Application of 3D printing from acrylonitrile/butadiene/styrene in the realization of prototypes of heels of women's shoes

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This paper researches the possibility of applying 3D printing in the footwear sector. On the 3D desktop printer MakerBot Replicator 2X with the process of Fused Deposition Modeling (FDM), women's shoe heel prototypes were made from acrylonitrile/butadiene/styrene (ABS). One of the limitations of FDM-ABS 3D printing on 3D desktop printers is the printing of monochrome or two-color 3D objects (depending on the number of printer nozzles), which makes it difficult to meet the requirements for high-quality reproduction. Therefore, the possibilities of dyeing the printed ABS heels subsequently with disperse dyes by the exhaustion process was investigated. The results confirmed the possibility of achieving multicolor effects with the aim of obtaining value-added products in the field of visual effects. The developed prototypes of ABS heels are in cooperation with the development team of the footwear factory Ivančica d. d. Ivanec built into functional and wearable models of women's pumps.
Keywords: *fused deposition modeling, 3D printing, footwear design, acrylonitrile/butadiene/styrene, dyeing, heel prototype*

1. Introduction

Product design is a significant segment in which advanced science and technology enable an increased number of innovations in the industrial process, including the field of footwear production.

One of the Additive Manufacturing (AM) processes that allows rapid creation of prototypes or small batches is the Fused Deposition Modeling (FDM) process [1-3]. There are different materials that can be used in the FDM process, acrylonitrile/butadiene/styrene (ABS) is one of the most commonly used materials for the fabrication of a variety of 3D objects for different applications. This is due to its dimensional stability and low glass transition temperature, although its application in the footwear sector has been insufficiently researched [4, 5]. AM offers greater flexibility compared to traditional production processes, and the main advantage is that these processes allow the production of creations in one step, directly from the model [3, 4].

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The use of AM processes and 3D printing is increasing in the fashion industry primarily due to a number of advantages over traditional production processes, such as accelerated design and construction process, shorter production time, and lower costs associated with the stock, storage, and more. AM is implemented in the fashion industry for the development of prototypes, innovative examples of high fashion (haute couture), or customizable personal creations [6].

The application of additive procedures focused on the development of new footwear models enables the production of three-dimensional prototypes, personalized examples as well as a small series of developed models [7]. Functional footwear parts of very complex geometries, good dimensional tolerances, and smooth surfaces of manufactured parts can be made with AM procedures. The application of 3D printing technology in the production of footwear prototypes includes tests that allow the conduction of a detailed aesthetic aspect analysis and the relationship of design elements with anthropometric characteristics and foot geometry [8, 9]. All of this in the early stages of development. The design of personalized footwear can be approached from 3 different points of view: aesthetic, dimensional, and functional. Shoes made by 3D printing procedures of various designs, from artistic design examples to functional and practical footwear for certain sports purposes or everyday use, have been introduced into the modern fashion industry [6]. Numerous experimental and artistic examples of footwear (Fig.1) clearly show the possibilities and advantages of AM procedures such as the creation of complicated geometry without restrictions and without the need for additional tools [10-14].

The application of AM in footwear can be divided into three segments:

- 3D printing of individual footwear parts such as soles, heels, decorative and/or functional details;
- 3D printing of complete models of simple or complex geometries;
- 3D printing of built-in parts, e.g. insoles.

Including orthopedic products, insoles are the first consumer products in the footwear industry to be mass-produced using AM personalized customization [15, 16]. Commercial availability is enabled through mobile apps, online stores, or feet scans directly at the store. A positive example of this is Bivics Wiivv Wearables Inc., which launched a Kickstarter campaign in 2016 to create custom 3D printed insoles. Their success has resulted in a collaboration with Scholl, which currently offers anatomical custom 3D printed shoe insoles [17].

The production of individual footwear parts such as flexible soles is also a consumer product that is mass-produced by AM, developed by Adidas, New Balance, and Nike [16]. In commercial production, Nike has been using 3D printing since 2012 to prototype and manufacture custom soles for Vapor Laser Talon, sports football boots (Fig.2a) [18]. In 2016, Carbon and Adidas introduced the Futurecraft 4D running shoe (Fig.2b), presented as the most innovative 3D printed product on the market [19], and since the same year, the New Balance running shoe has been available (Fig.2c) [20].

In addition to design and aesthetic features during the development of footwear models, it is necessary to meet functional and ergonomic criteria. Therefore, fashion footwear currently mostly combines 3D printed parts (soles and heels) with classic procedures and materials for making uppers, to create so-called ‘hybrids’. This combination ensures functionality and comfort as well as the personalization of footwear aimed at mass-adaptation of AM procedures in the footwear sector [19].

a) b) c) d)

Fig.1 3D printed experimental and artistic examples of shoes: a) Marieka Ratsma shoes „Biomimicry” 2012, b) Neta Soreg 2014, c) “Exobiology” Ica & Kostika 2018, d) Francis Bitonti 2014 [11-14]

a) b) c)

Fig.2 Examples of 3D printed flexible soles in sports shoes: a) Nike Vapor Laser Talon, 2013 b) Adidas Futurecraft 4D 2016, c) New Balance 2016 [18-20]

a) b) c) d)

Fig.3 Examples of women's hybrid shoes: a) company Delcam CRISPIN , b) designer Zoe Dai 2015, c) designer Kerrie Luft 2013, d) designer Ganit Goldstein 2018 [15, 21-23]

Some examples of this are Delcam CRISPIN hybrid shoes (Fig.3a) that combine a classic leather upper of a pump with a 3D printed bottom and heel [21], shoes by designer Zoe Dai (Fig.3b) [22], or innovative models of women's shoes with 3D printed titanium heels (Fig.3c) by designer Kerrie Luft publicly presented in 2013 [15]. By combining modern production technology and traditional footwear design, the shoes of fashion designer Ganit Goldstein were made, which combines 3D printing with traditional weaving techniques (Fig.3d) [23].

Although there is a large number of examples of the application of 3D printed footwear from AM procedures from different materials, the application of ABS in this sector is little researched.

2. Experimental part

The paper researches the process of applying 3D printing for prototyping women's heels from ABS, using the FDM process on a desktop printer.

2.1. Materials

ABS is a thermoplastic amorphous polymer prepared by the polymerization of styrene, acrylonitrile, and polybutadiene. Each of these monomers adds some advantage to the properties of ABS: acrylonitrile provides chemical and thermal stability, butadiene increases toughness and impact strength, and styrene gives the plastic a beautiful and glossy appearance [24, 25]. The polymer applied for 3D printing of test bodies for all research conducted is ABS made by MakerBot. The polymer in the filament form has a diameter of 1.75 mm on a reel weighing 1kg, and in addition to white, grey, black, and natural, all spectral colors are available. Different colors of the original ABS polymer (white, red, orange, green, and purple) were used during the printing of 3D heel prototypes. White ABS was applied for innovative post-dyeing process with disperse dyes to achieve colored ombre effects [26]. Three primary dispersed dyes of different chemical compositions were used during the research: Cibacet Yellow 2GC (BASF, Switzerland; C.I. Disperse Yellow 3 – DY3), Cibacet Red 3B (BASF, Switzerland; C.I. Disperse Red 15 - DR15) and Foron Blue RD GLF, (Sandoz, Switzerland; C.I. Disperse Blue 27 - DB27).

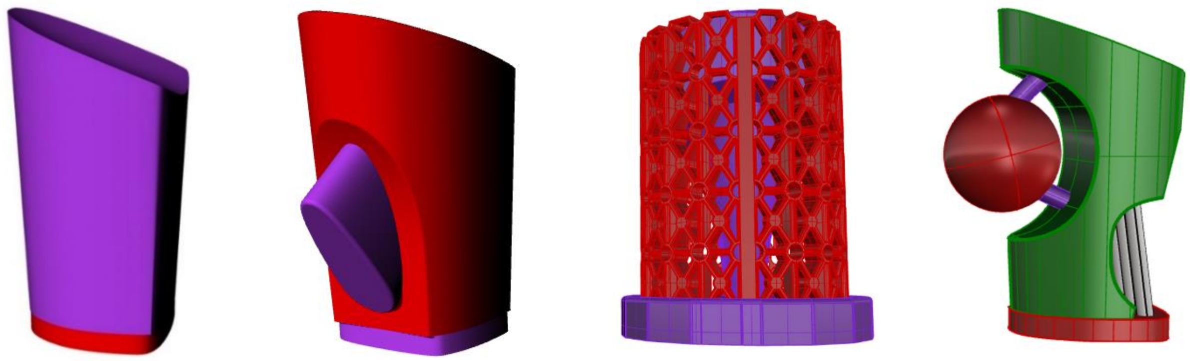
2.2. Constructing the heel prototypes

Due to geometric and dimensional accuracy, the original mold of the women's No. 37 shoe (factory name of the Pia mold) and the corresponding original 75 mm high heel were scanned for the purpose of constructing a computer 3D CAD model of the heel prototype. With this, a CAD mold model and CAD heel model were made. Based on the geometry and dimensions of the mentioned CAD models, simple CAD heel models with classic shapes (Figs.4a, 4b) were constructed in the computer program Rhinoceros 5. The aim was to test the possibility of mounting 3D printed heels by classic procedures for joining the upper with the outer sole as well as the behaviour of ABS material during the assembly process (connecting the heel to the upper of the shoe). ABS creations are light and strong, and the lack of elasticity of ABS materials can be solved to some extent by modeling hollow structures [8]. Following the aforementioned, CAD models of heel prototype heels of hollow structures (Fig.4c) and more complex geometric shapes (Fig.4d) were modeled [27, 28]. CAD models from simpler shapes (Fig.5a) were constructed for prototypes intended for subsequent dyeing with disperse dyes to achieve multicolor effects. This was done in order to emphasize the possibility of achieving tonal modulation of color from lighter to darker tones as well as more complex forms (Figs.5b, 5c).

2.3. 3D printing

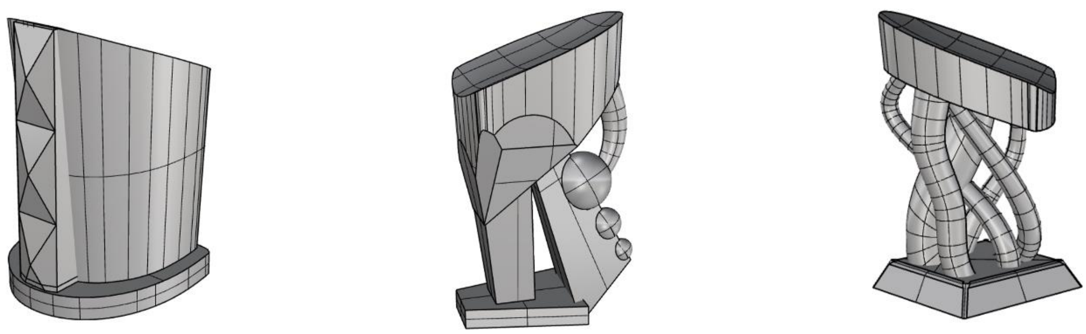
The specimens were fabricated using the FDM process from ABS on a MakerBot Replicator 2X desktop printer from MakerBot Industries, USA. After verifying that the CAD model is correct, the STL files were transferred to the desktop 3D printer MakerBot Replicator 2X and the 3D printing parameters were set in Maker Ware (printer software). The parameters of the 3D print were determined based on conducted research of mechanical properties (flexural and compressive properties and impact) of 3D printed test specimen in accordance with the targeted application to the final product, prototypes of shoe sole parts [27].

With insight into the results of complex optimization of a test specimen of linear filling at a 45° angle and honeycomb filling, the following parameters were defined: linear filling L45, layer thickness 0.15 mm, infill density 40 %, and printing temperature 205 °C [27]. The printing parameters of prototype heels are listed in Tab.1.



a) b) c) d)

Fig.4 CAD model of heel prototype: a) prototype 1, b) prototype 2, c) prototype 3, d) prototype 4



a) b) c)

Fig.5 CAD model of heel prototype: a) prototype 5, b) prototype 6, c) prototype 77

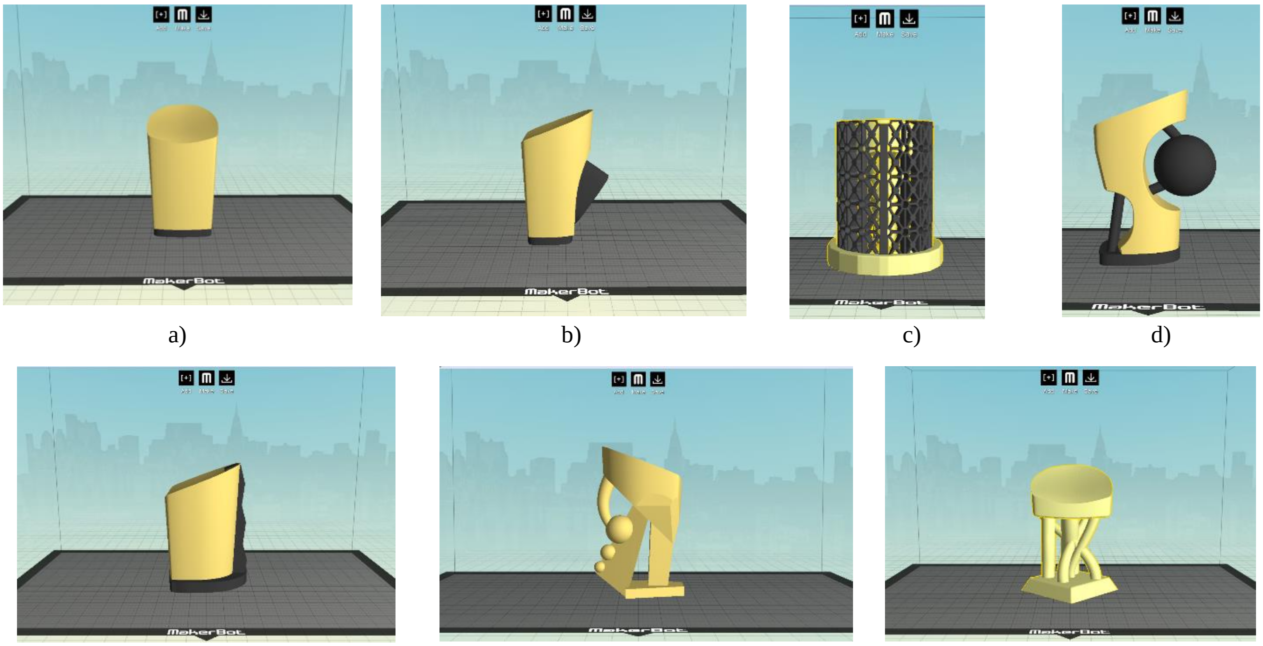
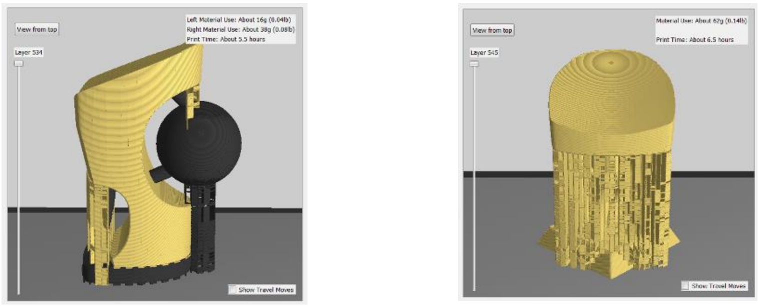


Fig.6 Positioning on the work surface of the 3D printer: a) prototype 1, b) prototype 2, c) prototype 3, d) prototype 4, e) prototype 5, f) prototype 6, g) prototype 7



a) b)

Fig.7 3D printing overview with support structure: a) prototype 4, b) prototype 7

Tab.1 3D printing parameters of heel prototypes

Print Parameter	**Value**
Layer thickness	0.15 mm
Infill density	40 %
Number of shells	3
Infill build speed	90 mm/s
Shell speed	40 mm/s
Infill Pattern	linear 45°
Roof Thickness	1.00 mm
Temperature nozzle	205 °C

The choice of the orientation of the creations during production depends on the design, the time of production, the supporting structure that must be separated later, or the target mechanical properties of the final product [28]. The vertical orientation of the prints of the heel prototypes was determined in accordance with the actual orientation of the heel and the central positioning on the working surface of the 3D printer (Fig.6) [27, 28].

Considering the selected parameters and the orientation of the print, the estimated total material consumption and 3D printing time for heel prototypes are shown in Tab.2. Prototypes 1 to 5 were made by printing polymers of different colors, so Tab.2 for the mentioned prototypes shows the consumption of material 1 and material 2.

In prototypes 4 and 7, individual surfaces close the angle with the Z-axis of the device greater than 45°, and it is necessary to add support structures during 3D printing (Fig.7). A separating layer was placed between the support structure and the creation so that after the creation is made, the support structure can easily be detached without damaging the creation. In two-color printing, the support structure will print by default with mixed materials, with each part corresponding to the part of the object it touches, as shown in Fig.7.

Tab.2 Consumption of materials and production of 3D prints of prototype heels

Value	**Prototypes 1**	**Prototypes 2**	**Prototypes 3**	**Prototypes 4**	**Prototypes 5**	**Prototypes 6**	**Prototypes 7**
Material 1 [g]	4	8	36	16	16	45	62
Material 2 [g]	53	50	61	38	70	-	-
Time [h]	7.5	8.5	13.5	5.5	8.5	4.5	6.5

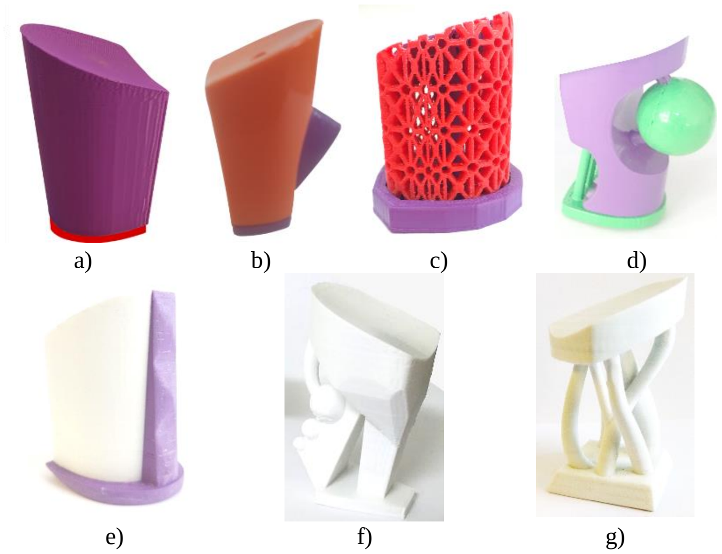


Fig.8 3D printed prototype heels: a) prototype 1, b) prototype 2, c) prototype 3, d) prototype 4, e) prototype 5, f) prototype 6, g) prototype 7

Tab.3 Heels prototype obtained with a mixture of dyes with an ombre effect

Prototype 5	**Dyes Dye Direction**	**Prototype 6**	**Dyes Dye Direction**	**Prototype 6**	**Dyes Dye Direction**
	1 % DB 27 ↓ 3 % DR 15 ↓ 3 % DR 15 + 1 % DB 27 ↓ 3 % DR 15 ↑		3 % DR 15 + 1 % DB 27 ↓ 3 % DR 15 ↓ 3 % DR 15 + 3 % DY 3 ↓ 3 % DR 15 + 1 % DB 27 ↑ 1 % DB 27 ↑		3 % DY 3 ↑ 3 % DY 3 + 3 % DR 15 ↓ 3 % DR 15 ↓ 3 % DR 15 + 1 % DB 27 ↓ 1 % DB 27 ↓

2.4. Dyeing Process

Ombre dyeing was performed by capillary movement of the dye solution along the substrate. The substrate stands vertically in the dye solution, and the dye is applied vertically, giving the substrate a colored fade effect. By rotating the 3D printed ABS specimens, i.e., changing the direction and type of dye, different shaded effects were obtained [26]. The bath ratio was 1:30, pH was adjusted with 20% acetic acid, Kemika, Croatia, color concentration (*Dc*) 1 and 3 and % by weight of the material.

3. Results

The results of the 3D printed heels prototype on the MakerBot Replicator 2X desktop printer made of ABS are shown in Fig.8. Prototypes 5, 6, and 7 made of ABS were colored with a combination of blue, red, and yellow disperse dyes by the depletion process, and the achieved colored effects shown in Tab.3. Considering concentrations and gradients, bath dilution was adjusted based on preliminary tests [25, 26].

The incorporation of the 3D printed heel prototypes from ABS (Fig.9) into functional models of women's shoes is combined with the classic production of shoes within the industrial production of footwear with the aim of creating personalized models of wearable

Fig.9 Realized prototypes of women's functional shoes: a) prototype 1, b) prototype 2, c) prototype 3, d) prototype 4, e) prototype 5, f) prototype 6, g) prototype 7

shoes or smaller limited series. The emphasis on the prototype of the heel, i.e. the application of new technologies (3D printing) in combination with traditional methods of footwear, is emphasized by the choice of contrasting colors of the upper material in relation to the heel. The upper of the realized prototypes is a model of a classic women's pump, with an ergonomically modelled cut according to the rules and requirements of shoe construction, made of leather which is still one of the most valued and high quality materials in footwear.

The upper of prototypes 1 and 5 is made of cow hide, and all the others are made of cow nappa leather, which in addition to good mechanical properties (tensile strength, tear resistance, softness, and pliability) also meets specific properties such as hydrophobicity, antibacterial, resistance to various environmental influences, environmental justification properties, etc. Insoles are made of pigskin lining which with its properties like resistance to sweat, good resilience, permeability to air and water vapor and moisture absorption, provides comfort and so-called hygienic properties of footwear [7].

4. Conclusion

In the footwear industry, increasing attention is paid to design-shaped heels. But that design involves production of the complicated geometry, personalised heels (i.g. small series), light weight heels and if possible cheap production. Technology that enables and combines that is additive manufacturing (AM). Prototypes of heels made of ABS by the FDM process were mounted in functional models of women's wearable shoes by industrial processes and technologies of assembling the upper and outer sole of footwear according to all operations of the assembly phase. Successful assembly procedure shows that the height of the heels and the geometry of the upper surface of the heel prototype are precisely modelled according to the mold, thus achieving technical and aesthetic requirements for assembling heels with a classic upper in industrial production conditions. It was also found that ABS as one of the most commonly used materials in the FDM process can be functionally applied for the production of prototypes and individual elements of the shoe sole, or in this paper high heels of women's shoes. Looking at the results of the multicolour ("ombre") effects, the opportunity to add value in the visual effects created by limiting printing to two colors in most desktop 3D printers can be recognized. When using shoes with heels made of ABS, slippage occurs, which could affect the impracticality of wearing, and it is recommended to add an anti-slip layer to the bottom of the heel.

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References:

[1] Matias E., B. Rao: 3D printing: On its historical evolution and the implications for business, Proceedings of the PICMET 2015: Management of the Technology Age, Portugal 2015, 551-558

[2] Calzado M., L. Romero, et al: Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects, Complexity (2019.) 1–31

[3] Gibson I., D. Rosen, et al: Rapid Prototyping, and Direct Digital Manufacturing, 2nd ed., Springer, New York, 2015

[4] Boschetto A., L. Bottini, et al: Finishing of Fused Deposition Modeling parts by CNC machining, Robotics and Computer-Integrated Manufacturing 41 (2016.), 92–101

[5] Bikas H., P. Stavropoulos, et al.: Additive manufacturing methods and modelling approaches: a critical review, The International Journal of Advanced Manufacturing Technology 83 (2016) 1-4

[6] Vanderploeg A., S.-E. Lee, et al: The application of 3D printing technology in the fashion industry, International Journal of Fashion Design, Technology and Education 10 (2017.), 170-179

[7] Kutnjak-Mravlinčić S., J. Akalović, et al: Merging footwear design and functionality, AUTEX research journal, 20 (2020) 372-381

[8] Vanderploeg A., S.-E.; Lee, et al.: The application of 3D printing technology in the fashion industry, International Journal of Fashion Design, Technology and Education, 10 (2017.), 170-179

[9] Kutnjak-Mravlinčić S., D. Godec, i sur.: 3D modeliranje i 3D ispis šupljikavih struktura u obućarstvu, Zbornik radova 9. znanstveno - stručnog savjetovanja Tekstilna znanost i gospodarstvo - Kreativni mikser, Zagreb 2016, 100-103

[10] Thompson M.K., G. Moroni, et al: Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints, CIRP Annals Manufacturing Technology 65 (2016.), 737-760

[11] Sun Lim H.: Development of 3D Printed Shoe Designs Using Traditional Muntin Patterns, Fashion & Textile Research Journal, Vol. 19 (2017.), 134-139

[12] Chalcraft E.: Biomimicry Shoe by Marieka Ratsma and Kostika Spaho, dostupno na: https://www.dezeen.com/2012/07/17/biomimicry-shoe-by-marieka-ratsma-and-kostika-spaho

[13] Yusuf B.: These Spring Heel Shoes Can Only Be Made with 3D Printing, Available from: https://all3dp.com/spring-heel-shoes/

[14] Watkin H.: Ica & Kostika Launch 3D-Printed Exobiology Shoe Collection, dostupno na: https://all3dp.com/4/ica-kostika-launch-3d-printed-exobiology-shoe-collection

[15] Kutnjak-Mravlinčić S., S. Bischof, et al: Application of additive technology in footwear design, Proceedings of the 8th Central European Conference on Fiber-grade Polymers, Chemical Fibers and Special Textiles, Zagreb 2015., 201-206

[16] Sher D.: Footwear industry leads in race for 3D printed consumer products, dostupno na https://www.3dprintingmedia.network/footwear-industry-leads-in-race-for-3d-printed-consumer-products

[17] Scott C.: Dr. Scholl's Partners with Wiivv for 3D Printed Custom Insoles, 3D Printing Industry, dostupno na: https://3dprint.com/233413/dr-scholls-partners-with-wiivv/

[18] Wilson M.: Nike Vapor Laser Talon: Football's First 3-D Printed Shoes, dostupno na https://www.fastcompany.com/1672004/nike-vapor-laser-talon-football-s-first-3-d-printed-shoes

[19] Koslow T.: Carbon & Adidas Unleash Revolutionary Futurecraft 4D Footwear, dostupno na https://all3dp.com/carbon-adidas-futurecraft-4d-footwear

[20] Molitch-Hou M.: New Balance Announces Date of Exclusive 3D Printed Shoe Sales, dostupno na: https://3dprintingindustry.com/news/new-balance-announces-date-of-exclusive-3d-printed-shoe-sales-76121

[21] Thimmesch D.: Delcam CRISPIN's 3D Footwear Design Software: Hybrid Shoes Combine Tradition and High-Tech, dostupno na: https://3dprint.com/40233/delcam-crispin-hybrid-shoes

[22] Krassenstein E.: Interview with Zoe Dai – Designer of Incredible 3D Printed High Heel Shoes, dostupno na https://3dprint.com/60746/zoe-dai-3d-printed-shoes

[23] Freier A.: Fashion Design Graduate Takes Major Step With Woven 3D Printed Shoes, dostupno na https://all3dp.com/fashion-design-graduate-takes-major-step-woven-3d-printed-shoes

[24] Chen G., C. Chen,et al: Color 3D Printing: Theory, Method, and Application, New Trends in 3D Printing, InTechOpen, London 2016., 25–51

[25] Kutnjak-Mravlinčić S., M.I. Glogar, et al: Determination the coloristic values of 3D objects printed from acrylonitrile/butadiene/styrene, Proceedings of the VI Scientific-Vocational Conference Development Tendencies in the Textile Industry—Design, Technology, Management, Beograd 2018., 101–105

[26] Kutnjak-Mravlinčić S., A. Sutlović, et al: Innovative Development of Batch Dyed 3D Printed Acrylonitrile/ Butadiene/ Styrene Objects, Molecules 26 (2021.), 1-14

[27] Kutnjak-Mravlinčić S. Utjecaj parametara 3D ispisa postupkom taložnog očvršćivanja i geometrije šupljikavih struktura na svojstva 3D ispisanih proizvoda od akrilonitril/butadien/stirena, doctoral dissertation, University of Zagreb Faculty of Textile Technology, Zagreb, 2021.

[28] Kutnjak-Mravlinčić S.; A. Pilipović, et al: Selection of appropriate 3D printing orientation considering actual product, Proceedings of the RIM 2019 — Development and Modernization of Production, Sarajevo 2019., 455–460