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3D-Printed shoe last for bespoke shoe manufacturing

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Abstract. This paper presents a new approach for the production of bespoke shoe lasts used in shoe industry. It is based on measuring key geometric features of existing shoe lasts and establishing a parametric system which can then be used to create a 3D model of a customized fit shoe last. Thus, instead of 3D-scanning the foot and then doing time consuming and skill intensive point cloud data processing, the proposed solution requires only taking several measurements of the customer's foot and inputting them into the parametric model to obtain the tailored shoe last 3D geometry. Furthermore, the internal geometry of this shoe last is topologically optimized to reduce material volume and 3D printing time, while still withstanding temperatures and loads specific to the shoe manufacturing process. The 3D model also includes geometrical features allowing the attaching of process-specific mounting hardware. Material Extrusion 3D Printing (ME3DP) was used to fabricate the shoe last from thermoplastic material. 3D-printed shoe lasts were tested in a real manufacturing setting, successfully producing bespoke canvas shoes with rubber soles. During testing, the shoe lasts were subjected to typical process loads and to high temperatures.

1 Introduction

In the case of bespoke, made-to-order shoe manufacturing, the first important step in the fabrication process is to obtain a last which is perfectly suitable to fit the dimensions and model of the desired shoes. Traditionally, lasts are made out of hard wood in order to withstand shoe production steps such as heating, mechanical deformation, leather stretching, painting, etc. More recently, due to cost related reasons, wooden lasts have been replaced with lasts made from metal or polymers, which are usually purchased by shoe manufacturers from third party sellers as bundles of multiple sizes. These lasts are hard to customize and may even be incompatible with the model and dimensions needed.

The main objective of this paper is to present a process which integrates reverse engineering, parametric 3D modeling and 3D printing for making personalized, one-of-a-

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kind lasts from thermoplastic material that offers advantages from a cost perspective compared to ordinary metal or wood lasts.

Bespoke products market is in a constant growth, people worldwide being more interested in acquiring custom made products which fit their individual needs, taste, personality and social status. In addition to standard shoe characteristics such as model, material and color scheme, bespoke shoes allow for a custom fit.

In this area of research, focus is on identifying sets of parameters that define the dimensions of the foot and which allow the creation of a system of measurements to be used in shoe design. For example, Cheng et al. have identified two important dimensions foot length and joint circumference, which have been measured in 2486 men, resulting in an anthropometric measure system of the foot [1].

The development of reverse engineering technology (3D scanning) has allowed the market to move towards solutions where the feet of customers are scanned and the last is designed based on geometry generated from the resulting point cloud [2-4]. This provides the advantage of being able to fit the shoe last precisely to the actual measured shape of customer's foot instead of relying on standardized sizing, in exchange for increased cost due to the required scanning equipment as well the qualified personnel needed to process resulting data and create last 3D CAD models from cloud points [5]. Witana et al. have compared various methods of creating 3D models using scanned data that comprised point clouds and selected landmarks [6].

2 Method and materials

Additive manufacturing (AM) is the process of fusing material to fabricate objects based on 3D model data, usually layer by layer [7]. In other words, objects can be manufactured by adding layers of material one on top of another, unlike other manufacturing processes which use material removal or redistribution to obtain the final object geometry.

Starting from the type of object to be produced, multiple criteria have been used to identify a suitable AM process: shoe last minimum strength and temperature resistance, post-processing needs in terms of equipment and labor, cost of 3D printer, raw material costs, and 3D printer maintenance requirements. The selected technology was Material Extrusion 3D Printing (ME3DP), which produces objects by depositing layers of extruded thermoplastic filament along a trajectory plotted based on sections from a 3D model of the desired object. In a typical ME3DP fabrication process, the 3D printer first forms the outer surface of the object (by depositing filament along the perimeter of the object section) and then completes the interior volume (infill) following a specific pattern.

3D printing main process parameters are: object orientation and position within the printer's workspace, layer height, raster angle, road width and the gap between roads. These parameters influence resulting object's precision and mechanical properties [8].

The shoe last design process starts with scanning an existing, standard size shoe last using a 3D scanner. The resulting cloud of points (fig. 1a) is then imported in the Digitized Shape Editor of CATIA V5 (Dassault Systèmes). Surfaces can be generated from this point cloud using Quick Surface Reconstruction after generating a triangle mesh. The result of this operation is a 3D surface CAD model of the shoe last.

Based on data taken from literature [6], several perpendicular planes have been defined using foot dimensions. The intersections between these planes and the 3D surface model obtained in the previous step are the curves which will be parameterized in the next step (fig. 1c). This process is done by replacing the intersection curves with parameterized splined curves (fig. 1d). Thus, by measuring specific dimensions of a customer's foot and correlating those dimensions with the newly parameterized spline curves, an accurate shoe last model can be automatically generated. The dimensions necessary to generate a suitable model can be seen in fig. 1b. These are foot length L, joint height H, toe height h and five curve lengths measured around the foot A-E. The parameterized model uses additional automatically generated curves in order to properly shape the shoe last.

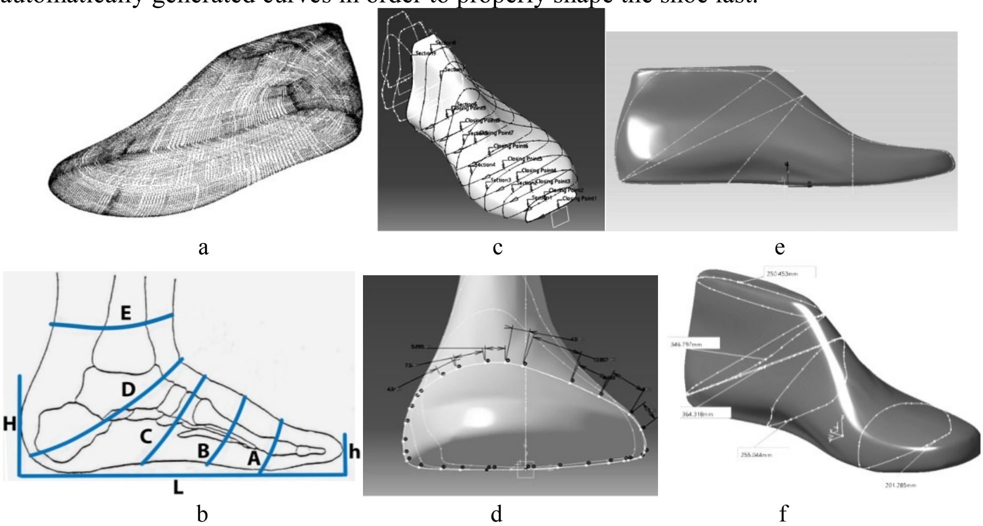


Fig. 1.a) Point cloud from scanned shoe last; b) Measured dimensions used to create the digital 3D model; c) 3D CAD model obtained after measuring the dimensions of a men's shoe last; d) Curves in the 3D model are replaced with parameterized splines; e,f) CAD model obtained after inputting the dimensions of a real foot (EU men's size 39) with A=201 mm, B=255mm, C=364mm, D=346mm, E=250mm, L = 217 mm, H =85mm, h = 28 input into the parametric model.

AM of objects with a large volume such as shoe lasts requires large production times and costs. For reducing them, the internal structure of the shoe last should be optimized in such a way that functional requirements such as part strength and temperature resistance are met while reducing material needs and manufacturing duration. This is achieved through a combination of topology optimization and process parameter selection.

In order to reduce thermoplastic material quantities required to manufacture the shoe lasts, the geometry of the virtual 3D model of the last has been put through topology optimization using Fusion 360 (Autodesk, Inc.) with a weight reduction target of 40%. Loads specific to the shoe manufacturing process have been applied to the model of the shoe last. These are the loads the shoe last is subjected to while being clamped for shoe canvas laying, stitching and bonding. Loads of 10N have been applied at the base of the shoe (fig. 2, blue arrows), and the critical points such as the heel and lace areas have been loaded with forces of 25N (fig 2, green arrows).

Geometry elements which serve a functional role during manufacturing, like the holes used to fix the shoe last while the shoes undergo heat treatment have been excluded from the optimization process, remaining unchanged in the resulting model. Meshing has been done using tetrahedral volumes with a maximum geometric size of 1% of part dimensions. The final 3D model consists of two distinct 3D bodies, one being the optimized interior structure and the second one being a hollow shell body of the shoe last (fig. 3). The model can be exported as two separate STL files, or as a single STL file containing the two distinct bodies.

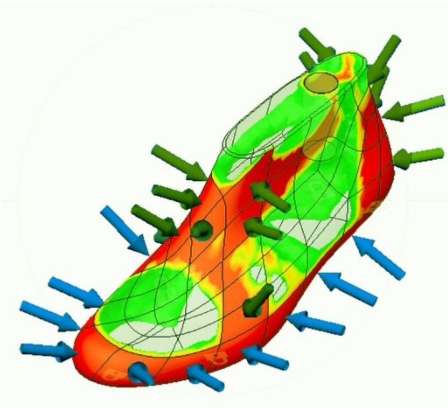
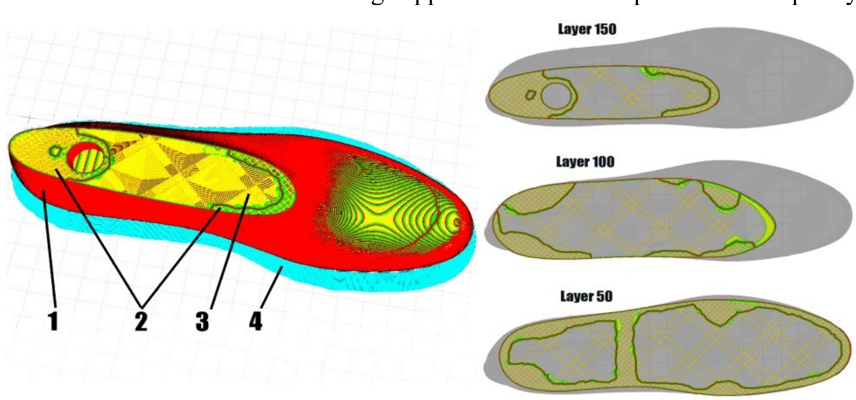


Fig. 2. Forces applied to the shoe last during shoe manufacturing process

Fig. 3. Overlay of the interior (green) and exterior (grey) structure 3D models.

The final step in the optimization process is model sectioning for 3D printing, done using specific software. The slicing software of choice must allow the use of separate parameter sets for each of the two bodies contained within the STL file or allow combining multiple STL files in the same printing process. Ultimaker's Cura v. 3.1 is one of the free slicing software options with these capabilities, allowing the user to insert multiple 3D models in the same workspace and to assign different sets of printing parameters to each of these models. More importantly, it allows the intersection of different meshes through the option "Cutting Mesh". As previously mentioned, in order to produce the model layers specific to the manufacturing process, the two 3D bodies need to be overlaid. The model containing topologically optimized geometry is used to form a structurally strong core and requires printing with a large infill percentage. The second model, an outer shell of the shoe last, is used to form the exterior surfaces, defining the exterior surface and shape of the shoe last. The space between these two models was 3D printed with a sparse infill to reduce weight, print time and material cost. Due to the slight curvature of the shoe's sole, the outer shell model needs to be held up by support structures. While using soluble material for these support structures would provide a better surface finish after support removal, using same-material supports decreases fabrication time and costs. If necessary, the base of the shoe last can be sanded down after clearing supports in order to improve surface quality.



a b

Fig. 4. a) Sectioned model ready for 3D printing 1 – exterior structure; 2 – dense infill; 3 – sparse infill ; 4 – support structure; b) Layer sections of the sectioned model

The parameter sets used for defining the model layers and extruder pathing can be found in table 1.

Table 1. 3D printing process parameters

Parameter	Exterior structure (shell)	Interior structure
Nozzle diameter	0.4 mm	0.4 mm
Layer height	0.25 mm	0.25 mm
Wall thickness	0.8 mm	1.2 mm
Infill	8%	50%
Support material	Yes	No
Print speed	60 mm / s	40 mm / s
Extruder temperature	205°C for PLA; 250°C for ABS; 235°C for PETG	

Three of the most commonly used thermoplastic materials in ME3DP, acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) have been used to manufacture test lasts. These test parts have been used in a real production setting to assess their viability.

3 Results

Test lasts of different sizes made from the three different materials mentioned previously have been printed on commercially available desktop 3D printers: Zortrax M200 (Zortrax, Poland) and Creality CR-10 (Creality 3D Technology, China). Topology optimization was used for the internal geometry of the shoe last, providing significant reduction of fabrication time and volume of required thermoplastic material. Compared to printing a 50% filled model using ME3DP and one of the standard infill patterns (grid infill in Cura V3.1), the optimized version provides on average 60% material savings and a 45% faster fabrication time (fig. 5). This is an important improvement from a production standpoint, as manufacturing time for a single last (EU size 39) dropped from 28 hours and 45 minutes to under 16 hours. Using two separate 3D printers, each printing one of the two lasts comprising a pair, the optimization process makes possible to have 3D printed lasts ready at the start of the next business day.

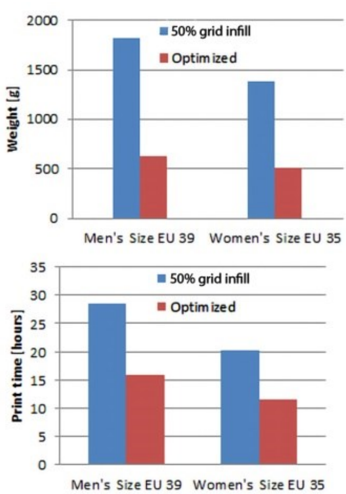


Fig. 5. Process metrics before and after body optimization (for 1 shoe last)

Fig. 6. 3D printed last used in a shoe manufacturing process.

These test parts have been included in a shoe production test run (fig. 6), being subjected to the same forces and temperatures encountered by commercially procured lasts. The shoe production process consists in laying canvas templates onto a last which is fixed onto a jig using the geometry described in the previous section. After stitching the canvas around the last, the midsole is stitched to the canvas. Glue is applied to the midsole and to the canvas and then the sole is attached. Following the heat treatment used to bond the shoe sole to its midsole, where shoes pass through an oven at 120ºC for 30 minutes, lasts made from PLA and PETG have softened considerably, indicating that these materials are not suitable for use in this specific production process. Specifically, PETG parts suffered catastrophic failure and were not able to maintain shape during the process. Lasts 3D printed from ABS filament held their form throughout the process and did not soften or deform, offering identical behavior to commercially sourced polymer lasts.

4 Conclusions

The current paper was focused on developing and testing a method of manufacturing shoe lasts for bespoke shoe production using an additive manufacturing process.

The development process consisted in designing and analyzing several models of shoe lasts whose internal geometry was created using topology optimization for low weight and material consumption. The optimized geometry includes geometrical features required during the shoe manufacturing process. Upon optimization, 3D printed samples have been fabricated on consumer-grade 3D printers. Canvas shoes with vulcanized rubber soles have been manufactured using these shoe last specimens.

Specimens printed with ABS have shown the best suitability for the manufacturing process which includes passing the shoes through an oven in order to vulcanize the rubber soles. Specimens made from PETG and PLA have softened and suffered catastrophic failure during the process.

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