related to the strength and elasticity of manufactured products. The main applications of additive technologies in the footwear industry include the production of specialized orthopedic models, sports footwear, and designer styles. Prominent global brands such as Nike, Adidas, Reebok, Under Armour, and New Balance are already utilizing 3D technologies in footwear manufacturing.

There are many studies and researches on 3D printing technologies and 3D printers [5-7]. From these studies, it is known that the primary raw material for manufacturing various parts and products is polymer material [5]. The trends that are driving the footwear industry towards wider adoption of additive manufacturing are primarily associated with the underlying macro trend of increased personalization in consumer goods [8, 9]. Indeed, the widespread adoption of additive manufacturing in the footwear industry is still in its early stages. Brands continue to be valued more than custom-made products. However, younger and future generations are beginning to appreciate the value of customized products, especially when they become more accessible.

3D printing is also an energy-efficient technology that can contribute to the eco-friendliness of the manufacturing process by utilizing up to 90% of the material [10]. In recent years, 3D printing has expanded beyond industrial prototyping and manufacturing processes. The technology has become more accessible to small companies and even individual users. It is now available to a wide audience, and its popularity is growing exponentially every year. There is a growing variety of materials and applications for 3D printing [11, 12].

Adjusting the Pad to the Parameters of the Foot

By analyzing the number of customer requests for custom-made handmade footwear, it can be noted that the areas of the shoe last most commonly not aligned with the anthropometric parameters of customers' feet are the following: the arch area, the instep area, or both the arch and instep areas simultaneously (Figure 1).

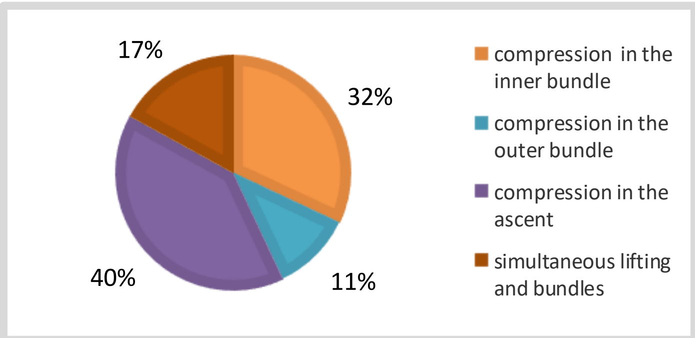

Figure 1. The areas of the foot that most commonly require adjustment in existing shoe lasts

For the purpose of verifying the proposed technology, a custom-made pair of shoes was manufactured for the consumer, whose foot circumference in the instep area exceeded the corresponding size of the shoe lasts. Comparative parameters were obtained based on non-contact measurements using a 3D scanner of the consumer's feet and scanned existing shoe lasts of the appropriate size, matched by the style (Table 1).

Table 1: The comparative analysis of anthropometric parameters of the foot and parameters of the shoe lasts

№	Parameter	Foot Measurement (mm)	Shoe Last Measurement 1, (mm) (Zotti)	Shoe Last Measurement 2, (JB Plast)	Shoe Last Measurement 3, (Lviv Plast)	Deviation of Last 1 from the Foot (1-2)	Deviation of Last 2 from the Foot (1-3)	Deviation of Last 3 from the Foot (1-4)
1	L1- Foot Length	275.0	290.0	292.0	294.0	-15.0	-17.0	-19.0
2	L2 – Length to the end of the 5th toe	243.0	242.0	244.0	243.0	1.0	-1.0	0
3	L3 – Length to the inner beam	190.0	187.0	191.0	189.0	3.0	-1.0	1.0
4	L4 – Length to	181.0	179.5	177.8	182.0	1.5	3.2	-1.0

№	Parameter	Foot Measurement (mm)	Shoe Last Measurement 1, (mm) (Zotti)	Shoe Last Measurement 2, (JB Plast)	Shoe Last Measurement 3, (Lviv Plast)	Deviation of Last 1 from the Foot (1-2)	Deviation of Last 2 from the Foot (1-3)	Deviation of Last 3 from the Foot (1-4)
	the outer beam							
5	C1 – Toe circumference	214.8	215.6	215.0	215.0	-0.8	-.02	-0.2
6	C2 – Bundle circumference,	**289.0**	**275.0**	**274.0**	**278.0**	**14.0**	**15.0**	**11.0**
7	C3 – Girth through the bend and heel	360.0	351.0	350.0	352.0	9.0	10.0	8.0
8	C4 – Lifting circumference	**301.0**	**287.0**	**289.0**	**285.5**	**14.0**	**12.0**	**13.5**
9	H1 – Height of the I toe	25.0	27.0	26.0	27.0	-2	-1	-2

The comparative analysis of the foot measurements and the existing shoe last revealed the need for significant adjustments in the basic shoe last, particularly in the girth parameters. The largest discrepancies were observed in the areas of the forefoot and instep girth (Figure 2).

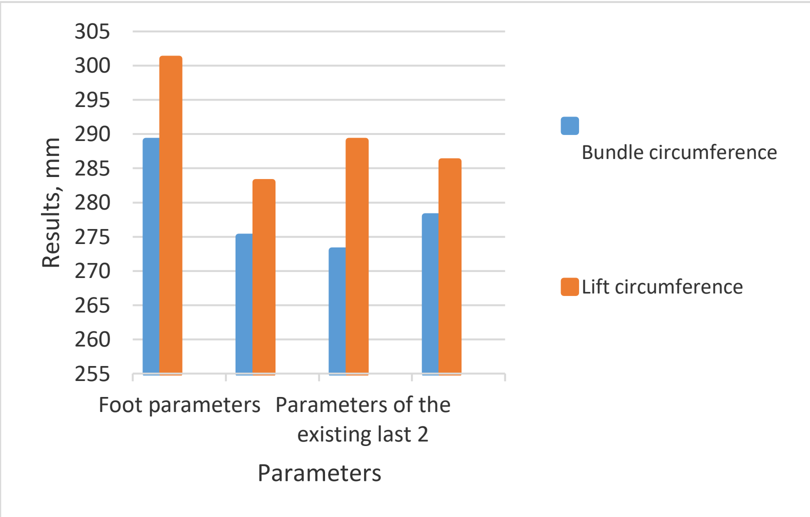

Figure 2. Comparative analysis of deviations in the circumferential parameters of the foot with the parameters of existing shoe lasts

It is advisable to make rational adjustments to the shoe last in areas where it does not correspond to the foot's anthropometric dimensions using overlays. This minimizes the time required to manufacture a new individual shoe last and reduces costs, allowing the same shoe last to be used for different customers by simply changing the individual overlays.

To enhance the performance characteristics of the overlays, it is recommended to manufacture them using 3D printing technology. Modern 3D printers have the capability to create models of various complexities using different types of plastics, at an affordable cost and with a fast turnaround time [13].

For the research purposes, five types of plastic were used for 3D printing, and the printing parameters were selected based on the recommended technical specifications for each material. As a result, samples for investigating the physical and mechanical characteristics were printed using the following materials: PLA (polylactic acid); ABS (acrylonitrile butadiene styrene); Elastan;

PCTG (polycyclohexanedimethylene terephthalate glycol); PETG (modified polyethylene terephthalate glycol).

With the aim of determining the physical and mechanical properties of the polymer materials, experimental investigations of tensile tests were conducted on samples obtained through 3D printing using an upgraded tensile testing machine. From the obtained experimental data on the tensile behavior of the polymer materials, a graph was constructed to illustrate the strength limits of the tested plastics (Figure 3).

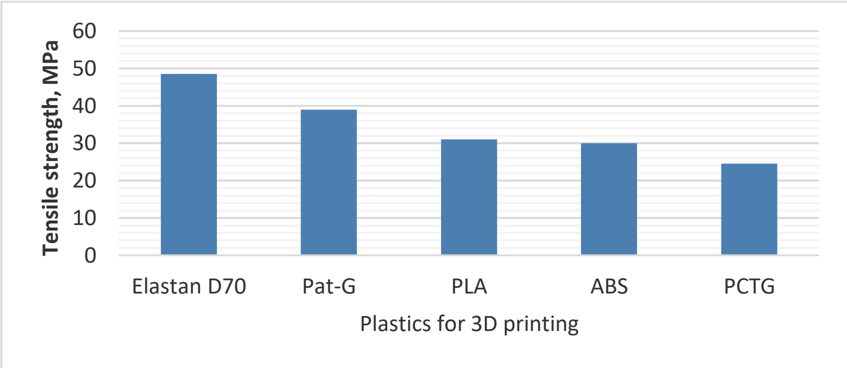

Figure 3. Strength limit of the investigated plastics

Based on the analysis of the research results for 3D printing of overlays, Elastan was chosen as it is an extremely flexible material with a high degree of strength. It is well-suited for producing a range of functional parts using 3D printing. The plastic withstands dynamic loads excellently and can be used in a wide temperature range (from -40°C to +120°C). Elastan is an excellent choice for both technical and decorative purposes. Its melting temperature ranges from 230°C to 260°C.

RESULTS AND DISCUSSIONS

Mathematical Modelling

In custom shoe manufacturing, there are often cases where the customer has a higher arch height, which requires increasing the height of the shoe last to ensure comfortable pressure on the foot from the upper during wear [15]. Increasing the height of the shoe last in the arch area while maintaining the necessary shape and proportion can be achieved by using special inserts made through 3D printing technology. These inserts are designed to fit tightly onto the surface of the shoe last, providing the desired elevation.

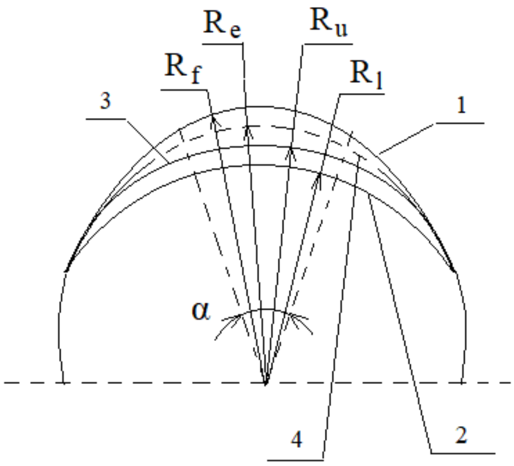

Figure 4. The cross-sectional diagram of the foot - last - pads - footwear system is as follows: 1 - foot contour; 2 - last contour; 3 - pads contour; 4 - contour of the foot-to-upper distribution surface

To determine the thickness of the overlay in the area of the foot arch, we will use the calculation scheme shown in Figure 4.

When manufacturing custom-made footwear, tightening of the upper is primarily done in the toe and heel areas, while in the arch area, the tightening force is almost absent. Therefore, it can be considered that the outer contour of the pads aligns with the contour of the inner surface of the finished footwear. During the wearing process, it is necessary to ensure a comfortable pressure on the surface where the foot and the upper of the footwear come into contact. The magnitude of this pressure, which is 9943 Pa, has been determined in the study [14]. Under the mentioned pressure, there is a slight compression of the foot and stretching of the upper part of the footwear, resulting in the surface where the foot and the upper of the footwear come into contact occupying an intermediate position between the foot surface and the inner surface of the upper part of the finished footwear, which is determined by the radius.

Let's consider a segment of the cross-section of the system: foot - last - pads - footwear, bounded by an angle α. We assume that within this angle, all contours can be approximated as segments of circles drawn from a common center located on the lower surface of the upper part of the footwear. Then, the pressure on the surface where the foot and the upper of the footwear come into contact can be represented based on Hooke's law as follows:

$$P = \frac{R_f - R_e}{R_f} E_f \qquad (1)$$

where: P – pressure, (Pa); R_f – radius of the foot contour, (m); R_e – radius of the foot-distribution surface – upper of the footwear contour, (m); E_f – elastic modulus of the foot, (Pa).

From equation (1), we obtain:

$$R_e = R_f \left(1 - \frac{P}{E_f}\right) \qquad (2)$$

When the foot is compressed, the upper of the shoe stretches, and the stresses that arise in it can be expressed as circumferential stresses in a cylindrical shell.

$$\sigma = \frac{P R_e}{\delta} \qquad (3)$$

where σ – is the tensile stress, (Pa); δ – the thickness of the shoe upper.

Taking into account the small thickness of the upper compared to the radius of its inner surface, the same tensile stresses can be expressed based on Hooke's Law as:

$$\sigma = \frac{R_e - R_u}{R_u} E_u \qquad (4)$$

where R_u – radius of the inner surface of the finished footwear, (m); E_u – modulus of elasticity of the upper material of the footwear, (Pa).

By equating the right-hand sides of equations (3) and (4) and performing the necessary transformations, we obtain:

$$R_e = \frac{1}{\frac{1}{R_u} - \frac{P}{\delta E_u}} \quad (5)$$

Similarly, by equating the right-hand sides of equations (2) and (5) and performing the necessary transformations, we obtain an expression for determining the radius of the inner surface of the finished footwear or the outer contour of the pad:

$$R_u = \frac{1}{\frac{1}{R_f\left(1-\frac{P}{E_f}\right)} + \frac{P}{\delta E_u}} \quad (6)$$

By substituting equation (6) into equation (5), we obtain an expression for determining the radius of the surface contour between the foot and the upper of the footwear during wear:

$$R_e = \frac{1}{\frac{1}{\frac{1}{R_f\left(1-\frac{P}{E_f}\right)} + \frac{P}{\delta E_u}} - \frac{P}{\delta E_u}} \quad (7)$$

One of the most common materials used for the upper part of footwear is genuine leather, which has a complex internal structure [15]. The magnitude of the elastic modulus of the upper material of footwear depends on the direction of stretching relative to the orientation of fibers for natural leather or the supramolecular structures for synthetic polymer materials [16].

The graphical dependencies of the calculated radius of the external contour of the overlay on the thickness of the upper material of footwear are presented in Figure 2 for different values of its elastic modulus to ensure the desired comfortable pressure on the foot $P = 9943$ Pa, calculated using equation (6), assuming the radius of the foot contour $R_f = 7 \cdot 10^{-2}$m, elastic modulus of the foot $E_f = 616.9 \cdot 10^3$ Pa [14].

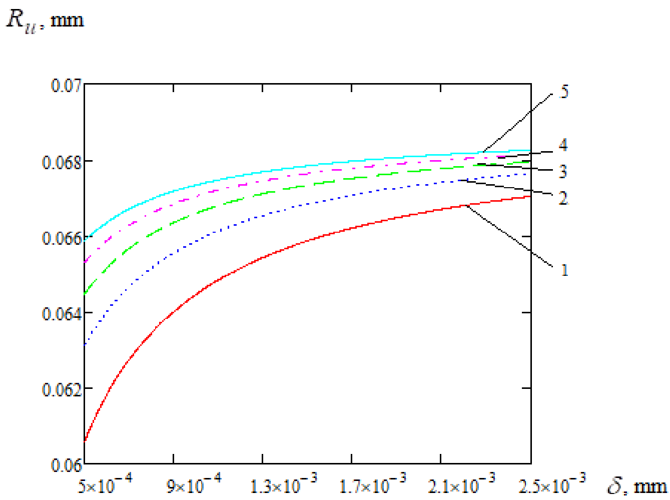

Figure 5. The dependencies of the calculated radius of the outer contour of the overlay from the thickness of the upper material are shown: 1 – $E_u = 10^7$ Pa; 2 – $E_u = 1.5 \cdot 10^7$ Pa; 3 – $E_u = 2 \cdot 10^7$ Pa; 4 – $E_u = 2.5 \cdot 10^7$ Pa; 5 – $E_u = 3 \cdot 10^7$ Pa.

As can be seen from Figure 5, with an increase in the thickness and modulus of elasticity of the upper material, the calculated radius of the outer contour of the overlay increases.

Research Results

Overlays for the lift area were designed for the pre-selected footwear lasts (Figure 6). The radius of the contour of the outer surface of the overlays is determined using formula (6), where the parameter values are substituted: $P = 9943$ Pa; $R_f = 7 \cdot 10^{-2}$ m; $E_f = 616.9 \cdot 10^3$ Pa; $\delta = 1.5 \cdot 10^{-3}$ m; $E_u = 2 \cdot 10^7$ Pa.

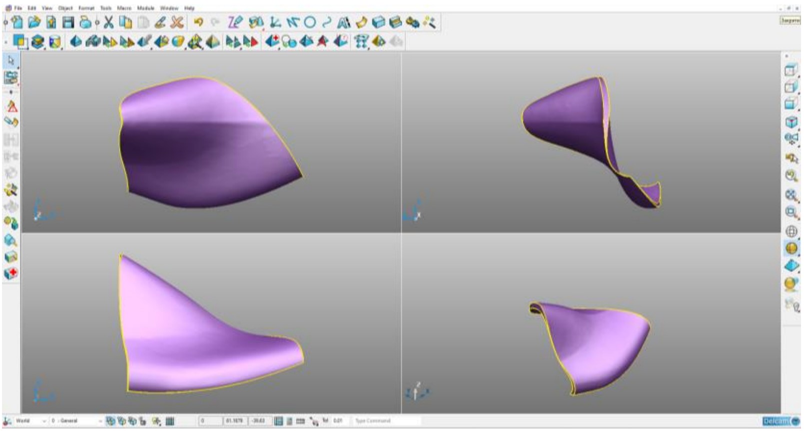

Figure 6. The anthropometric overlay was designed using the Delcam Crispin graphical environment

Below is an image of the tested overlay on the footwear last in Ultimaker Cura slicer, which is necessary to enhance comfort for custom orders. The required settings and estimated print time for the part have been selected (Figure 7, Table 2).

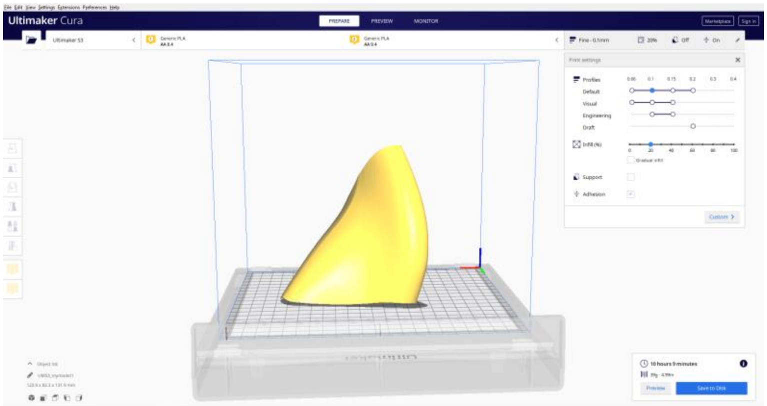

Figure 7. Completed 3D image of the insole in Ultimaker Cura slicer

Table 2: Printing parameters for Elastan D70 plastic insoles

Print settings	Standard values D 70	Settings used for printing the pads D 70
Printing temperature	230-260°C	250°C The optimal printing temperature at which the polymer extrudes uniformly.
Bed temperature	90-110°C	90°C If a lower temperature is chosen, the first layer of the polymer may not adhere firmly to the build platform. On the other hand, a higher temperature, typically by a few tens of degrees, can cause the polymer to not have enough time to cool and solidify, leading to excessive melting and deformations.
Printing direction	Horizontal, Vertical x-y, Vertical z	Horizontal
Line infill	10-100	20
Fan cooling	+	+
Print speed	30 - 80мм/с	50 мм/с The optimal printing speed is the speed at which the polymer consistently and evenly cools and adheres layer by layer.
Printing shrinkage, %	0.7	0.7
Support density, %	20-30	24

Figure 8. a) The custom insole for the shoe was manufactured using 3D printing;
b) The printed insole is attached to the shoe last

The obtained custom insoles were attached to the existing shoe lasts using brackets, which ensure a secure fit and attachment of the insoles to the lasts (Figure 8.b). Using the shoes with the attached insoles, comfortable footwear was made according to the individual anthropometric data of the customer (Figure 9).

Figure 9. The photo of the custom-made pair of comfortable shoes has been taken

The proposed approach to manufacturing customized footwear allows for achieving the desired pressure on the individual's feet, not only in cases where anthropometric parameters differ from the average statistical values but also when each foot has its unique characteristics. In this scenario, individual inserts are used to create each half pair of shoes.

CONCLUSIONS

Based on the experimental study the following conclusions can be drawn:

The method of adjusting the shoe last shape based on the individual parameters of the customer's foot has been improved using inserts manufactured using 3D printing technology. The interdependencies between stress and deformation during stretching have been established, and the strength limit of the polymer material samples for corrective inserts obtained through 3D printing has been determined.

Optimal technological parameters for the 3D printing process of elastane corrective inserts on the shoe last have been identified and implemented in the production of custom-made footwear. An individual pair of men's half shoes has been manufactured using the improved methodology for adjusting the fullness of the shoe last in specific anthropometric areas.

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