

# Testing the abrasion resistance of 3D printed test specimens made of acrylonitrile/butadiene/styrene by fused deposition modeling

## Ispitivanje otpornosti na plošno habanje 3D ispisanih ispitnih tijela iz akrilonitril/butadien/stirena postupkom taložnog očvršćivanja

Scientific paper / Znanstveni rad

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### Abstract

Additive manufacturing processes are of great importance for the development of modern production, which is why much research is being carried out to determine or improve the properties of 3D printed products depending on the desired application. In this work, the abrasion resistance of acrylonitrile/butadiene/styrene (ABS) test specimens was investigated using fused deposition modeling (FDM) for the production of shoe heels or shoe bottoms. The test was performed using the Martindale wear method on 3D printed ABS test specimens colored with disperse dyes in the depletion process and on 3D printed test specimens colored in the mass of the original ABS polymer. In accordance with HRN EN ISO 12947-3:2008 Determination of abrasion resistance using the Martindale method: determination of mass loss, the results show the mass loss in % and the change in thickness of the test specimen in %. Abrasion resistance was tested on substrates of varying fineness, with the outer and inner surfaces simulated according to the intended application. Six abrasive substrates were selected and three test specimens were tested for each substrate. The results of the test showed a higher abrasion resistance of the test specimens painted in the mass (original ABS polymer in color) compared to the test specimens subsequently painted with dispersion paints.

**Keywords:** fused deposition modeling; 3D printing; acrylonitrile/butadiene/styrene; abrasion resistance; shoe sole

### Sažetak

Postupci aditivne proizvodnje značajni su u razvoju suvremene proizvodnje stoga se provode mnoga istraživanja kako bi se utvrdila ili poboljšala svojstva 3D ispisanih tvorevina u skladu sa željenom primjenom. U radu je ispitana otpornost na habanje ispitnih tijela izrađenih iz akrilonitril/butadien/stirena (ABS) postupkom taložnog očvršćivanja (e. *Fused Deposition Modeling* – FDM) s ciljanom primjenom izrade potpetica cipela ili donjišta obuće. Ispitivanje je provedeno postupkom nahabavanja prema Martindaleu na 3D ispisanim ABS ispitnim tijelima obojenim disperznim bojilima postupkom iscrpljivanja i 3D ispisanim ispitnim tijelima bojenim u masi originalnog ABS polimera. Prema normi HRN EN ISO 12947-3:2008. Određivanje otpornosti na habanje metodom po Martindaleu: Određivanje gubitka mase, u rezultatima su prikazani gubitak mase u % i promjena debljine ispitnog tijela u %. Otpornost na

habanje ispitana je na podlogama različite finoće kojima su simulirane vanjske i unutrašnje površine u skladu s ciljanom primjenom. Odabrano je šest abrazivnih podloga i za svaku podlogu ispitana su tri ispitna tijela. Rezultati ispitivanja pokazali su veću otpornost na habanje ispitnih tijela bojanih u masi (original ABS polimer u boji) u odnosu na ispitna tijela naknadno bojana disperznim bojilima.

**Ključne riječi:** taložno očvršćivanje; 3D ispis; akrilonitril/butadien/stiren; otpornost na habanje; donjište obuće

## 1. Introduction

The fused deposition modeling (FDM) process, which is part of the additive manufacturing (AM) process, enables the rapid production of prototypes or small series with greater flexibility compared to conventional production processes. The advantage of the AM process lies in the production of objects in a single step, directly from a computer-aided design (CAD) model without the use of additional tools [1-3]. The FDM process is a key enabling technology (KET) and one of the most commonly used techniques for prototyping and personalized production [4, 5]. There are a number of materials suitable for the FDM process, including acrylonitrile/butadiene/styrene (ABS), polycarbonate (PC), blends of acrylonitrile/butadiene/styrene and polycarbonate (ABS/PC), polylactide (PLA), poly(methyl methacrylate) PMMA, polyamide (PA), polyetherimide (PEI) and others [6, 7]. One of the most commonly used materials for the production of 3D printed objects for various applications is ABS due to its dimensional stability and low glass transition temperature as well as its beautiful and glossy appearance [8]. ABS is a plastomeric amorphous polymer composed of polymerizable styrene, acrylonitrile and polybutadiene and generally has good flexural strength at reduced temperature, satisfactory stiffness and dimensional stability, glossy surface and the ability to perform functional testing of parts [9, 10].

The application of AM processes in the footwear industry for the production of complete shoe models or individual parts such as soles or heels is becoming increasingly important [11-14]. Shoes or their parts produced using the FDM process are no longer a novelty, but represent a hybrid fusion of traditional footwear and innovative 3D printing technology [15-18].

The application of AM in the footwear industry can be divided into three segments: 3D printing of individual shoe parts such as soles, heels, decorative and/or functional details, 3D printing of

complete models with simple or complex geometries, and 3D printing of built-in parts, e.g. insoles [11, 18].

Numerous scientific studies have been conducted in the last decades, providing a large amount of data on the influence of 3D printing parameters in the FDM process on the mechanical properties of the objects, such as flexural and/or tensile strength [19-22].

From the available literature, it appears that there are only a few papers dealing with testing the wear resistance of materials for additive manufacturing. As part of a PhD thesis [23], extensive research was conducted on the fabrication of prototype heels using the 3D printing process and their characterization, and some of the research results were published in a scientific article in an international journal [24].

## 2. Experimental part

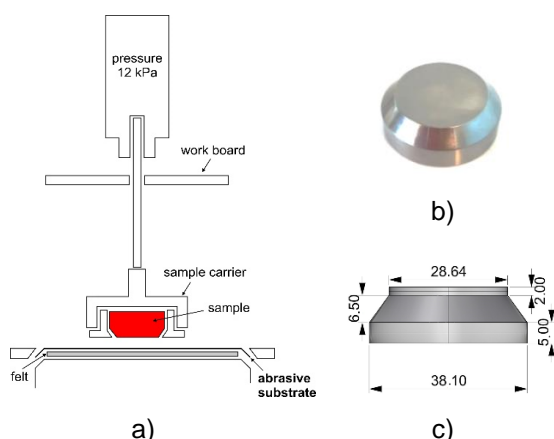
### 2.1. Acrylonitrile/butadiene/styrene material

ABS is a polymer that was used for the 3D printing of test specimens (manufactured by MakerBot, MakerBot Industries, New York, NY, USA). The polymer is in the form of a filament with a diameter of 1.75 mm, the mass of the spool is 1 kg, and test specimens were made from the filament colours True red and Natural for research purposes. The 3D printed test specimens made of natural ABS were dyed with the disperse dye C.I. Disperse Red 15 using the batch dyeing method prior to wear [24, 25].

### 2.2. 3D printing test specimens

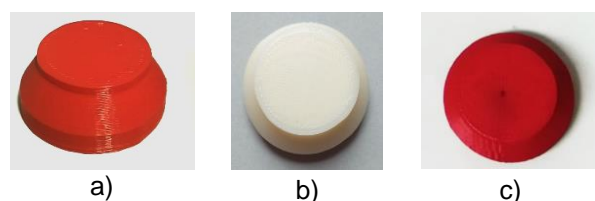
The test specimens are manufactured from ABS using a desktop 3D printer that works according to the FDM process. To perform the abrasion resistance test, the CAD model of the test specimen (Figure 1c) was modeled using the Rhinoceros 5 computer program according to the

Martindale test specimen fixture (Figures 1a and 1b) and the dimensions specified in the standard ( $\varnothing 38.1 \pm 0.05 \times \varnothing 28.65 \pm 0.05$  mm) [26], taking into account a tolerance of 2 mm due to the performance of the test.



**Figure 1.** Test specimen for abrasion: a) scheme of the abrasion tester, b) original support cover and c) CAD model of the test specimen [24].

A MakerBot Replicator 2X desktop 3D printer (MakerBot Industries, USA) was used to produce 3D printed specimens using red ABS (Figure 2a) and natural ABS to colour the specimens (Figure 2b). An example of a specimen coloured with C.I. Disperse dye. Disperse Red 15 is shown in Figure 2c.



**Figure 2.** 3D printed wear test specimens: a) and b) coloured in the mass from original red and natural ABS and c) post dyeing with disperse dye [24].

The parameters of the 3D printing of coloured and post-coloured test specimens are listed in Table 1.

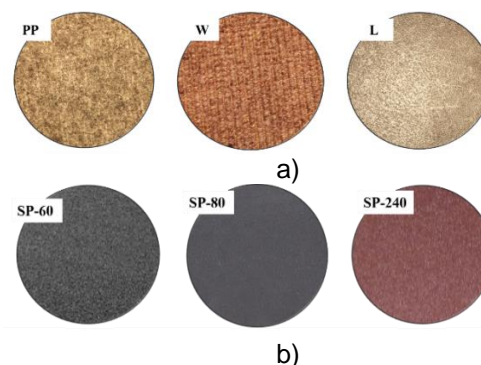
**Table 1.** Parameters of the 3D printing of ABS test specimens.

3D Print Parameter	Value
Layer thickness	0.20 mm
Infill density	40 %
Infill build speed	90 mm/s

Shell speed	40 mm/s
Number of shells	3
Infill pattern	honeycomb
Extrusion temperature	230 °C
Platform temperature	110

### 2.3. Abrasive surfaces for testing

The wear surfaces on which the test was carried out under simulated conditions were also selected according to the intended application of the end product. Substrates for indoor surfaces and substrates simulating outdoor surfaces were selected. Since most indoor areas use floor coverings made of natural and synthetic fibers and polymers, commercially available floor covering samples were selected: Carpets made of polypropylene and wool fibers (PP and W) and linoleum (L), which are shown in Figure 3a. Abrasive papers of different grits (SP-60, SP-80, SP-240) were used to test abrasion resistance when the final product was applied to exterior surfaces (e.g. asphalt or concrete and exterior/interior surfaces such as ceramic tiles) (see Figure 3b); their specifications are listed in Table 2.



**Figure 3.** Samples of wear surfaces: a) carpet made of polypropylene and wool fibers (PP and W) and linoleum (L) and b) sandpapers with granulation (SP-60, SP-80, SP-240).

**Table 2.** Specification of abrasives

Abrasive substrates	Label	Thickness, mm
Polypropylene carpet	PP	1.52
Wool carpet	W	4.80
Linoleum	L	1.28
Sandpaper, grit sizes 60	SP-60	0.94
Sandpaper, grit sizes 80	SP-80	0.74
Sandpaper, grit sizes 240	SP-240	0.50

## 2.4. Testing the Abrasion Resistance according to Martindale

The abrasion resistance test was carried out using a Martindale abrasion resistance and peel tester from Mesdan S.p.A., Italy, model Martindale 2561E. The device is used to test flat textiles and leather for flat abrasion and to test the peel tendency of flat textile materials [26]. The device has 6 working positions, i.e. wear heads that change the direction of movement (Lissajous curves that determine the correct operation) depending on which test is being performed [26].

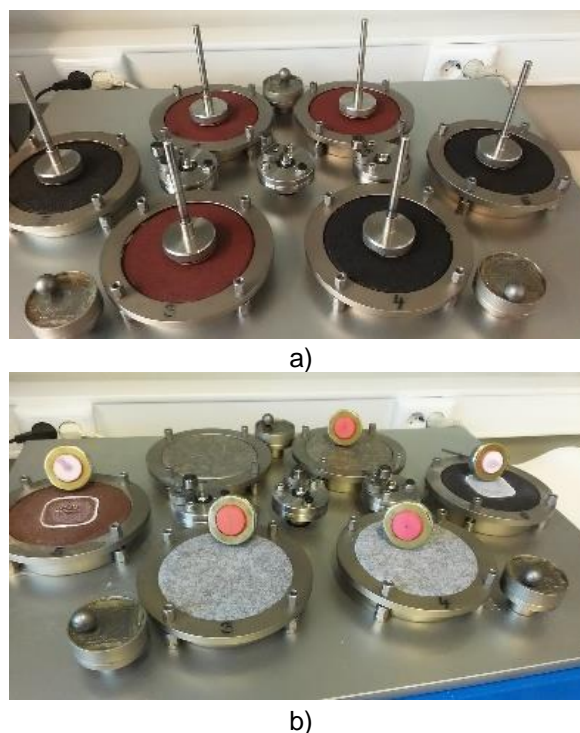
The wear resistance test is carried out in accordance with the HRN EN ISO 12947-3:2008 standard at a load of 9 kPa and 12 kPa [26], depending on the type and intended use of the textile material. The tests are carried out under standard test atmosphere conditions (HR = 65±4 % and temperature 20±2 °C). When submitting the results, the test conditions, including the wear agent used, the test method and other necessary information must be specified.

Prepared cylindrical grinding wheels with a diameter of 140 mm were placed on the working plates of the wear fixture and the test specimens were inserted into the fixture (Figure 4). The wear was performed with a load of 12 kPa. The main objective of the test is to analyze the wear resistance of 3D printed ABS specimens to simulate the wear of functional soles (soles) of shoes.

The test was performed according to the wear method [25] on 3D printed ABS test specimens that were colored in the mass and on 3D printed ABS test specimens that were subsequently colored to determine their performance characteristics.

Material wear is caused by the relative movement of the specimen under test against the wear medium, with the friction causing wear of the tested material for a certain time, i.e. up to a certain number of cycles. If the wear process is carried out until visible damage to the flat product occurs, it is referred to as a wear process and the result is the number of cycles that lead to visible damage to the specimen. The result of the test is expressed as a loss of mass in % and as a change in thickness of the specimen in %. Given the particularities of the specimen in terms of material, appearance and intended use, the test procedure must be adapted and modified,

especially when preparing and manufacturing special 3D printed specimens for testing (t. 2.2).



**Figure 4.** Martindale abrasion resistance test: a) prepared wear surfaces and test specimens and b) test specimens after completion of the test.

During the abrasion resistance test of 3D printed ABS test specimens, the mass loss (according to expression 1) and the thickness change (according to expression 2) of the worn part of the sample were monitored.

$$\Delta m = \frac{m_{cycles} - m_{initial}}{m_{initial}} * 100 [\%] \quad (1)$$

$$\Delta d = \frac{d_{cycles} - d_{initial}}{d_{initial}} * 100 [\%] \quad (2)$$

where:  $\Delta m$  [g] - change in the mass of the wear sample,  $m_{cycles}$  [g] - mass of the sample after the cycle,  $m_{initial}$  [g] - initial mass of the sample,  $\Delta d$  [mm] - change in the thickness of the wear sample,  $d_{cycle}$  [mm] - thickness of the sample after the cycle and  $d_{initial}$  [mm] - initial thickness of the sample.

## 3. Results and discussion

To test the functionality of the prototypes, the abrasion resistance of the colored 3D printed test specimens was tested on six substrates with






different structures. This ensures a simulation of the abrasion resistance tests on the inner and outer surfaces, which is important with regard to possible use in shoe production.

Three specimens were tested for each abrasion surface, resulting in a total of 36 specimens. When analyzing the abrasion resistance of the monitored measurements, i.e. mass loss and thickness change, the mean value of the test specimens was used as the analysis value. Snapshots of the surface structure of the worn specimens are also shown for better illustration and to identify significant differences in the results tables.




### 3.1. Results of testing abrasion resistance of post dyeing test specimens

Tables 3 and 4 show the mean values of the results for the mass loss ( $\Delta m$ ), the thickness changes ( $\Delta d$ ) of the test specimens and the appearance of the surface structure of the tested mass coloured test specimens.

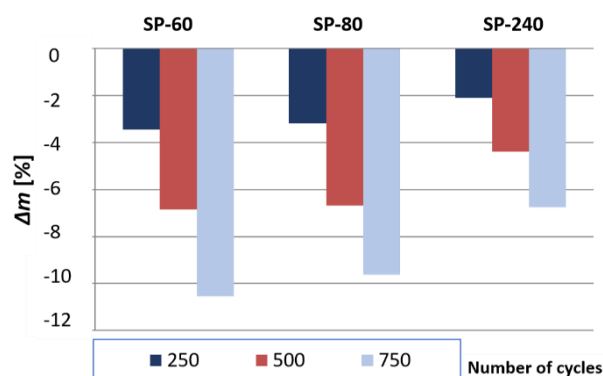
**Table 3.** Test results of mass coloured test specimens on abrasive surfaces for exterior surfaces.

Condition/ parameter	Number of cycles		
	750	750	750
	Abrasive substrates		
	SP-60	SP-80	SP-240
$\Delta m$ [%]	-10.55	-9.62	-6.76
$\Delta d$ [%]	-10.81	-9.88	-5.85
Surface topography			

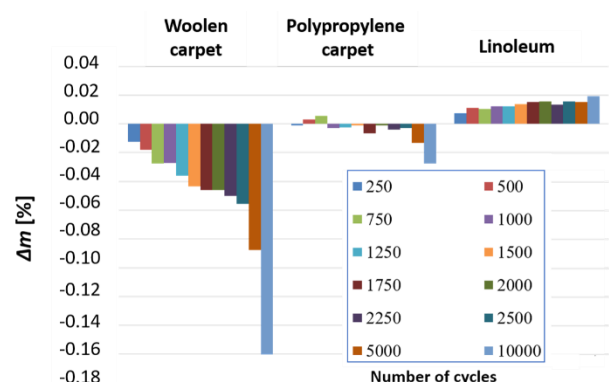
**Table 4.** Test results of mass-coloured test specimens on abrasive surfaces for interior surfaces.

Condition/ parameter	Number of cycles		
	10 000	10 000	10 000
	Abrasive substrates		
	PP	W	L
$\Delta m$ [%]	-0.03	-0.16	0.02
$\Delta d$ [%]	-0.15	-0.72	-0.44
Surface topography			

Figures 5 and 6 show diagrams of the change in mass for all abrasive substrates as a function of the wear cycles for test specimens coloured in mass.



**Figure 5.** Diagram of the mass loss of mass coloured test specimens after cycles for the abrasive substrates SP-60, SP-80 and SP-240.



**Figure 6.** Diagram of the mass loss of mass coloured test specimens as a function of the cycles for W, PP and L abrasive substrates.

A comparison of the results obtained as a function of the abrasive substrate shows a significant influence of the substrate on the wear of the test specimen (Table 3). This is confirmed by the results obtained after wear with different abrasives used as outer substrate, where a change in mass loss between -6.76 and -10.55 % was observed for the same number of cycles (750).

In contrast, for abrasives used as indoor floor coverings, the changes in mass loss even after 10 000 cycles are almost unchanged with respect to the initial mass and range between -0.02 and -0.16 % (Table 4). These results are supported by the measured thickness changes of the worn part of the test specimens, which are fully dependent on or consistent with the wear medium and range between -5.85 % and -10.81 % for external wear surfaces and between -0.15 % and -0.72 % for internal wear surfaces (Tables 3 and 4).

From Table 3 and the graph showing the decrease in thickness versus mass (Figure 5), it can be seen that the greatest loss in mass is seen in the test specimens with wear on substrate SP-60 (-10.55 %) and the test specimens with wear on substrate SP-80 (-9.62 %), which depends on the appearance of the surface. The greatest change in the form of a reduction in the thickness of the test specimens where the outer surface is worn or eroded by abrasion and a visible inner infill of the honeycomb is also experienced by the wear test specimens on the SP-60 substrate (-10.81 %) and the wear test specimens on the SP-80 substrate (-9.88 %). The test specimens worn on the SP-240 substrate also show a considerable loss of mass (-6.76 %) and a smaller reduction in thickness (-5.85 %), which is reflected in a partial internal honeycomb infill of the test specimens.

Table 4 shows that the specimens worn on carpet (W and PP) exhibit almost imperceptible changes in the appearance of the outer surface and the mass loss is minimal, amounting to only -0.03% for the specimens worn on the PP substrate and -0.16% for the specimens worn on the W base.




A minimal increase in mass (+0.02 %) is observed for the specimens worn on a linoleum surface after 10,000 cycles, suggesting that fragments of the abrasive substrate became partially embedded in the surface structure of the specimens during wear, as can be seen in Figure 6, although these specimens showed a minimal -0.44 % decrease in thickness at the end of the test (Table 4). The above results show that the abrasion resistance of abrasive substrates simulating outdoor surfaces is significantly lower than that of indoor carpet and linoleum substrates.

From the results of the abrasion resistance test with indoor floor coverings, it can be concluded that the mass-coloured test specimens have excellent abrasion resistance and their potential use for the manufacture of heels or shoe soles would be justified. On the other hand, the results of the abrasion resistance test under outdoor conditions show that the wear of the outer layers of the test specimens occurred at a significantly lower number of cycles (750), which is to be expected given the roughness of such solid surfaces.




### 3.2. Results of testing abrasion resistance of test specimens that were coloured with a disperse dye

Tables 5 and 6 show the mean values of the results for the mass loss ( $\Delta m$ ), the thickness changes ( $\Delta d$ ) of the test specimens and the appearance of the surface structure of the tested test specimens, which were subsequently dyed with disperse dye.

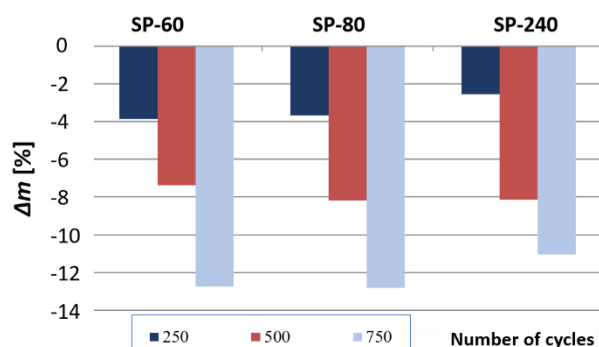
**Table 5.** Test results of test specimens subsequently colored with disperse dye on abrasive surfaces for exterior surfaces.

Condition/ parameter	Number of cycles		
	750	750	750
	Abrasive substrates		
	SP-60	SP-80	SP-240
$\Delta m$ [%]	-12.74	-12.81	-11.03
$\Delta d$ [%]	-10.79	-12.56	-6.52
Surface topography			

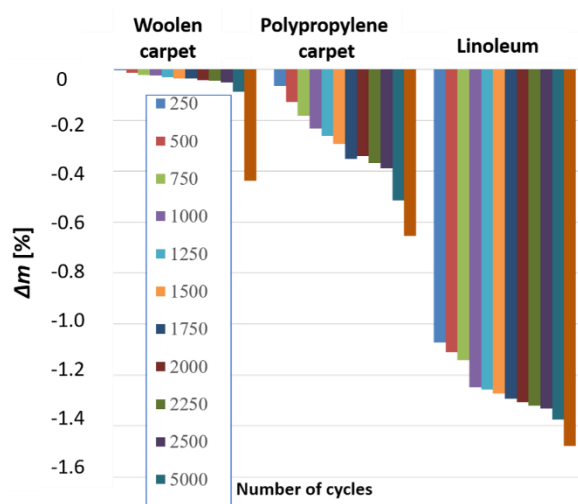
**Table 6.** Test results of test specimens subsequently coated with disperse dye on abrasive surfaces for interior surfaces.

Condition/ parameter	Number of cycles		
	10 000	10 000	10 000
	Abrasive substrates		
	PP	W	L
$\Delta m$ [%]	-0.65	-0.16	-1.48
$\Delta d$ [%]	-0.24	-1.03	-0.24
Surface topography			

Figures 7 and 8 show diagrams of the mass losses for all abrasive substrates as a function of the wear cycles for test specimens that were subsequently coloured with disperse dye.



**Figure 7.** Diagram showing the mass loss of test specimens colored with disperse dye as a function of the cycles for the abrasive substrates SP-60, SP-80 and SP-240.



**Figure 8.** Diagram showing the loss of mass of test specimens colored with disperse dye according to cycles for abrasive substrates W, PP and L.

A comparison of the results obtained as a function of the abrasive substrate shows a significant influence of the substrate on the wear of the test specimen (Table 5). This is confirmed by the results obtained after wear with different abrasives as the outer substrate, where the mass loss increased from -11.03 % to -12.81 % with the same number of cycles (750).

In contrast, for abrasives used as indoor flooring, the changes in mass loss were minimal, from -

0.16 % to -1.48 %, even after 10,000 cycles compared to the original mass (Table 6). These results are supported by the measured thickness changes of the worn part of the test specimens, which are fully dependent on or consistent with the wear medium and range between -6.52 % and -12.56 % for external wear surfaces and between -0.24 % and -1.03 % for internal wear surfaces (Tables 5 and 6).

Table 5 and the mass loss diagram (Figure 7) show that the highest mass loss was recorded for the test specimens with wear on substrate SP-80 (-12.81 %) and for the test specimens with wear on substrate SP-60 (-12.74 %), depending on the appearance of the surface. The greatest change in thickness loss of test specimens where the outer surface was worn due to abrasion or wear and the appearance of internal honeycomb infill was also observed in the wear specimens on substrate SP-80 (12.56 %) and the wear specimens on substrate SP-60 (-10.79 %). The specimens worn on substrate B-240 also showed a considerable loss of mass (-11.03 %) and a reduction in thickness of -6.52 %, which is reflected in the partial occurrence of internal infill in the specimens.

Table 6 of the results shows that the test specimens subsequently dyed with disperse dyes, which were worn on carpet and linoleum substrates (PP, W and L), exhibited a greater loss of mass and a change in thickness compared to the results of the test specimens dyed in the mass. The loss in mass of the test specimens worn on the PP substrate was -0.65 % and the change in thickness was -0.24 %. For the test specimens worn on the W substrate, the loss in mass was -0.16 % and the change in thickness was -1.03 %.

The test specimens worn on a linoleum substrate showed a mass loss of -1.48 % after 10,000 cycles, which is in complete contrast to the test results of the test specimens painted in mass on the same substrate, where a minimal increase in mass was observed. The decrease in thickness was at least -0.24 %.

#### 4. Conclusion

The development of additive manufacturing processes and the use of 3D printing in the

footwear industry offer new production potential and opportunities as well as a change to the traditional model of footwear production. At the same time, it enables faster product development, the design of complex geometries without additional tools, the adaptation of the design to specific features or conditions, the harmonisation of aesthetic and ergonomic requirements, faster prototyping and faster verification of design and/or functional solutions, which also has an impact on reducing production costs. Depending on the target application of the end product, extensive tests on the influence of mechanical properties are

carried out during the development of new products. In this test, the wear resistance of 3D printed ABS test specimens was examined using the FDM process to test the wear of shoe soles or prototypes of the heels of functional shoes. The test specimens were tested on six substrates with different properties. The selection of substrates enables the simulation of wear resistance tests on inner and outer surfaces.

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