LatticeShield: Pioneering Socially Sustainable Safety Footwear through Innovative Toe Cover Design

A Case Study

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Executive Summary

Additive Manufacturing has revolutionized footwear design, being used for recreational footwear (Lord, 2018), athletic performance footwear (Horaczek, 2018), and medical-grade custom orthotics (Carolo, 2024). In this case study, a natural expansion of additively manufactured footwear into the realm of safety-oriented footwear is explored and the potential benefits are discussed.

Between 2021 and 2022 there were over 90,000-foot injuries that resulted in days away from work (U.S. Bureau of Labor Statistics, 2024) This is down about 17% since 2005 but remains an ongoing issue.

There is a clear need for customization in shoe sizes for workers especially where standardized shoe sizes do not accommodate well for certain groups (Habib & Messing, 129–132). It is important to make sure that for minority groups in construction, industrial, mining, and other industries that make use of protective footwear, that everyone can find well-fitting boots or shoes that will provide the correct protection. The difference between male and female feet is not insignificant and requires a shift in design and manufacture of women's shoes, but consistent sizing differences can even affect different regional groups (Jurca, Žabkar, & Džeroski, 2019). Shoes designed for a different size of foot, exposes women and other groups to unsafe ergonomic conditions (Akinlolu & Haupt, 2020), and could even promote the misuse or failure to use protective safety shoes in hazardous conditions.

This case study presents an approach to improve PPE in the form of toecaps by using additive manufactured lattice structures to decrease weight, increase ergonomics, and maintain appropriate safety standards. Using design principles, scientific simulations, testing, and analysis, a model for a durable toecap is demonstrated which provides sufficient safety while also showing multiple other benefits. Discussed is how this can help increase safety for workers, the design process and decision making, the design itself and how it fulfills safety, personalization, and weight requirements, and provides an analysis of the process.

Industry Overview

The safety shoe industry generated a market revenue of $2.134 Billion dollars which is relatively small with little space for growth under current conditions (R. & ltd, 2024). While no single AM manufacturer could cover this amount of production immediately, there is a space for ergonomics and customization.

The inadequacy of standardized shoe sizes in meeting the diverse needs of workers, particularly in industries such as construction, industrial, and mining, underscores the necessity for additional customization in protective footwear. Traditional sizing metrics fail to accommodate various groups adequately, including women and individuals from different regional backgrounds (Buldt & Menz, 2018). This discrepancy not only overlooks the distinct anatomical differences between male and female feet but also poses ergonomic challenges and safety risks for minority groups within these professions.

Recognizing this pressing need for inclusivity and safety, the design team proposes a novel solution in the form of a lattice-based or additive manufacturing (AM)-based toe cover for safety shoes. This innovative approach aims to address the deficiencies inherent in conventional designs by offering enhanced customization options tailored to the unique foot shapes and dimensions of diverse workers.

The proposed lattice-based or AM-based toe cover presents a paradigm shift in the design and manufacture of safety footwear. By leveraging advanced manufacturing techniques, the design can accommodate a wider range of foot sizes and shapes with precision and efficiency. This transformative approach not only ensures a better fit for traditionally underserved groups, including women and individuals from different regional backgrounds, but also promotes safer ergonomic conditions in hazardous work environments.

Furthermore, the proposed design mitigates the risk of misfit or non-utilization of protective safety shoes, which could compromise the well-being of workers and increase the likelihood of workplace injuries. By prioritizing inclusivity, ergonomic integrity, and safety, the lattice-based or AM-based toe cover represents a crucial step towards fostering a more equitable and secure working environment for all individuals in high-risk industries.

By improving the availability and effectiveness of safety footwear, the proposed design contributes to the overall well-being of communities by reducing workplace injuries and associated healthcare costs. Additionally, by promoting inclusivity and diversity in the workforce, the solution fosters a more equitable and supportive working environment, which can have positive ripple effects throughout communities.

Existing solutions to address the issue of ill-fitting safety footwear include traditional manufacturing methods such as simple stamping or composite molding that offer limited customization options and standardized sizing charts. However, these solutions often fail to adequately accommodate the diverse range of foot shapes and sizes present within the workforce. Furthermore, alternative approaches such as bespoke shoemaking or aftermarket modifications may offer improved customization but are often prohibitively expensive or impractical for widespread adoption.

The current limitations of these solutions underscore the need for a more scalable and accessible approach. By harnessing advanced manufacturing techniques, a cost-effective and efficient means of providing customized safety footwear to a diverse workforce becomes possible, thereby addressing the shortcomings of existing approaches and promoting safer, more inclusive workplaces.

All this said, there are recognized industry standards by ASTM, notably ASTM F2412 and ASTM F2413, which guide the testing and development of toecaps in safety footwear. While these standards do exist, they do not provide any specific guidance for toecaps produced via additive manufacturing.

The standards do however include guidance directed to composite-made toecaps which is relevant, such as in Section 5.8 of ASTM F2413 where guidance is provided that “devices shall show no sign of delamination” after performance testing is conducted on them. Delamination is a potential failure mode of additively manufactured toecaps, indicating some allowance in the standard exists to allow for AM production.

Design, Functionality and Durability

By leveraging additive manufacturing and advanced design techniques, toecaps can be designed on an as-individual basis and in remote locations.

Requirements

The toecap is designed for safety footwear, to provide protection to the toe area of the foot against compression loads, and to meet a selection of functional and performance requirements guided by international safety standards in safety footwear design such as ASTM F2413.

1. Functional Requirements

1. The toecap shall provide protection for the toe area of the foot, in safety footwear, against compression loads in industrial environments.

1.2 The toecap shall be capable of integration into common commercial safety footwear designs.

1.3 The toe-cap design shall encompass a similar volume as common commercial toecaps, to ensure compatibility and interchangeability with current safety footwear designs.

2. Performance Requirements

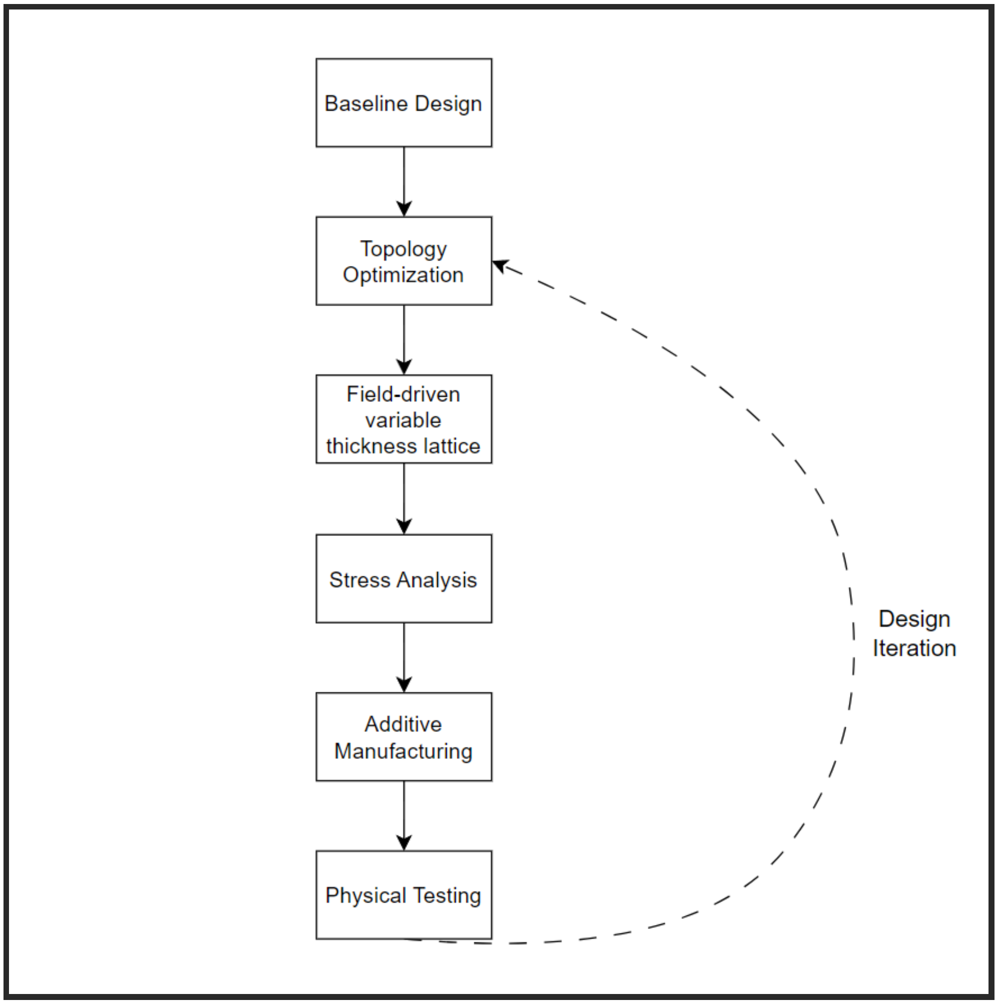
2.1 When subject to a load of 11121 N, the toecap shall provide a minimum interior height clearance of 12.7 mm in men's footwear, as per ASTM F2412 and ASTM F2413 standards.

2.2 The toe-cap design shall achieve a material reduction of at least 20% compared to common commercial toecaps.

Proposed Solution

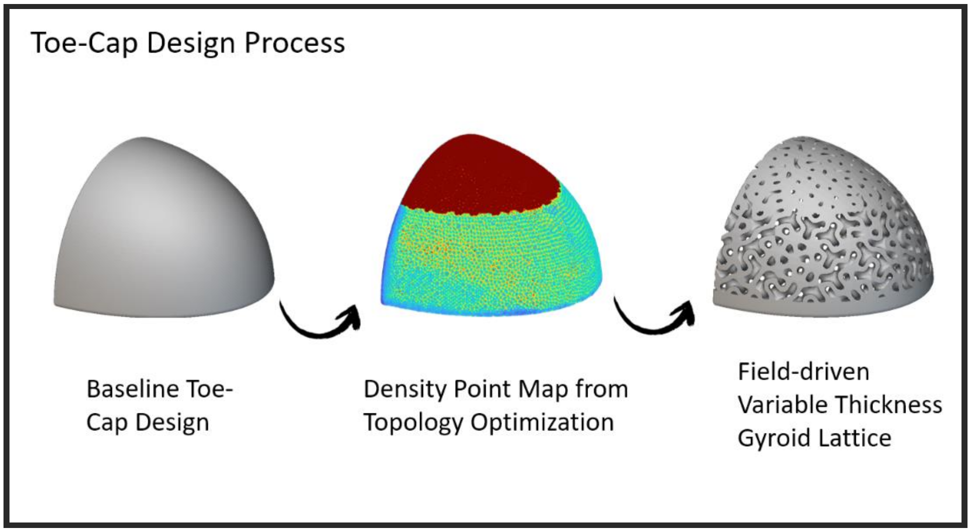
The proposed design focuses on leveraging additive manufacturing processes to enable advanced design techniques which increase material efficiency while maintaining or exceeding the functional and performance requirements when subject to compressive loads.

The overall external volume and geometry of the toecap mimics that of a common commercial toe-cap design, which ensures the design process can be easily integrated into existing safety footwear designs, without needing significant design changes to the work boots themselves. This design consideration highlights the adaptability of additive manufactured parts to be used in pre-existing designs, and this can facilitate the widespread adoption of AM made toecaps in a variety of existing safety footwear.



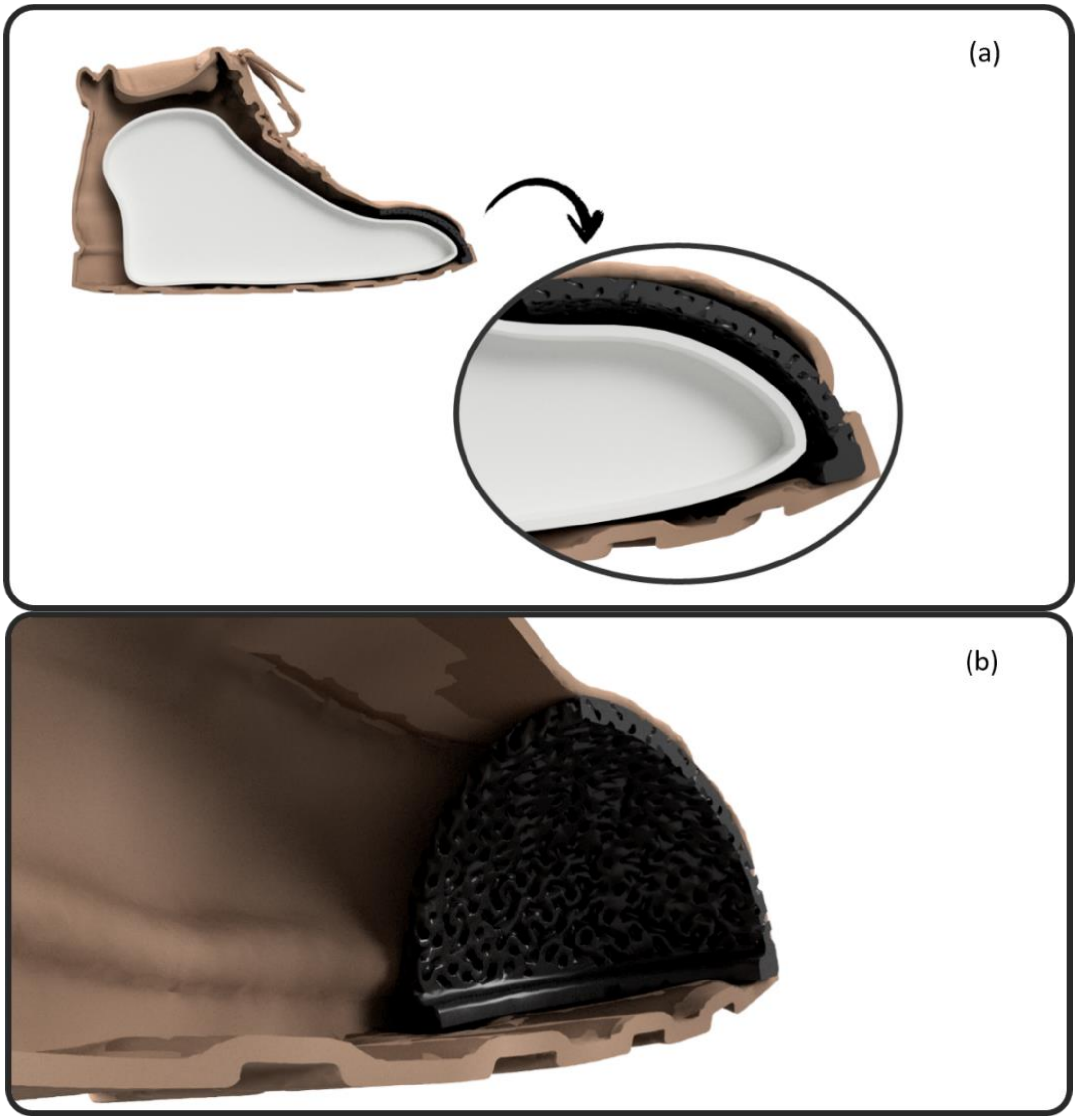
Overall Process Workflow

The toecap is manufactured from a polycarbonate based - carbon fiber filled (PC-CF) material, selected for its robust strength, durability, and lightness, and its resistance to wear and corrosion so it may be used in a variety of environments. The design utilizes topology optimization to minimize the compliance of the toecap, while adhering to a displacement constraint set by ASTM F2413. This technique optimizes the material to be distributed where it is most needed to withstand the specified compression load.



Design Process Workflow

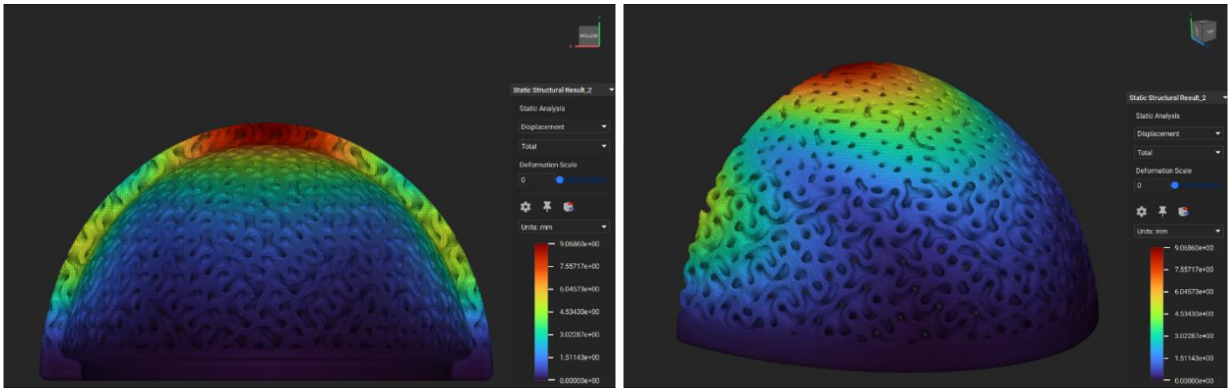
The topology optimization results are then used to drive the design of a Triply Periodic Minimal Surface (TPMS) gyroid lattice structure via a field. A gyroid unit cell was determined to be used for the lattice due to the relatively isotropic nature of its geometry, offering resistance against compression from any load direction. The lattice structure has a variable thickness that aligns with the load paths of the topology optimization, so that the lattice is thicker in areas necessary to resist displacement, and less thick in areas where less displacement resistance is needed.



(a) Cross-section view of a work boot with the inserted toecap and shoe last (b) Cross-section view of work boot with toe-cap.

With the resulting lattice geometry, the toe-cap design is then verified via simulation through a static analysis to determine the maximum displacement that occurs, and a weight savings analysis is conducted, before it is additive manufactured and physically tested to ensure it meets requirement acceptance and compliance with the international safety footwear standards set by ASTM F2412 and F2413. Impact testing according to ASTM F2413 was also conducted on a sample printed using an Intamsys Funmat HT, demonstrating that the PC-CF material held up to the required impact load sufficiently according to the standard.

The final proposed lattice toe-cap design is to be additive manufactured using a material extrusion process (fused filament fabrication). The material extrusion process enables the complex geometry of the toe-cap design to be created using the selected material, and the process is widely available globally with accessible price-points.



Static analysis displacement verification of the final toe-cap design. Load case driven by ASTM F2412 and F2413.

Health, Safety, and Quality Considerations

While an additive manufactured toecap offers unique benefits compared to traditionally manufactured toecaps, when considering the health, safety and quality of the proposed design, there are both positives and negatives to the design.

Positive:

- Improved Gait – because the toecap can be manufactured to be more lightweight than conventional toecaps, the design is a step towards improving the comfortability of safety footwear, whereas current designs have been linked to negatively affecting the gait of workers.
- Mass customization – because additive manufacturing enables the design of complex and personalized toecaps, the design is a step towards creating custom safety footwear specifically for each individual worker, again offering pathways to improving the long-term health of workers by improving their gait and comfortability.

Negative:

- Material handling – because PC-CF filaments contain fine chopped carbon fibers, this can pose a risk to the health and safety of AM process operators who could have these carbon fibers embedded into their skin or inhaled into their lungs, and primary engineering controls (PEC) should be in place and operational while proper PPE should be worn when handling the equipment.

Quality Considerations

Positive:

- Material efficiency – by utilizing additive manufacturing, complex geometries can be designed where material is placed only where it is needed structurally.
- Sustainability – in combination with the toecap being made with less material, additive manufacturing also wastes less material overall, leading to a more sustainable solution than traditional manufacturing.

Negative:

- Life cycle uncertainty – additive manufacturing can sometimes be susceptible to issues such as fatigue cracks and creep, so a fatigue analysis would be necessary to understand its longevity.
- Simplified design space – all the requirements and possible certification 'stamps' set by ASTM F2413 were not considered in this design, and only compression loads were considered for the design. The design space should be expanded for future work.

Part Quality Considerations

The qualification of the additive manufactured toecaps, designed specifically for work boots, are assessed by testing the toecaps following the existing ASTM F2412 (Standard Test Methods for Foot Protection) and ASTM F2413 (Standard Specification for Performance Requirements for Protective Safety Toe Cap Footwear) standards, specifically for toecaps under compression loads. Additionally, because additive manufacturing is a domain that contains many different processes and materials, communication material regarding the manufacturing of AM parts should follow ISO/ASTM 52900 (Additive manufacturing - General principles - Fundamentals and vocabulary) to minimize any confusion that could potentially arise.

As additive manufacturing rapidly evolves as a process, the approach to designing for additive manufacturing and qualifying AM made parts must evolve too. For AM parts with complex geometries, it is essential to create additional standards for inspecting these parts on top of existing standards, to guarantee their safety and efficacy, as well as for communicating design intent. Areas identified for the creation or expansion of standards include:

- Geometric Dimensioning and Tolerancing (GD&T) for Additive Manufactured Lattices – Developing specific GD&T standards for lattice structures would be very beneficial for communicating design intent for complex lattice structure geometries. This could include defining the overall unit cell geometry (strut thickness, geometry of connecting nodes), as well as how to define testable tolerances for these features.

- Testing and Qualifying Additive Manufactured Lattice Structures – Standard test methods for qualifying additive manufactured lattice structures under various loads, such as under compression, would further guarantee the safety and efficacy of these parts. At the time of this report, there exist standards which are in-development to tackle this issue, such as ASTM WK76163 (New Test Method for Additive Manufacturing - Test Artifacts - Compression Validation Coupons for Lattice Design

Design Integration and Utilization

Due to the unique geometric freedom provided by AM, integration of parts manufactured via AM and more traditional methods is relatively straightforward. Per ASTM F2413 for safety footwear, toecaps must be permanently affixed to the shoe materials – which can be accomplished with adhesives. Due to the porosity of the lattice structures used, adhesives have a greater surface area to connect to, reducing the possibility for them to become detached and causing issues for the wearer. Modification of outer geometry to ease installation into the shoe during manufacture is also possible. This means in the case of a problem with the fit during development or initial production, rather than having to try and adjust the shoe itself and the associated attached materials the designers can potentially focus on changes to the toecap exterior itself, allowing for faster resolution to problems involving fewer moving pieces.

Material Extrusion (MEX) was chosen as the preferred method as this process allowed for early studies the greatest breadth of material options, including those with fillers. MEX equipment is one of the most popular on the market (Grand View Research, 2024) and has the greatest reach, being found in even remote environments throughout the world (Knefel, 2016). It has a high degree of flexibility in where it can operate, and the post-processing is often simple or non-existent past the harvesting stage if models are properly designed for the process; while this may not always be possible in the realm of customized footwear, work done experimentally has shown the supports required are minimal across multiple designs and take little time to remove.

Alternate methods may be possible for creating the toecaps for AM safety footwear. Vat Photopolymerization (VPP) technology, for example, has materials which may provide the correct level of toughness in order to meet the performance requirements laid out in ASTM standards F2413 (Formlabs, 2024) (Loctite AM, 2024). However, additional post-processing considerations would need to be considered, with resin prints often requiring extensive cleaning and curing, slowing the process of manufacture. Resins used in VPP also tend towards being more brittle compared to those used in MEX processes – provided that this brittleness can be addressed, and the material qualified for use through testing to verify that they and the process are reliable and repeatable.

Some powder bed fusion (PBF) materials may also be suitable, such as carbon fiber-filled polymers which exhibit good impact strength (EOS, 2024). In-situ monitoring technologies fueled by AI have been shown as capable of fault and error detection in PBF technologies, leading to parts able to be 'born qualified' (McCann, et al., 2021) and while these processes have not been directly applied outside of metal technologies the principles can cross over and apply.

The materials chosen for this project were primarily carbon-fiber filled polycarbonate composite which provided the best blend of impact strength and strength. Traditional materials for toecaps include steel or high strength composites. Steel, while straightforward to manufacture with a simple stamping process, cannot easily be customized via traditional manufacturing processes as machining would be cost-prohibitive, as would having to create new stamping molds for each foot and fit. Time is another factor to consider – the ease of customization through AM allows for rapid creation of the toe caps while traditional processes (with the customization factor applied) are more time consuming.

In terms of life cycle for the manufactured product, polycarbonate is highly recyclable and is uniquely suited for recycling as the material can get up to its melting point without loss of value (Rinkesh, 2024). Provided the toecaps can be removed from the footwear, they would be fully recyclable. However as previously discussed, the toecaps do require being permanently affixed to the shoe materials per ASTM F2413. This being the case, the materials surrounding the shoe as well as the adhesives used would also need to be recyclable or some method for removing the permanent affixation would be necessary.

The shoe materials surrounding the toe caps similarly can and should be considered for environmental friendliness. Sustainable, eco-friendly materials exist and are in use (Mila, 2023). The durability of these materials is proven through widespread utility, though more work would be required to prove their viability for long-term use.

Digital and Physical Infrastructure

The dissemination of designs for personalized toe covers and the coordination of manufacturing processes can occur through various channels, depending on factors such as market demand, accessibility of technology, and the expertise of involved parties.

Major footwear manufacturers or corporations with significant resources and expertise in both additive manufacturing and footwear production could take the lead in designing and manufacturing personalized toe covers. They would likely have in-house teams of designers, engineers, technicians, and marketers to handle all aspects of the process. These corporations could collaborate with specialized companies or service bureaus for specific tasks or expertise.

Service bureaus specializing in additive manufacturing could offer personalized toe cover design and manufacturing services to footwear companies or individual consumers. These bureaus would have the necessary equipment and expertise to produce high-quality toe covers based on customer specifications. They could collaborate with footwear companies for distribution or directly serve consumers through online platforms.

Collaborations between specialized companies across different sectors could also facilitate the production of personalized toe covers. For example, an additive manufacturing company might partner with a footwear manufacturer and a design studio to offer comprehensive solutions. These collaborations could involve sharing resources, expertise, and intellectual property to streamline the manufacturing process.

While hobbyist makers might not play a significant role in large-scale manufacturing, they could contribute to innovation and customization in the design of personalized toe covers. Open-source platforms and communities could facilitate the sharing of designs and ideas among enthusiasts, leading to the development of new features or functionalities. However, hobbyist production is unlikely to meet the rigorous quality and safety standards required for industrial-grade protective footwear.

In any scenario, coordination among stakeholders is crucial to ensure quality control, adherence to safety standards, and efficient production processes. This coordination could involve the use of digital platforms for communication and collaboration, standardized protocols for design and manufacturing, and ongoing quality assurance measures. As demand for personalized protective footwear increases, the industry may see further specialization and optimization of manufacturing processes to meet consumer needs efficiently.

The digital infrastructure for development of the toecaps exists to a certain extent, such as CAD tools which is widely used as well as communications platforms and data management tools for handling the personal data of the individuals taking advantage of this unique technology.

The physical infrastructure required would include AM facilities, footwear production facilities and a distribution network for the footwear containing the custom toecaps. Such infrastructure does exist but would require augmentation to be able to fully realize what is possible with this sort of custom safety footwear.

In the digital arena, automated software tools would need to be developed to streamline the process of creating the toecaps to minimize the amount of labor required for modeling them. For the purposes of this case study, it was learned early on that while standard shoe toecaps are relatively simple to model, the customized portion take time and would require some development, possibly within existing software tools available, to make the process financially feasible.

As an example of the work needed in physical infrastructure, existing footwear manufacturing facilities would need to adapt AM into their existing processes to create custom footwear and distribution channels would need to be adjusted to allow for custom footwear options – neither of these are insurmountable tasks. For minority countries where limited resources exist, however, more work would be required.

Cost/Benefit Analysis

Additive manufacturing (AM) presents a promising avenue to produce safety toecaps to be integrated into footwear, offering a blend of cost-effectiveness and enhanced safety features. Traditional methods of manufacturing safety toe caps often involve multiple production steps, such as stamping, bonding, trimming, cutting, etc. resulting in increased costs and lead times. By leveraging AM technology, these toe caps can be fabricated in a streamlined manner, reducing both production costs and time-to-market be removing steps (such as welding two stamped parts together) or easing the amount of labor required to do them (by making the bonding process simpler with improvements to the surfaces being bonded through AM). Moreover, the flexibility inherent in AM allows for the customization of toe caps to meet specific safety standards and individual foot sizes, enhancing the overall comfort and functionality of the footwear.

Beyond cost-efficiency, the adoption of AM-printed safety toe caps represents a significant value-add to the safety of individuals wearing the shoes. AM enables the incorporation of innovative design features and materials, such as lightweight yet durable composites or lattice structures, which can enhance both the protective capabilities and wearer comfort of the toe caps. Additionally, the ability to rapidly prototype and iterate designs using AM facilitates continuous improvement and optimization, ensuring that the toe caps meet evolving safety requirements and user preferences. Ultimately, the integration of AM-printed safety toe caps into footwear not only enhances the safety and comfort of individuals in various industries but also showcases the transformative potential of AM in revolutionizing traditional manufacturing processes.

The utilization of additive manufacturing for Personal Protection Equipment (PPE) has been employed in various applications previously, including helmet liners for sports, safety glasses frames, and, as showcased in this paper, safety toe caps. The significant impact of this technology can be particularly crucial for disaster-stricken areas or third-world countries facing challenges with their supply chain.

In recent years, researchers and innovators have explored the potential of additive manufacturing to address critical needs in PPE production. By harnessing the power of additive manufacturing, it becomes possible to create PPE tailored to specific needs, ensuring optimal protection and comfort for users.

Moreover, the decentralized nature of additive manufacturing enables the establishment of local production hubs, especially in regions where traditional manufacturing infrastructure is lacking. By strategically placing 3D printers in these areas and providing access to raw materials, communities can gain self-sufficiency in producing essential PPE. This not only reduces dependency on external suppliers but also empowers local economies and fosters resilience against disruptions in the global supply chain.

Furthermore, the potential cost savings associated with additive manufacturing are substantial. Traditional methods of PPE production often involve complex supply chains and high transportation costs. By producing PPE on-site with 3D printers, these expenses can be significantly reduced, making essential protective gear more accessible to those who need it most.

However, there are challenges associated with additive manufacturing which creation of customized toecaps are not immune from. The upfront costs of adopting additive manufacturing technology, including 3D printers and associated equipment, can be high, posing a barrier for some manufacturers. While additive manufacturing is suitable for rapid prototyping and small-batch production, its limited production speed may be a drawback for large-scale manufacturing but if focused on customization, the market may be small enough for the initial development with scaling through additional equipment and facilities being brought online or additional suppliers being added to the existing chain.

Material limitations and the need for post-processing steps to achieve specific properties add complexity to the production process. Despite these challenges, the numerous advantages make additive manufacturing an attractive option for enhancing the design and production of safety equipment.

Production issues can be a challenge to overcome as well. Encountering errors and anomalies, particularly during the prototyping phase, is commonplace. When experimenting with novel designs that pose printing challenges, users frequently encounter numerous failures owing to the intricacies of the design. Additionally, machine bugs or glitches are a common occurrence, particularly with new machines, which often require significant time to familiarize oneself with their quirks and intricacies. Normally with additive manufacturing there are assumed costs up front but once the parts have been developed, tested, and qualified the costs of overall production can be reduced.

Moreover, there are ASTM standards that need to be modified as well to address specific parts of the AM process and qualification which currently have not been addressed in the standard; much of the issue with qualification may be perception-driven which presumably will dissolve in time. The layered nature of AM parts and strength of those parts, specifying acceptable materials and possibly process parameters may be necessary to ensure parts meet ASTM standards.

The progression of parts achieving compliance with testing standards is closely tied to various factors such as research, design, simulations, and understanding of processes. Despite advancements in technology, ensuring compliance with testing standards remains a persistent challenge for AM parts. Having parts ‘born qualified’ would be the goal to overcome this issue.

The iterative nature of the additive manufacturing process necessitates a readiness to pivot away from initial designs and embrace redesign or re-execution of developmental builds. By recognizing the iterative nature of the process and leveraging insights from testing outcomes, manufacturers can navigate challenges more effectively and enhance the overall quality of AM-produced parts.

Conclusion

Additively manufactured lattice structure steel toes can be just as safe as traditional steel toe shoes with the added benefit of being lighter than most traditional steel toe shoes, and customizable to each person and boot type. This is especially impactful for women and other groups whose presence in the workforce and need for safety footwear is growing. The shape and size of the steel toes was based on ASTM F2413, using a nylon-carbon fiber material. Then using the data from a simulated load using nTop software, the design was given a lattice structure in which the portion of the toecap that had the greatest strain could smoothly incorporate thicker walls in the lattice leading to a lighter toe-cap. By concentrating the material where it is needed and removing it where it is not, this allows for the toecap to be lighter than a typical steel toe while satisfying the same safety standard.

While there are other solutions to making lightweight safety toecaps, only additive manufacturing allows customization, and a simple way to use these variable walled lattice structures to put material where it is needed the most. This concept can be implemented with small companies, and in small communities, and then scaled up as demand increases.

Future Issues and Opportunities

There are a few different directions future work can go to expand this case study:

- Further work can be done to explore different materials besides the nylon carbon fiber materials used in this case study.
- Work can be done to evaluate how to build a custom design and test it to ensure it satisfies safety standards effectively and efficiently.
- Further work to extend the design further up the shoe providing protection to more of the foot while remaining comfortable and light weight.
- Work to explore how breathability can affect the comfort of the shoes using these lattice designs.
- Work to print the design and build into a safety shoe could be used to explore and test the comfort and safety provided by the design.
- This design work focused on a narrow portion of the possible certifications available under ASTM standards; more work could be done to expand to additional certifications.

References

Akinlolu, M., & Haupt, T. (2020). Women and Occupational Hazards . *Construction Journal of Construction*, 49.

Carolo, L. (2024, January 26). *3D Printed Orthotics: Most Promising Projects*. Retrieved from All3DP.com: https://all3dp.com/2/3d-printed-orthotics-most-promising-projects/

EOS. (2024). *High-Performance Polymers*. Retrieved from EOS.com: https://www.eos.info/en-us/polymer-solutions/polymer-materials/high-performance

Formlabs. (2024). *Tough 2000 Resin*. Retrieved from Formlabs.com: https://formlabs.com/store/materials/tough-2000-resin/

Grand View Research. (2024). *Additive Manufacturing Market Size, Share & Trends Analysis Report By Component, By Printer Type, By Technology, By Software, By Application, By Vertical, By Material, By Region, And Segment Forecasts, 2024 - 2030.* Online: Grand View Research.

Habib, R. R., & Messing, K. (129–132). Gender, Women's Work and Ergonomics. *Ergonomics*, 2012.

Horaczek, S. (2018, April 17). *Nike hacked a 3D printer to make its new shoe for elite marathon runners*. Retrieved from Popular Science: https://www.popsci.com/nike-3d-printed-sneakers/

Jurca, A., Žabkar, J., & Džeroski, S. (2019). Analysis of 1.2 million foot scans from North America, Europe and Asia. *Sci. Rep., vol. 9*.

Knefel, J. (2016, September 16). *How 3D Printers Are Saving Lives in Remote Parts of the World*. Retrieved from Inverse.com: https://www.inverse.com/article/20840-how-3d-printers-are-saving-lives-in-remote-parts-of-the-world

Loctite AM. (2024). *High Performance Photopolymer Resins for End-Use Part Production*. Retrieved from Loctite AM: https://www.loctiteam.com/materials/

Lord, B. (2018, August 3). *REEBOK'S 3D PRINTED SHOE LINE DASHES INTO PRODUCTION*. Retrieved from 3D Printing Industry: https://3dprintingindustry.com/news/reeboks-3d-printed-shoe-line-dashes-into-production-137497/

McCann, R., Obeidi, M. A., Hughes, C., Egan, É. M., Vijayaraghavan, R. K., Joshi, A. M., . . . Brabazon, D. (2021). In-situ sensing, process monitoring and machine control in Laser Powder Bed Fusion: A review. *Additive Manufacturing*.

Mila. (2023, July 7). *Treading Lightly – What is Sustainable Footwear?* Retrieved from makemesustainable.com: https://makemesustainable.com/what-is-sustainable-footwear/

R., & ltd, M. (2024, March 8). *COVID-19 Drives North American Protective Footwear Market to Streamline Supply Chains and Pursue Inorganic Growth*. Retrieved from www.researchandmarkets.com: https://www.researchandmarkets.com/reports/5311260/covid-19-drives-north-american-protective

Rinkesh. (2024). *Is Polycarbonate Recyclable? (And Is It Biodegradable?)*. Retrieved from Conserve-Energy-Future.com: https://www.conserve-energy-future.com/is-polycarbonate-recyclable.php

U.S. Bureau of Labor Statistics. (2024, March 8). *Survey of Occupational Injuries and Illnesses Data* . Retrieved from U.S. Bureau of Labor Statistics: https://www.bls.gov/iif/nonfatal-injuries-and-illnesses-tables.htm