3D Direct Manufacturing and Decoration of Made-to-measure Performance Footwear

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Abstract

High performance football boots for professional players have the potential to take the proof-of-concept of an approach focusing on highly individualized products to a market success. At the same time, they point to a long term strategy to enable the development of the manufacturing technologies involved to a cost and performance level that would serve in the production of consumer products on a mass-customization scale.

This paper presents the background, motivation and research targets of a research project dealing with various finishing technologies to influence the performance of laser sintered parts with the focus on football boot outsoles for professionals.

The gap between the performance and appearance of the pure sintered part, and the ideal performance and appearance of the finished product is elaborated. Various processes to bridge the gap and their level of performance are presented.

Finally a recommendation for the ongoing work with the target of a market conformal selection is given and an assumption about the relevance to other applications is made.

Keywords

Direct manufacturing, Rapid Prototyping, Personalisation, Mass-customisation, Laser Sintering, e-Manufacturing, Surface Decoration, Sports Footwear

Introduction

This paper provides an appraisal of the first 6 months of a 12 month London Development Agency funded project under the Jumpstart initiative, which brings together SME's and HEI's to undertake applied research to develop products to market. The research partners are Prior2Lever, an interdisciplinary partnership of podiatry and design, established to create functional bespoke footwear; and the University of the Arts, London (London College of Fashion) an academic research department with a long established history of expertise in fashion, footwear design and research.

Aims & Objectives

The motivation for this project is in the potential offered by new and emerging Direct Manufacturing techniques arising from Rapid Prototyping (RP) technologies that enable functional parts to be produced directly from a 3D CAD model without the need for tools or moulds, utilising an additive layer by layer build process, in this case laser sintering of Polyamide 12.

These raw parts, however, lack the aesthetic and tactile, as well as the required performance characteristics of a finished part. The aim of this project is to address the sensory and aesthetic preconceptions which arrive with a prototype, and to investigate a range of finishing strategies which will give the required characteristics, where surface, colour, handle and performance are all critical components of any new product being introduced into a competitive market.

Background

Why Mass customisation?

Mass customisation as defined by Davis (1987) states that "the same large number of customers can be reached as in the mass-market of the industrial economy, and simultaneously they can be treated individually as in the customised markets of pre-industrial economies…The ultimate logic of ever-finer differentiation of the market is markets of one, that is, meeting the tailored needs of individual customers and doing so on a mass-basis."

Varying levels of customisation have been identified:

- **Soft Customisation**: retail and offline, post-production customisation occurring in a retail environment e.g. Levi's customisation shop/American Eagle. These allow customers to manually alter products once they have been purchased in store, using workshop facilities for surface decoration-embroidery etc. This type of customisation is easily integrated into existing business as it requires no adoption of the manufacturing cycle, but adds value in the perception of an ultimately individualised product. It also offers a "safe" environment in which to customise.

- **Hard Customisation**: covers a wide range of customisation options from personalised products to online style customisation. Some of these customisation models require new adaptive e-manufacturing approaches, and are more high risk for adoption as a new business model may be necessary for implementation.

Taking the example of the “Euroshoe” project, a 3-year EU funded project on Mass Customised footwear, these can be further broken down into:

- **Style Customisation**- allows the customer to customise a limited number of style choices for the individual configuration of an existing product e.g. Colour, materials (Nike ID, Puma “Mongolian Shoe BBQ”, see below.)

- **Best-Fit**- Foot scan or manual measurement data is used to match to a database of existing lasts and components to find the best fit for a consumer. This may also include a style customisation module to increase customisation options. (MiAdidas, Otabo, Leftfoot, Selve AG)

- **Custom Fit**- Foot scan and biomechanical data are used to create a CAD model from which a personalised last, insole and sole can be created for a consumer. A style customisation option may also be added. (Euroshoe)

Puma: Mongolian Shoe BBQ

In addition there is a further option:

- **Co-Creator**- Allowing the direct interaction of the consumer with the designer in co-creating a personalised style. This may involve elements of style customisation but goes a stage further than choosing from a range of options to the origination of ideas driven by the consumer, with the designer as facilitator and advisor.

Identifying the market sectors to which these formulae may be applied successfully, as has been demonstrated for some time in the automotive and personal computing industries (e.g. Dell), is key to its success in the apparel markets. Individualisation, the active involvement of the consumer in the design process and a level or perceived service are all key criteria in the new "customer centric enterprises"(Pillar et al 2004). But key questions arising are whether mass customisation may lead to "mass confusion"(Teresko 1994, Piller et al 2004) due to:

- **Burden of choice**-to many options for customisation/lack of support.
- **Matching needs to product specifications**-Consumers do not want to pay for excess functions with no perceived value.
- **Information Gap**-uncertainty of consumer satisfaction with an untried product that they must pay for in advance.

How does P2L address the Mass Customization model?

In reference to the modes of customisation described above, the P2L model is based on a Custom Fit model+ Style customisation/Potential Co-Creator. However in the early stages, the manufacturing plugs directly into conventional and existing systems. As the CAD model is created from foot scan and biomechanical data to create a unique last and outsole that may be Direct Manufactured and then closed in a conventional manner to the upper. In the mid- term there is the vision of a potential digital process based on existing technologies from 3D foot scanning via product design and adaptation to control of the manufacturing process. In the long term it is the aim to finally develop these technologies to a cost level that allows their use for "everyone's", i.e. Mass-customized products aiming at the same price level as a comparable non-individualised product.

Since today highly flexible manufacturing systems and processes tend to be cost intensive, their use in the manufacture of individualised products can only be justified by the outstanding value of the product delivered. There must be a perceived benefit in paying a premium for an individualised product, which can be identified in the field of athletics and professional sports, where rewards for improved performance are quantifiable.

Outstanding in performance: From a functional point of view if the target is fulfilled to design and manufacture a boot that serves the needs of each player, or better each player's foot, in a way that protects it from injuries and reduces the load on the musculoskeletal system (health protection), and to improve his game by reducing the energy "lost" due to non perfect boot design (increased performance)

Outstanding in design and perception: The value of individualised football boots can be very high, from an aesthetical point of view, the boot offers the potential to express their personality in the design, apart from the comfort created, by adding player name and number for every day kit maintenance in the clubs.

Addressing the risks of “mass confusion”:

In case of high performance footwear the burden of choice is minimised due to the fact that the customer has not much more to decide than whether he wants this type of footwear. Most of the decisions that have to be made are a consequence of the foot dimensions, the skeleton and the biomechanics.

Apart from the choice of minor individual adaptations like name, squad number or tags like left and right, the individual choice is limited to leather type, colour and outsole appearance.

The core work with the customer to define the optimised footwear performance for their personal situation also gives room for consultation on pros and cons of the different choices.

- Athletes in performance sports are already used to a high degree of personalisation, which reduces the burden of choice on them as the consumer
- The perceived advantages negate the added cost issues-it is already well proven that the perceived added value of competitive advantage has a premium.
- A personal level of service through direct offline consultation with the athletes/clubs/teams to bridge information gap. The option to reorder or make style customisation choices online after initial consultations may be viable.

Why the selected route of manufacturing using laser sintering?

There are many Rapid Prototyping technologies that allow the direct fabrication of 3D parts from a 3D CAD model. These include (Selective) Laser Sintering, Stereolithography, Fused Deposition Modelling, Layered Object Manufacture and 3D Printing. However not all of these technologies are suitable for producing functional parts, due either to the robustness of the parts produced, or the stability of the materials used.

Laser Sintering describes the process of bonding of sand, plastic or metal powders with laser energy in an additive, layer-by-layer build process directly from a CAD model. The technology was developed for Rapid Prototyping and helped to reduce development times and cost significantly, especially in the automotive industry during the 1990’s. The resulting reduction in both time and cost for rapid product development translated to savings of 70-90% compared to traditional prototyping routes.

Today, Laser Sintering is also associated with “Rapid Manufacturing” which is “the direct production of finished goods from a RP device”(Wholers 2003), where highly variable functional component parts and assemblies could be produced to satisfy variable customer requests without the need for tooling. The term Rapid

Manufacturing however emphasises two aspects, “Rapid” also in association with Rapid Prototyping and “Manufacturing”. Both aspects are true, but lose sight of a significant aspect of laser sintering for mass customisation. This aspect is expressed in the term “e-Manufacturing”, the fast, flexible and cost-efficient production of parts directly from electronic data. (Junior & Shellabear, 2003)

The fact that the machine control information for the laser sintering process can be automatically derived from the 3D CAD description of the product fills in one important step on the way from the data generation with the help of foot scanning to the fully customized finished product.

In an individualised product, such as custom fitting sports footwear, laser sintering offers the means to use existing materials (PA12 based) that have the potential to serve as a basis for football boot outsoles.

Design Freedom

Current mass-production methods such as injection moulding offer the ability to build outsoles with variable performance characteristics using multiple assemblies of materials with different characteristics, however the constraints remain within “Design For Manufacture”, as the designer must take into account the wall thickness, flow of materials into the mould etc. “Manufacture For Design”, on the other hand offers the designer freedom to produce parts of any complexity, geometry or wall thickness as there is no link between complexity and cost. The only cost implications are in the build volume. The higher the functional integration into one part (i.e. the more parts that have to be moulded separately and mounted afterwards are subsidised by one integrated layer manufactured part), the higher the number of parts integrated gives the economic advantage for laser sintering technology. (Junior & Shellabear, 2003)

Materials Properties

While laser sintering of plastics currently offers only homogenous materials, it is expected that heterogeneous characteristics may be applied to the materials through CAD modelling and optimisation, or variable laser scanning. In the near future it is foreseen that graded functional materials and multiple material builds will be achieved using new dispensing and laser scanning technologies. Indeed we will begin to see much more specialised new technologies develop for the production of specific types of materials, or even, as suggested by the Rep Rap project at University of Bath, self-replicating machines able to exponentially produce components and products based on evolutionary theory.

Sustainability

The nature of Laser Sintering being self supporting i.e.-The powder supports the structure as it is built, means that there is very little waste material, and a significant proportion of the powder may be recycled. Also homogenous parts are simple to recycle in comparison to injection moulded, multi-component parts. As all tooling is eliminated, the physical iterations of prototyping are replaced by CAD and virtual prototyping, and with the ability to ship digital information around the globe rather than physical objects; the impact on the environment is significantly reduced. The old adage of “think local, act global” may now be reversed to “think global, act local” as the ability to ship data rather than materials to highly adaptive rapid manufacturing units local to the consumer-in the future perhaps even in the home of the consumer where fabricators may produce products on demand (Gershenfeld 2005).

What is missing technology wise?

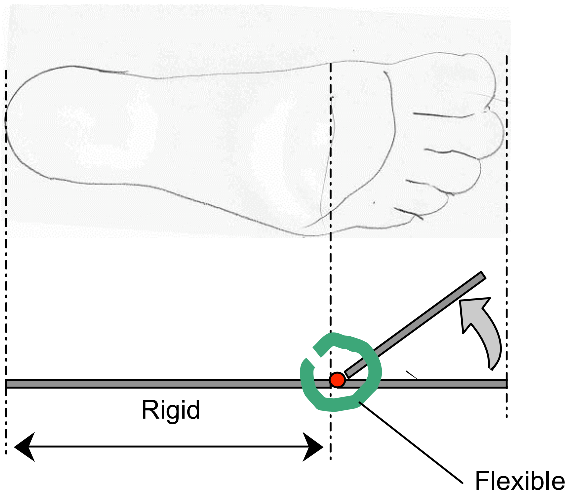
Piller, Möslein and Stotko (2004) discuss the advantages of mass customized market approaches using the term “economies of integration”. This describes the potential benefit for producers based on the advantage of information about the customer and the products needed leading for example to lower stock, reduced fashion risk or higher customer loyalty. However, the high level of specialisation in manufacturing, and extremely low costs for high quality products due to the traditional economies of scale approach, create a highly competitive benchmark. In the case of football boots it may be worth mentioning that the market price of today’s football boots including all the costs for development, manufacture, transport, sales and marketing as well as manufacturers and the retail margin compare to the full labour cost of a CAD designer for between half an hour and half a day. Thus it is easy to see that the cost of labour for individual service and adaptation of products asks for additional cost saving potential in order to achieve the cost target.

A solution to this conflict has been offered by the approach of Klotz (1999) in his discussion about the influence of information technology also on products and production. In traditional manufacturing the cost reducing effect called “economy of scale” is achieved by repeating the production of a fixed geometry, typically using tools. In terms of IT, the economy of scale can be achieved by repeating processes rather than fixed geometries. The individual adaptation of geometries is delivered “for free” if it is described by electronic data. Today’s digital printing technologies describe the potential of IT based economy of scale on a process level. Consequently individualised calendars and books have been among the first financially successful product examples of mass- customisation.

Therefore, a complete automated data processing route, from foot scanning to shoe production control is needed to achieve a mass customisation approach. In this respect the importance of laser sintering offering the e-Manufacturing potential for production can be understood. Also in the area of manufacturing technology for shoes like last production and leather cutting for the uppers, the first industrial e-Manufacturing solutions are becoming available.

However, a consecutive data model from scanning to product that fulfils the mass-customisation needs in terms of cost, automation and production control is not yet available and has to be developed. Current solutions are better described as a new tool for a skilled craftsmen doing the individualisation, or the work of a skilled shoemaker on a CAD system rather than on a fully hand made last or shoe. Apart from the technology gap on the data process level, a significant one also has to be bridged on the product level. The demands for the upper are known as the technology and materials for manufacturing remain more or less unchanged. This does not apply for the outsole using laser sintering.

A football boot outsole should be highly flexible in the articulated areas and rigid in the areas supporting for example the arch.



Of course it has to withstand all media that it is exposed to during its use, typically water and sun light (UV radiation) as well as grass, Astroturf or the surfaces outside the field. Also, it must protect the foot from media coming from below e.g. stones or water. Furthermore the surface must not be a threat for the wearer or other players during contact. It has to withstand the abrasive forces during use on various surfaces and during cleaning.

Finally, due to the effort taken to ensure optimum performance and individual design following the biomechanics of the player, the retail price of the product is higher than a standard one, and then the appearance of the product and the long-term aesthetic appeal must be outstanding

The mechanical performance of laser-sintered outsoles could be predicted from the design and the material properties and have been confirmed by long term flexibility testing. Also the protection of the foot and water resistance can be achieved without additional treatment.

Looking at the standard surface of laser sintered parts it varies depending on technology and process related factors like build direction, material or build strategy. Beside the surface structure that occurs as a consequence of a layer manufacturing process, there is also a surface texture possible as a result of the grain of the powder or the exposure strategy. Finally, the colour of the powder – originally white – is not ideally suited to easy maintenance. It tends to oxidise and yellow over time, while the part itself could be easily cleaned in a dishwasher for example, it is hard to keep clean if attached to a boot.

Therefore a surface treatment is needed to make the final product fulfil the demands that cannot be covered by the raw sintered part alone for this application:

Aims of surface finishing are:

- To ensure strong aesthetic appeal to reinforce the brand
- To ensure the long term aesthetic appeal of the boot and outsole
- To offer the potential to customize the appearance of the outsole
- To protect the outsole against intensive wear on various surfaces

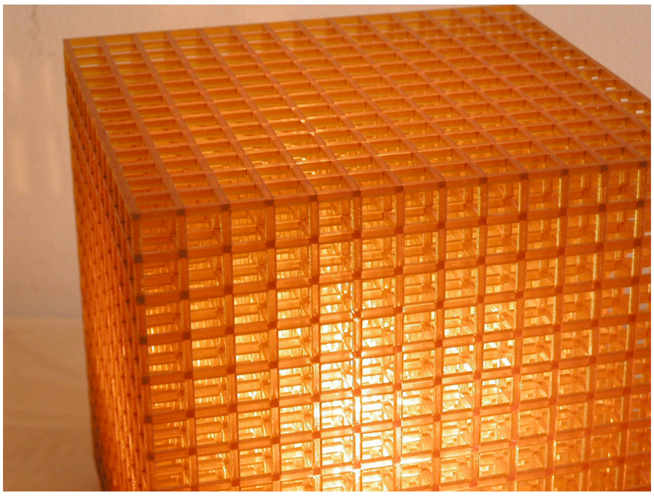
The surface treatment may change the existing surface or add one or more layers of material to the existing outsole. If an additional material layer or coating is applied this has to fulfil the demands that were listed for the raw part. In addition it must bind to the laser sintered part in such a way that it does not reduce the flexibility or performance of the complete unit.

With the surface treatment the following objectives need to be achieved

- Aesthetic appeal
- Abrasion resistance
- Flexibility
- Water resistance
- UV resistance

Aesthetics

An emerging generation of artists and designers have embraced the opportunities offered by Rapid Prototyping for concept modelling, mould making and investment casting, and by direct manufacturing techniques to produce finished artworks using all of the available Rapid Prototyping processes. One of the first to commercialise this was Freedom of Creation in the Netherlands who developed a range of light fittings using stereolithography, and latterly bags and accessories using laser sintering of polyamide. A number of Rapid Prototyping service providers have developed spin-off design studios that collaborate with product designers and artists to produce individual pieces and editions. Industreal from the Milanese RP company One Off, and .MGX from Materialise in the Netherlands are examples of these joint ventures with online stores.



Cube Lamp: Freedom of Creation/Materialise

A Moth to a Flame: Industreal

This relationship between the industrial or manufacturing process, or rather the reaction against industrialisation by the use of these technologies has been compared to the Arts & Crafts movement of the late 19th Century, and that the parallels between mass customisation and art may well revive the ornamental approach to design which was marginalized through mass production techniques" resulting in a situation that could perhaps be dubbed the renaissance of applied art – or art customization" (Gros, 2004).
Traditionally this approach to ornament has been the preserve of luxury goods, the fine arts and crafts such as jewellery and ceramics, where the high costs were perceived as acceptable for a unique piece that reflects the taste and status of the patron. The notion of art customisation could now be the preserve of the co-creator or "prosumer" (Toffler 1980), the consumer who is a willing and active participant in the style customisation of a product
In the case of sports men and women who are already used to a highly individualised product offer through sponsorship deals and endorsements, it is envisaged that the potential for high levels of personalisation, both in terms of performance but also of individual expression and identification of a personal brand may be positively received.

Potential areas of individualisation of boot appearance:

Outsole

- Integration of stud configuration and orientation
- Texture mapping of surface
- Unique Player Identification
- Surface decoration

Upper

- Materials
- Variable surface characteristics/finishes
- Colour/style
- Unique Player Identification

A list of potential applications and initial evaluation of each process appears in the following table (see Appendix A for photographic documentary of processes)

Process	Aesthetic appeal	Abrasion resistance	Flexibility	Water resistance	UV Resistance
Untreated laser sintered part	Poor	Moderate	Good	Good	Mechanically good Aesthetically poor
VibroFinishing	Poor	Moderate	Good	Good	Mechanically good *) Aesthetically poor
Additional layers					
Multipurpose Dye	Moderate	Moderate	Good	Poor	N/a
Sublimation Print (Raw Part)	Good	Moderate	Good	Poor	Good
Sublimation Print (+ Top Coat)	Good	Moderate	Moderate	Good	Good
Sublimation Print (Under + Top Coat)	Good	Moderate	Moderate	Good	Good
Spray Coat	Good	Moderate	Good	Good	Good
Dip Coat (Water)	Good	Moderate	Poor	Good	Good
Dip Coat (+ top coat)	Good	Moderate	Moderate	Good	Good
Electroplating	Good	Good	Poor	Good	Good
Electro less plating	Moderate	Good	Poor	Good	Good
Rubber Coat	Poor	Poor	Moderate	Good	Good
Rubber Coat (alt)	Moderate	Moderate	Moderate	Good	Good

Conclusion

In conclusion we can say that laser sintering has been identified as a good basis for producing a homogenous outsole that may well deliver the necessary performance characteristics for mass-customised sports footwear. Initial trials have confirmed that the flexibility and rigidity required are available for the performance, but that the raw parts require surface treatment to give the necessary performance and aesthetic qualities desired for a marketable product.

Evaluation of solutions tested

- Spray coating most successful overall, giving required aesthetic, flexibility and resistance.
- Electro/less plating most successful for abrasion resistance in target areas
- Sublimation printing most successful for personalisation
- Flexibility is a key issue

As a result of the surface trials we can suggest that not one of the single treatments tested provided the answer to all the questions being asked, and it is fairly safe to say that combination or multiple processes will be necessary. Mindful of the cost implications inherent with increased post-processing there will be suggestions for how the processing may be consolidated, or indeed what new solutions may be required in the longer term. For example it would seem ideal for the colour printing options available in 3D Printing to be transferred to Laser Sintering to facilitate personalisation options.

Expectations of tests to come

- A 2nd stage is being undertaken to compare successful processes identified above from a range of suppliers, and to establish partnerships for product development.
- Report on combinations of processes and localised processes
- Wearer trials of selected processes with players to assess performance and provide feedback on desirability in regard to function and aesthetics.
- Report on Co-creator trials

Relevance to other applications is highlighted, as discussed earlier in the paper with regard to the possibilities of new and individualised decoration being made not just apparent, but desirable, by the new direct manufacturing technologies which offer the possibility “for free”. Broad applications across art and design can be foreseen, as well as many possibilities for body-conformal or individualised products from shoes, clothing and wearable technology to car interiors, furniture and consumer electronics which may soon be possible, as printing of conductive inks and machines capable of building in gradable materials will become available. The other trait that may emerge from this type of mass-customisation approach is that with increased personalisation of products the counterfeiting of goods may become increasingly redundant. It remains to be seen to what extent the individual will wish to express him or herself through apparel and consumer goods, and how successfully the new business models for e-Manufacture deliver those products to the consumer.

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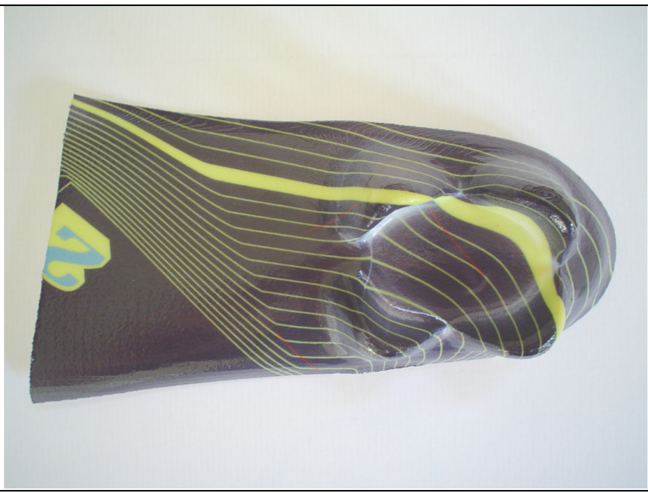
Appendix A:_Picture of the outsole using various finishing techniques:

Process	
Multipurpose Dye(Raw Part)	**SublimationPrint (Raw Part)**
	
Sublimation Print (+ Top Coat)	**Sublimation Print (Under + Top Coat)**
	
Spray Coat (Automotive)	**Dip Coat (Water)**
	

Process	
Dip Coat (+ top coat)	**Electroplating(Selective)**
	
Rubber Coat (Stonechip)	**Rubber Coat (Automotive)**