Influence of orientation on mechanical properties in fused deposition modelling

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Abstract:

In the footwear industry, increasing attention is paid to design-shaped heels. But that design involves production of the complicated geometry, personalised heels (i.e. small series), light weight heels and if possible cheap production. Technology that enables and combines that is additive manufacturing (AM). One of AM low budget technology and machine is fused deposition modeling (FDM). In FDM, product is built layer by layer and with different types and density of inside mesh structures which enables complex geometry and low mass. When walking, the heel is loaded from above with compression force of the person's weight, while lateral, heel is loaded with flexural force and impact. Considering the design of the heel itself, it is necessary to orientate the product correctly in the working space of the machine. Orientation further raises the question of mechanical properties on such produced heel. In this paper it is tested flexural properties of two different orientation considering production of the actual heel. Furthermore, the analysis of the processing parameters (layer thickness, infill density and temperature) have been done to determine their influence on the flexural properties in these two orientations.

Keywords:

3D printing, footwear, fused deposition modeling – FDM, heel, mechanical properties, orientation, processing parameters

1. Introduction

Since the appearance of high-heeled shoes, their use is widespread in modern society in a professional or social context and often plays a key role in some activities for achieving aesthetic and cultural needs of urban society. High heels make an important part of female gender identity, although there are numerous issues of explicit and implicit use and the consequences of wearing high heels shoes. It has been scientifically proven that high heel shoes are often associated with the development of various foot deformations, lower back pain, foot pain or discomfort and tiredness of the leg and foot muscles, and there is also an increased risk of injuries due to muscle strain caused during the long wearing of the heels [1-3]. Research has also shown that high heels increase the attractiveness of women in men and that men are more concerned about the physical features of potential partners of the opposite sex [3, 4].

Historically observed, the function of the first examples of high heel shoes in the west (or in Europe) was primarily practical, inspired by weather and street conditions. Examples are wooden base attached to precious shoes during the late Middle Ages, called Pattens and shoes with a very high wooden platform Chopines, the popular women's footwear in Venice during the Renaissance. High heels shoes became an important status symbol and the dominant fashion style of men's and women's footwear during the seventeenth century (figure 1). In the French court, Louis XIV popularized red leather heels, and today one form of heel still bears his name [5-7].

France 1680-1700 Portugal 1695

Fig. 1 Men's shoe with red leather heel, France 1680-1700. and women's shoe with wooden heel, Portugal 1965. [7]

High heels are a type of shoe in which the heel, compared to the toe, is considerably higher than the ground. High heels shoes make the wearer taller, emphasizing the muscles and length of the whole legs. High-heeled shoes have a heel height of up to 10 cm or even higher compared to typical shoe instances that have a heel height of approximately 1 cm to 2.5 cm. The heels represent assembly of the shoe bottom and differ in size, height, shape, dimension, material, design, decorative accessories, applications, etc. With the development of science and technology and the changes in aesthetic standards there are apparently numerous forms of various heels, which can be reduced to common types of heels, such as military, spanish, kitten, cone, spool, continental, chunky stileletto and others (figure 2) [8, 9].

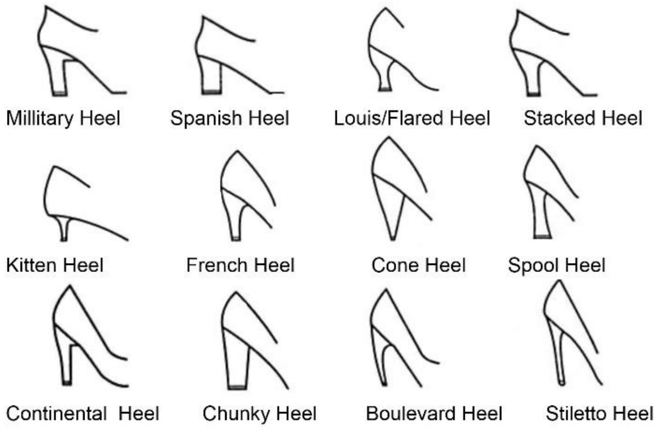


Fig. 2 Examples of common types of heels [8]

The shape, height and look is a very significant segment of the overall design of high heels. Both shoe manufacturers in the past and today's shoe designers pay great attention to innovation of the heel design (figure 3). They experiment with different materials and type of decoration for creating and beautifying high heels [7-11].

Advanced technology that has become increasingly popular in the design and production of the shoe for decades is additive manufacturing (AM). With AM can be produced functional parts of the shoe with very complex geometry, good dimensional tolerance and smooth surface. AM production of prototype forms and shoes provides the ability to create individual footwear segments; the bottom, sole, heels and the complete model of simple or complex geometry (an example of a 3D printed design by Kerrie Luft, the last illustration in Figure 3) [7-11].

Fig. 3 Examples of innovative design solutions for the heels [7, 8, 11]

Additive manufacturing in design of the heels

AM offers greater design flexibility in comparison with the traditional manufacturing processes, and provides the following unique capabilities: shape, hierarchical, functional and material complexity [12]. Based on these capabilities, design for AM (DFAM) has been explored as a means to overcome the traditional design limitations due to constraints in manufacturing processes, including machining, metal forming, casting, and injection molding [13]. By overcoming these manufacturing constraints, DFAM has versatile applications including integration of multiple parts, multifunctional part design with complex material composition, and the development of lightweight structures [14-16]. In the paper done by authors Lim, Y-E. et al. [17] it was found that a well-designed cellular cube could endure 10 000 times heavier load than its own weight (figure 4). In addition, the proposed lightweight structure can be used as real products because the generated cellular structures are conformal to their boundary surfaces and can be assembled with other solid parts effectively (figure 5).

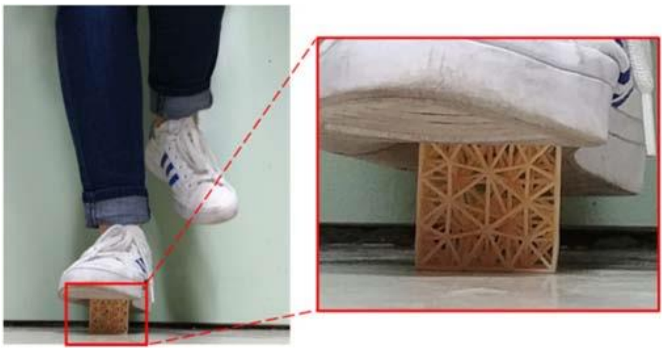


Fig. 4 Load testing of a cellular cube (40 x 40 x 40 mm; l = 15 mm, d = 1.2 mm) [17]

2. Experimental part

2.1. Production of the heel with fused deposition modeling – fdm

In this paper, the heel was made by the fused deposition modeling (FDM) on the low-budget 3D printer Makerbot Replicator 2x and two orientations were chosen as shown in figure 6. In fused deposition modeling (FDM) the polymer material in the shape of wire passes through the nozzle. The material leaves the nozzle in softened condition and at room temperature solidifies quickly. After production of the first layer, the working platform is lowered for the thickness of the new layer and the new layer is extruded through the nozzle [18]. First the external contour is made for the product and then the interior (infill). For the production of the thick-wall products the wall interior can be filled with different structures: solid structure, mesh structure (circles, lines, rectangles) and honeycomb structure (hexagonal structure) [18]. The thickness of the layer depends on the nozzle opening, material dosage and the speed of the extruder head. It usually amounts to 0.18 mm to 0.26 mm [18]. The choice of orientation depends on the design, the time of production, the supporting structure which must be separated later (the supporting structure in fused deposition modeling is separated by the breaking, and accordingly it is sometimes necessary to choose the orientation which takes longer time for production but avoid the supporting structure which is difficult to separate if it is made with low-budget 3D printers with one nozzle). For the heel in figure 6a with vertical orientation, it is necessary 46 g of material for the heel and 3 g for supporting structure and it takes 7.5 h for production, while for the second orientation, horizontal orientation (figure 6b) we need 46 g of the material for the heel, 4 g for the supporting structure, and it takes 6.5 h for production.

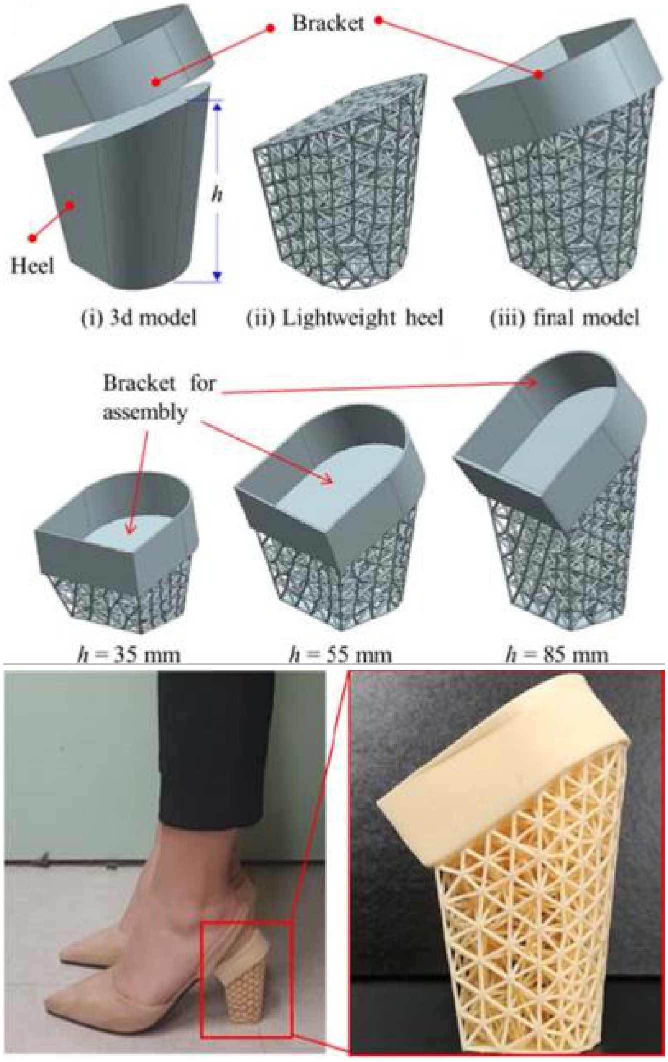
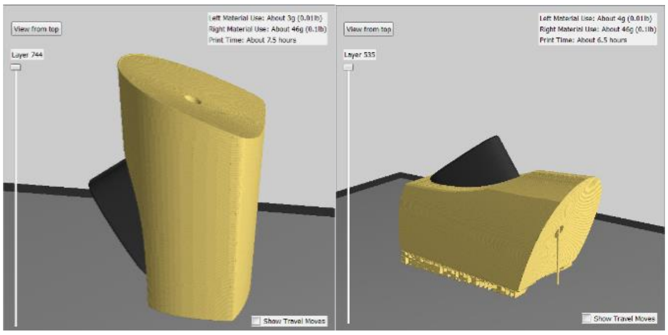


Fig. 5 Application of a lattice structure on the actual product - the heel [17]



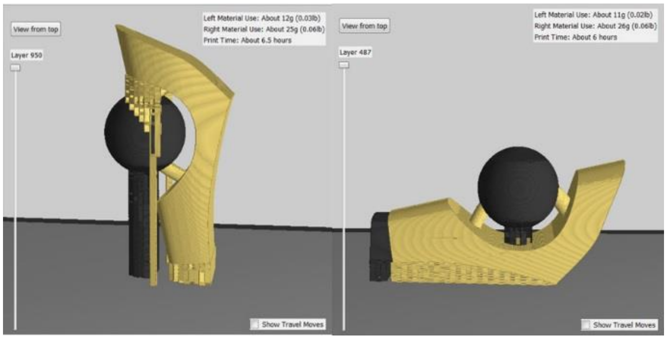
Left Material Use: About 3g (0.01lb)
Right Material Use: About 46g (0.1lb)
Print Time: About 7.5 hours

Left Material Use: About 4g (0.01lb)
Right Material Use: About 46g (0.1lb)
Print Time: About 6.5 hours

a b

Fig. 6 Orientation of the first design of the heel: a) vertical orientation, b) horizontal orientation

For other design of the heel (figure 7) in vertical orientation (figure 7a), it is necessary 25 g of material for the heel and 12g for supporting structure and it takes 6.5 h for production, while for the horizontal orientation (figure 7b) we need 26 g of the material for the heel, 11 g for the supporting structure, and it takes 6 h for production.



a b

Fig. 7 Orientation of the second design of the heel: a) vertical orientation, b) horizontal orientation

3. Results and discussion

When walking, the heel is loaded from above with compression force of the person's weight, while lateral, heel is loaded with flexural load and impact. For the purpose of this paper, flexural properties have been tested. Test specimen were made with different processing parameters (layer thickness, infill density and temperature) and with linear structure under 45 degrees. The test specimen were made according to the standard HRN EN ISO 178: 2011 for flexural properties. However, because one of the parameter is infill density and influence of the lattice structure on the heel, dimensions of the test specimen have been increased from 10 x 4 x 80 mm to 15 x 10 x 80 mm (width x thickness x length) to make the lattice structure more noticeable.

Constant production parameters were:

- material: ABS (acrylonitrile butadiene styrene)
- number of shells (external contour): 3
- temperature of the working platform: 110 °C
- infill build speed: 90 mm/s
- shell speed: 40 mm/s

According to the orientation of the heel in figure 6 and 7 and the way of testing flexural properties (three-point test) test specimens were made on the 3D printer according to figure 8.

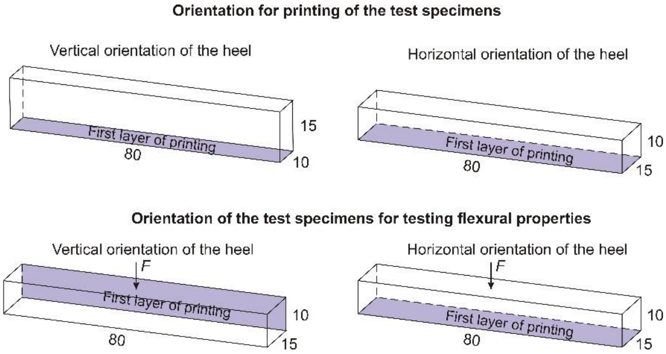


Fig. 8 Orientation of the test specimen for the printing and testing of the flexural properties: a) for vertical orientation of the heel, b) for the horizontal orientation of the heel (all dimensions are in mm)

Detailed analysis is shown for flexural strength, and 3 test specimens were tested in each experiment run and the mean value and standard deviation was calculated. Table 1 shows only mean values of flexural strength. It is necessary to carry out 19 experiment runs (condition in the centre was repeated five times).

Table 1. Processing parameters and results of flexural strength for two orientations

	Factor 1	Factor 2	Factor 3	Flexural strength	
	A: Layer thickness	B: Infill density	C: Temp.	Vert. orient.	Horiz. orient.
	LT, mm	*ID*, %	ϑ, °C	σfmV, N/mm^2	σfmH N/mm^2
1	0.2	25	230	36.20	35.53
2	0.15	35	245	37.68	36.98
3	0.2	40	230	41.66	39.96
4	0.1	25	230	35.7	33.72
5	0.2	25	230	38.10	35.43
6	0.2	25	230	36.79	35.41
7	0.2	25	255	35.47	35.51
8	0.2	25	205	37.35	34.91
9	0.15	15	245	34.15	33.35
10	0.15	15	215	36.19	33.93
11	0.25	35	245	39.81	37.60
12	0.2	25	230	36.09	34.78
13	0.3	25	230	40.47	36.58
14	0.25	15	215	35.52	30.95
15	0.25	15	245	33.83	32.59
16	0.2	25	230	34.79	34.35
17	0.2	10	230	32.91	31.86
18	0.15	35	215	39.96	37.50
19	0.25	35	215	39.75	36.91

3.1. Vertical orientation of the heel

For flexural strength for vertical orientation the cubic model and curve has been selected as the approximation curve. All other models (mean, linear, etc.) have not significant parameters and have also significant lack of fit which is not good, so cubic curve best describes the model. Table 2 shows the results of the variance analysis. In order for a certain factor to affect the change, the value in table 2 in the last column (Prob > F) should be smaller than 0.05.

Table 2. Results of the variance analysis – flexural strength of the vertical orientation of the heel

	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1143.2	14	81.65	56.61	0.0007
A	116.33	1	116.33	80.64	0.0009
B	56.26	1	56.26	39.0	0.0034
C	125.47	1	125.47	86.98	0.0007
A^2	4.13	1	4.13	2.87	0.1658
B^2	47.95	1	47.95	33.24	0.0045
C^2	$3.7\cdot10^{-4}$	1	$3.7\cdot10^{-4}$	$2.5\cdot10^{-4}$	0.9881
AB	135.38	1	135.38	93.85	0.0006
AC	93.23	1	93.23	64.63	0.0013
BC	12.11	1	124.11	86.04	0.0008
A^3	92.98	1	92.98	64.45	0.0013
B^3	51.53	1	51.53	35.72	0.0039
C^3	51.31	1	51.31	35.57	0.0040
A^2B	40.89	1	40.89	28.34	0.0060
ABC	127.92	1	127.92	86.68	0.0007
Pure error	5.77	4	1.44		
Cor Total	1148.9	18			

In this case A, B, C, B2, AB, AC, BC, A3, B3, C3, A2B, ABC are significant model terms. A2C,B2A B2C, C2A, C2B have no effect and are completely excluded from the analysis.

Table 3 shows the basic statistical data about the model. The R-squared (r2) is the measure of deviation from the arithmetic mean which is explained by the model. The closer r2 is to 1, model better follows the data.

Table 3. Overview of statistical data about the model for flexural strength for vertical orientation

	Flexural strength
Standard deviation	1.20
Mean	35.39
Coefficient of determination (R-squared (r^2))	0.995

Figure 9 shows the dependence of the flexural strength on the layer thickness and infill density.

The production temperature was taken as a constant (ϑ = 230 °C).

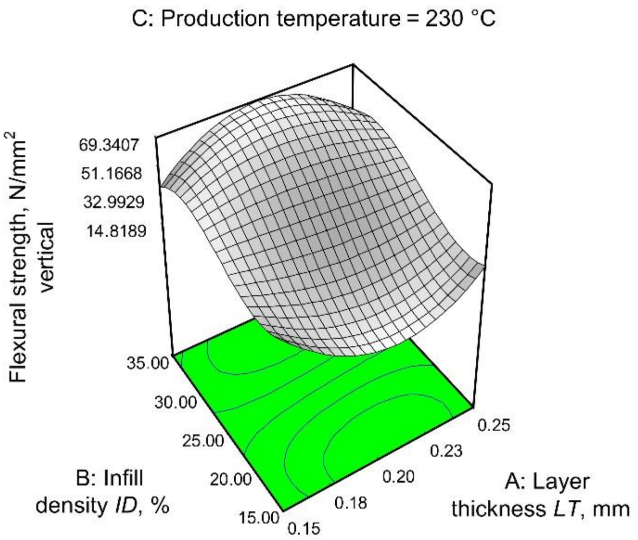


Fig. 9 Dependence of flexural strength on the layer thickness and infill density at constant temperature for vertical oreintation

From Figure 9 it may be concluded that with the increase in the infill density and with layer thickness 0.2 mm flexural strength is the highest.
The model for flexural strength can be described by equation 1 in the actual factors:

$$\sigma_{fmV} = -6964.3 - 6600.4 \cdot LT - 63.6 \cdot ID + 103.7 \cdot \vartheta + 22149.3 \cdot LT^2 + 1.6 \cdot ID^2 - 0.4 \cdot \vartheta^2 + 360.7 \cdot LT \cdot ID - 17.9 \cdot LT \cdot \vartheta - 0.08 \cdot ID \cdot \vartheta + 12856.7 \cdot LT^3 - 0.02 \cdot ID^3 + 6.4 \cdot 10^{-4} \cdot \vartheta^3 - 1187.7 \cdot LT^2 \cdot ID + 0.5 \cdot LT \cdot ID \cdot \vartheta \qquad (1)$$

3.2. Horizontal orientation of the heel

For flexural strength for horizontal orientation the linear model and curve has been selected as the approximation curve. Table 4 shows the results of the variance analysis.

Table 4. Results of the variance analysis – flexural strength of the horizontal orientation of the heel

	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	73.72	3	24.57	29.54	<0.0001 signif.
A	0.25	1	0.25	0.3	0.589
B	73.1	1	73.1	87.89	<0.0001
C	0.37	1	0.37	0.44	0.5166
Residual	12.48	15	0.83		
Lack of fit	11.42	11	1.04	3.94	0.0988 not signif.
Pure error	1.05	4	0.26		
Cor Total	86.2	18			

In this case only B (infill density) is significant model term. Table 5 shows the basic statistical data about the model.

Table 5. Overview of statistical data about the model for flexural strength for horizontal orientation

	Flexural strength
Standard deviation	0.91
Mean	35.15
Coefficient of determination (R-squared (r^2))	0.8553

Figure 10 shows the dependence of the flexural strength on the infill density and production temperature. The layer thickness was taken as a constant (LT = 0.2 mm).
From Figure 11 it may be concluded that with the increase in the infill density flexural strength for horizontal orientation of the heel is the highest

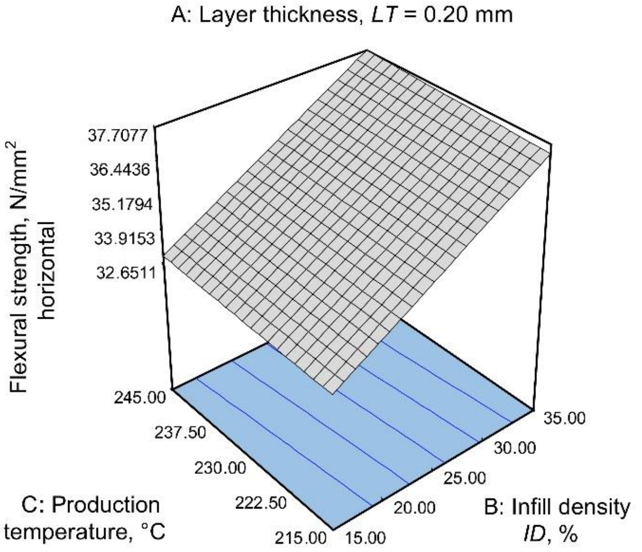


Fig. 10 Dependence of flexural strength on the infill density and at temperature constant layer thickness for horizontal orientation

The model for flexural strength can be described by equation 2 in the actual factors:

$$\sigma fmH = 26.2 + 2.5 \cdot LT + 0.24 \cdot ID + 0.011 \cdot \vartheta \qquad (2)$$

3.3 Comparison of two orientation and discussion

If we compare these two orientations according to Table 7, it can be seen that, in the case of production of the heel in the vertical position, in all test runs, flexural strength has higher values (from 0-15% depending on the run of the experiment) (Figure 11). Generally speaking, the total average value of flexural strength for the heel produced in the vertical position is 5.2% higher compared to the horizontal production of the heel.

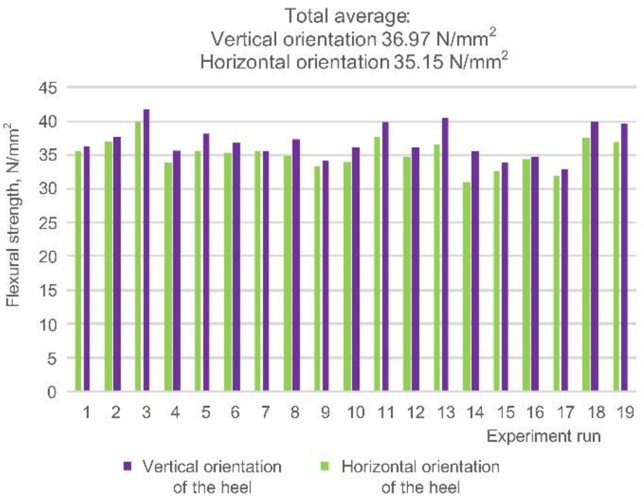


Fig. 11 Flexural strength for all experiment run

There is no good or wrong orientation, but orientation must be chosen according to the design, the possibilities of production, separating the supporting structure, the mechanical properties, the time of production, etc. Although the values for vertical orientation are higher, it also takes 1 hour longer for production, so according to each product it is necessary to decide what is more important: time of 10 production, certain mechanical properties or the quality of the product itself in accordance with its design (figure 12).

Fig. 12 Printed heel mounted on the shoe

4. Conclusion

Problems with the feet can lead to problems with the legs, hips, and back, and problems with the back can lead to problems with the rest of the body. Unfortunately, daily activities such as walking can do a lot of damage without the right kind of shoes – and the right kind of shoes can be hard to find, not to mention expensive.

That's changing with additive manufacturing. Additive manufacturing also enables personalized production, enabling us to have unique heels on shoes, with the ability to make any design (without limitation), but also to obtain certain mechanical properties with processing parameters and orientations when printing. The technology has allowed us to design and manufacture customized shoes that not only perfectly fit every customer's feet, but also target trouble spots.

5. References

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