Direct Digital Manufacturing of shoe heels through Fused Deposition Modeling

Abstract

Additive manufacturing process chains for direct part production in the footwear sector are being investigated almost exclusively for athlete shoe soles and orthotics. This paper focuses on the direct digital manufacturing of high heels for woman shoes, which could provide solutions for personalized production and complex design for high added-value shoes. The study aims at testing the introduction of additively manufactured components into conventional shoe production lines. Sample heels of two common designs have been fabricated by the Fused Deposition Modeling technique, assembled with conventional mounting machines, and tested for wearability according to standard procedures. The experimentation has shown that fully process compatible and functional heels can be produced for a basic design under some restrictions, and has allowed to identify critical issues to be dealt with for future applications on more critical heel shapes. These results will help to develop methods for a robust heel design exploiting the flexibility and creative freedom allowed by additive processes.

1 Introduction

The footwear sector is a mature industry where price competition is saturated and innovative design as well as advanced technology can become relevant levers to emerge in the global market [1]. Due to its ability to foster design freedom and production flexibility, additive manufacturing (AM) is deemed as a disruptive technology for the development of big trends in the market, such as personalized production and complex design for high added-value shoes [2]. In fact, dozens of designs exploiting these processes have been presented in the last few years, but most of them are just prototypes which are not required to be really wearable and comfortable. A shoe is a varied and complex product that combines many different materials and processes: it typically includes both a flexible and a structural part, where the former affects comfort and fitness and the latter ensures strength and durability (Fig. 1). Differently, most of the AM shoes developed to date are only made of a single rigid material, usually polyamide (PA) processed through Selective Laser Sintering (SLS), with obvious limitations on wearability and functionality. Only a few studies have been focused on structural parts, fabricated through SLS or Fused Deposition Modeling (FDM) and assembled to a conventionally manufactured shoe. Even in these cases, functional performance has seldom been demonstrated. Data from wearability and functionality tests have been conducted rigorously only on running soles [3], insoles [4] and orthotics [5].

This paper deals with the possibilities of Direct Digital Manufacturing (DDM) for fashion shoe heels, describing and quantifying the performances of a DDM component introduced in the conventional production chain. Several heels have been designed, manufactured, assembled and tested through standard EN ISO procedures. The study was carried out at the Integrated Pilot Plant (IPP), a pilot factory for high added-value shoe established in Vigevano by ITIA-CNR and Synesis European Consortium. The laboratory activities are focused on the development and implementation of advanced technologies for shoe parts and final products manufacturing.

Figure 1: Flexible and structural components of a shoe.

2 Aim of the work

In a previous paper [6] heel requirements were analyzed for each type of artefact needed during shoe development, from concept models that are needed only for aesthetical validations to finished products that can be proposed to the market, in order to evaluate the possibilities of AM for the different applications. Final production components were characterized mainly by aesthetical quality, ease of post-processing, ease of assembly to the shoe, complete functionality and possibility of cost scaling for short-to-medium run production. In the present work the focus is shifted from prototyping to final production of components, where an increased attention to all functional requirements is needed. The most compelling aspects were tested in order to develop a proper characterization of the performance of DDM heels and validate the possibility of their application for the production of complete and really functional shoes. The following subsections describe the specific choices made in the experimentation and the details of the involved tests.

2.1 Choice of the manufacturing process

Most shoe heels are currently made of injection moulded acrylonitrile butadiene styrene (ABS) with an embedded steel insert when needed. They are usually leather covered or painted and assembled to an interchangeable top piece which protects them from wear. The fastening to the shoe is carried out with a heeling machine which introduces 3 to 6 nails crossing the insole from inside the heel seat. In the above cited study [6], ABS heels made by FDM proved to be suitable to the prototyping phases and competitive with conventional shoe heel manufacturing processes (CNC machining and injection moulding) in terms of complexity management, cost, response time and efficiency. These results as well some additional positive aspects noted for prototyping applications, such as the good mechanical properties obtained on FDM heels, have suggested to test the same additive manufacturing technique for final production applications. In principle, the above choice appears to be compatible to conventional shoe manufacturing. Few changes were actually required to the overall design of the shoe (materials and components) and most parameters of the process chain were not influenced by the use of FDM. The only exception was related to the metal insert, which could not be embedded in the polymer matrix during fabrication as it is the case in injection moulding. Differently, it had to be assembled to the heel body by interference fit into a hole created within the additive process. Finishing treatments are also unaffected by the adoption of FDM: no additional steps were required by leather covering, while some post-processing is likely to be needed for painting because of the typical roughness resulting from the process. The chance of improving the surface quality of FDM heels by means of chemical or mechanical finishing was not investigated in this work.

2.2 Heel design

The additive manufacturing of shoe heels can give the opportunity to explore unique complex designs which would be unsuitable to injection moulding. For a validation of such designs, a thorough understanding of mechanical issues during the use of the heel will have to be pursued. The component is subjected to maximum stresses during heel strike, when its bottom is the only shoe part in contact with the ground. This impact is repeated at each step during walking, thus heel fatigue resistance is highly challenged. To date, research on high heels seems to be focused mainly on gait analysis [7] and plantar pressure distribution [8], less attention being devoted to structural design. In the lack of rules and criteria for a proper sizing and optimization of heel shape, a novel design can be validated only by an iterative procedure supported by CAD-based simulations. Leaving these developments to future studies, the present work has only focused on conventional designs that are completely functional when manufactured through the usual process chains.

The actual heel shapes to be used for the tests were chosen among the basic conventional shapes that are equipped with a metallic insert. The two selected designs are shown in Fig. 2: the Tapered Heel (TH) is representative of a class of particularly lightweight and slim shapes, while the Pump Heel (PH) is representative of more bulky shapes found in most woman's shoes. Both shapes were designed with respect to the same shoe-last dimensions: they have a height of 95 mm and fit to a conventional steel heel insert of 5 mm diameter and 75 mm of length as well as to a 5 mm high top piece; other dimensions were set in order to ensure compatibility to heeling machine fixtures available at the IPP facility. If the heels selected are confirmed to be adequate for DDM they could be used as a starting base to create more peculiar and complex designs.

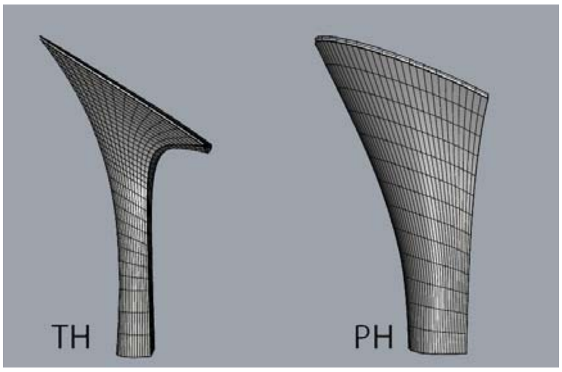

Figure 2: The two selected designs: a Tapered Heel (TH) and a Pump Heel (PH).

2.3 Equipment and build parameters

The heels were fabricated at IPP by a Fortus 250mc system (Stratasys, Inc.) in proprietary ABS M30 resin. Design and process planning were carried out through software tools such as Rhino®, Insight® and Control Center®. FDM components do not have the same properties of conventionally manufactured parts and they can be substantially affected by process strategies [9]. Selecting the adequate trade-off between manufacturing parameters, in order to maximize the performances for all the evaluations chosen, is a nontrivial task; for this study it was chosen to select a single combination of the involved factors, to be used as a benchmark for further studies. All the specimens were manufactured with a layer thickness of 0.254 mm, with a self-supporting angle value of 40° and with the maximum infill to obtain the better results in terms of mechanical behaviour. The heels were oriented with the seat heel edge parallel to the platform as the best compromise between cost, aesthetical quality and functionality (Fig. 3).

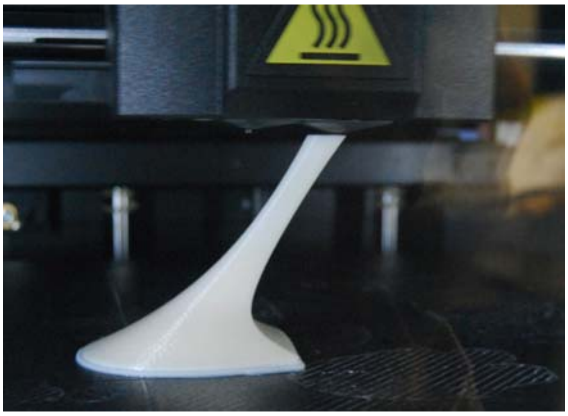

Figure 3: A TH specimen during the FDM process with the chosen orientation.

This orientation ensures a good lateral surface quality as well as an optimal realization of the heel seat edge; moreover it was assumed to be the most adequate to withstand fatigue stress among the orientations suggested and examined in previous studies [6]. As fatigue behaviour of FDM parts has been treated only in few studies [10] and in the lack of quantitative data, the following assumptions were made to predict possible influence factors on heel strength during use. Since the heel undergoes forces that act perpendicular to build direction, a horizontal build strategy was believed to fail due to delamination at the base of the stem (Fig. 4).

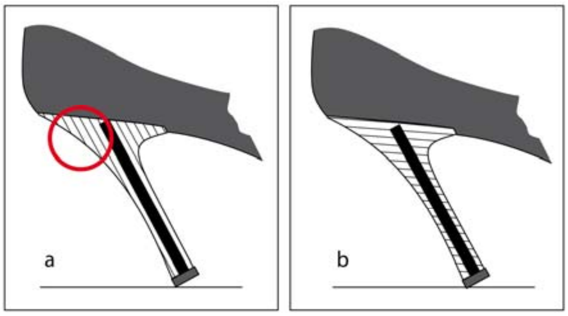

Figure 4: Fatigue stress hypothesized consequences on heels manufactured in two alternative orientations: a) horizontal build strategy (the circle highlights the expected point of delamination); b) chosen orientation.

Besides, this configuration is much more wasteful due to the need of support material to hold up the overhangs; this may be a critical point, considering that the presence of trapped support volumes inside the hole for the insert is sometimes reported during the chemical removal of horizontally oriented heels [6]. The chosen orientation is more efficient from both a material and a structural viewpoint, especially considering the contribution of the metal insert.

2.4 Performance criteria and tests

The performance of sample heels manufactured by FDM was assessed by reporting the following data:

- build time (BT), in hours;
- manufacturing costs (C) in €;
- model material quantity (MM), in cm^3;
- support material quantity (SM), in cm^3;
- assembly fulfillment (A);
- weareability assessment results (W);
- standard test “Heel pin holding strength” result (T1);
- standard test “Fatigue resistance” result (T2).

Build time and materials amounts were estimated by the software tool used to prepare data for the FDM machine. Manufacturing cost was estimated as

$$C = C_b + C_m$$

where C_b is the build process cost and C_m is the cost of used materials. Hourly costs were estimated from operating parameters which are specific to the IPP. Calculations are related to the manufacturing of a single part, since each component has to be individually processed, making build time and cost not significantly affected by the batch size produced in a single manufacturing cycle [6].

The heels were manually equipped with the metal insert and assembled to conventional woman shoe insoles on a 5-bar heeling machine with three standard nails (Fig. 5). Assembly fulfilment was considered adequate when the heel appeared intact with no visible damage on the lateral surfaces. The assembly was completed for three specimens per heel design.

Figure 5: Heeling machine.

The wearability test was performed by a 26 years old woman of 50 kg wearing a pair of complete shoes, assembled with FDM heels, for 8 hours a day for a complete work week. The integrity after the test was qualitatively checked reporting any deviation from the original state in terms of visible defects on the surfaces of the heel and detachment of the seat heel from the shoe.

The standard tests chosen are part of the CEN ISO/TR 20573:2008 which establishes the performance requirements for heel and top piece components for footwear, in order to assess the suitability for the end use and/or fitness for purpose [11]. Among the tests included in the standard, the two most critical ones were selected, namely "Heel pin holding strength" (T1) [12] and "Fatigue resistance" (T2) [13]. The first one measures the force required to pull a single nail out of a heel, whereas the second measures the ability of heels of ladies' shoes to withstand the repeated small impacts imposed by normal walking. T1 can be compelling to assess the eligibility of the conventional heeling method on FDM processed ABS with defined parameters, and T2 is a fatigue test that is indispensable to certify the mechanical resistance of a specific FDM heel. For components as dynamically stressed as shoe heels, the latter is considered the most selective, also for conventionally manufactured heels. A heel passes T1 if the holding strength of standard pins with 1.9 mm diameter and 18 mm length, previously inserted by a commercial heel nailing machine, exceeds 80 N/mm. The resulting value is calculated as

$$H = F / (d\text{-}4)$$

where H (N/mm) is the pin holding strength, F (N) is the maximum load recorded in pulling the pin from the heel by the arranged tensile testing machine and d (mm) is the hole depth created by the insertion; d-4 (mm) is the corrected value to represent the effective clinching length of the nail. Specimens pass T2 if failure does not occur after 15.000 blows, received at 6 mm from the tip, on the back of the heel and perpendicular to the stem direction. Each impact has an energy of 0.68 J, delivered at the rate of one per second by a free-falling pendulum. Heels are firmly clamped to a base by pouring a low melting point metal alloy and inspections are made at given intervals to check the occurrence of failure (Fig. 6). Damages localized on the tip of the heel are not considered in the test since they are due to the effect of the striker rather than a fracture of the heel due to the impacts.

All the tests have been performed on three specimens for each design. The two standard tests were certified at CIMAC, the Italian Centre for Footwear Application Materials, in compliance with the requirements prescribed by the National and European authorities responsible for the operation of certification organisations.

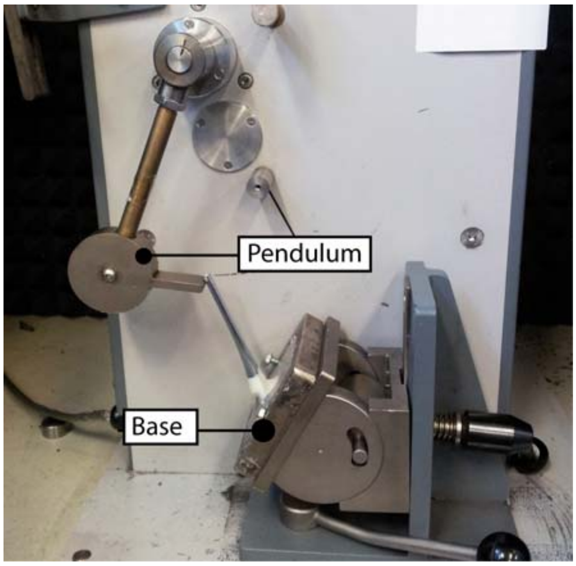

Figure 6: Test machine employed in the fatigue resistance test for shoe heels (T2).

3 Results

Table 1 lists the results reported for the evaluations and tests performed on the two heel designs.

Table 1: Results of the evaluations and performed tests.

	TH			PH		
Specimen	***1***	***2***	***3***	***1***	***2***	***3***
BT (h)	1,43			2,48		
C (€)	14			27		
MM (cm^3)	18,921			47,049		
SM (cm^3)	3,345			3,245		
A	fail	fail	fail	pass	pass	pass
W	/			pass		
T1	/			pass (average 90 N\mm)		
T2	fail (average 7.500 blows)			pass (all > 20.000 blows)		

As a first remark, it can be noted that build times and costs estimated for both heel designs can be acceptable for prototypes, samples and small batches of high added-value shoes. In fact, when dealing with big batches of very basic designs, injection moulding allows shorter cycle times (few minutes) and costs (usually not exceeding 6 Euros) [8]. Time and cost for the FDM process also depend on the amount of deposited material: in the present work this was always equal to part volume, since the part interior style was set to the maximum possible infill. The support material was located only at the base to allow the concavity of the heel-seat; the amount of support material was similar for the two designs, which were intended to comply with the same shoe-last dimensions. As a result, when manufacturing basic shapes with this specific orientation the expectable amount of waste material depends exclusively on the seat heel dimension and concavity.

The assembly of the FDM heels was completed with no visible damage for the PH specimens, whereas none of the tested TH specimens passed the test. Each TH heel broke similarly with a crack initiating at the base of the stem. To better understand the causes that led to this kind of fracture, which is unusual for conventionally manufactured heels, an injection moulded specimen of TH was assembled to the same shoe. It was noticed that if the surfaces of shoe and heel do not match properly, a common occurrence in shoe manufacturing, the injection moulded TH heel deforms without breaking, thus permitting the coupling, while this is not the case for the FDM TH heel (Fig. 7). These issues are clearly related to a brittle behaviour of the material; as a matter of fact, FDM processed ABS is known to have a more limited elastic-plastic deformation range than the same injection moulded material. Further tests will help to understand to what degree this disadvantage can be offset by a proper selection of manufacturing parameters for the specific application [14]. Assembly results showed that the conventional heeling method can be inadequate for tapered heel design where the base of the stem is particularly slender and the material resistance is more challenged. Thus for these shapes it is crucial to contemplate other or new assembly methods specifically meant for FDM shoe heels.

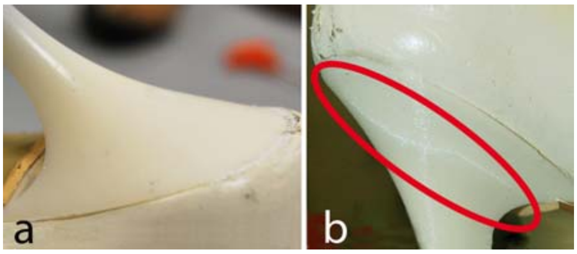

Figure 7: Assembly issues on TH heels: a) injection molded part with no damages; b) FDM part with a fracture at the base of the stem.

Since TH was not assemblable with the conventional process, W and T1 tests could not be performed on this design. A pair of shoes, provided with the PH heels and top pieces, was worn for the duration of the wearability assessment and did not report any visible defect (Fig. 8). The PH specimens also passed the T1 test, with a measured value of 90 N/mm which exceeds the suggested limit of 80 N/mm; this seems to prove that standard nails can be inserted and fixed correctly to FDM processed ABS with the chosen build strategies (Fig. 9).

Figure 8: PH specimens during the wearability test.

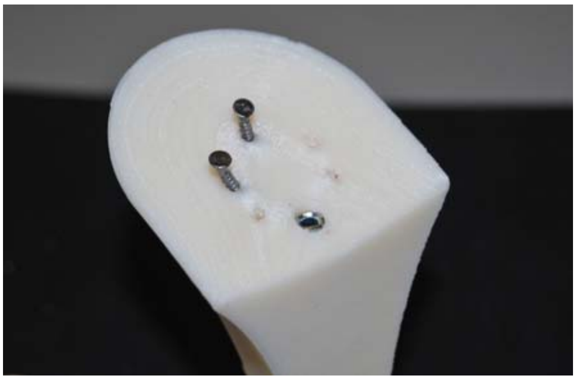

Figure 9: Passed T1 test for PH.

The T2 test gave different results for the two designs (Fig. 10): all the three PH specimens stood more than 20.000 blows (approximately 5h-30mins), thus passing the test and showing damages only on the tip of the heel which, as already noted, are not to be considered; all TH samples, instead, broke at about 7.500 blows. The TH specimens showed defects at the beginning of the stem, mainly located on the interface of two layers. This kind of failure can be explained by delamination issues: the bonding between layers is less strong than the layer itself, because filaments adhere only partially to each other [16], so when a component is subjected to a stress this interface is more likely to yield. Moreover the roughness of the material can make each layer a crack initiation.

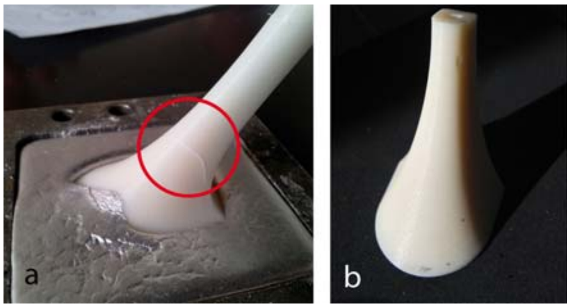

Figure 10: a) Failed T2 test for TH; b) Passed T2 test for PH.

The above issues could be solved for the TH heel by finding the correct combination of manufacturing strategies and orientation that could better absorb the repeated impact energy. T2 results indicate that a FDM heel with a thick shape, as PH, manufactured as described above and assembled with a standard insert can fully withstand the fatigue stress. On the other hand narrow shapes, as in the case of TH, can have insufficient strength even if reinforced with the standard metallic spine. To improve the fatigue stress of FDM heels, the influence and interference of multiple factors are to be considered: material selection, manufacturing parameters, orientation, dimension, position and shape of the metallic insert along with the overall design.

4 Conclusions

The introduction of direct digital manufactured heels into conventional assembly shoe processes was analyzed and tested in terms of build time, manufacturing cost, material consumption, assembly fulfillment, wearability, nail holding strength and fatigue resistance. Results indicated how a FDM heel with a basic thick shape is fully compatible and functional, having passed all the mentioned tests. For different shapes where stress conditions are likely to be more critical, the FDM process showed limitations in terms of compatibility with conventional assembly processes and fatigue strength. These results underline the need of wider investigations, aimed at finding more suitable assembly methods and discerning how involved manufacturing factors impact on heel performances, with the intent to develop a method for robust heel design. This study starts looking through the real possibilities of AM for fashion shoes and suggests further areas of research to completely exploit the innovative potentialities of these technologies for the footwear sector.

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