Chapter 11
Nano Plants (Nanostructured Implants)

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Abstract

Aesthetic/medical considerations often motivate individuals to seek treatments that enhance dental appearance. However, the high cost of dental implants can discourage many patients from pursuing such procedures. A similar situation arises with ceramic hip, knee, and shoulder implants, which are associated with substantial financial burden. In addition to cost concerns, zirconia-based ceramic implants are susceptible to degradation through Hydrothermal Ageing (HTA), a well-documented limitation that affects their long-term performance and reliability.

At Loughborough University, we have investigated the processing of nanocrystalline-ceramic powders into useful biomedical implants via several projects each focusing on a different stage of the manufacturing route viz., (i) the ability to control the agglomerates for achieving flowable-and-crushable powder for die pressing, (ii) the formation of low viscosity but high-solids-content suspensions suitable for 3D printing, and (iii) the use of sustainable microwave-assisted sintering techniques. This holistic approach helped to reduce material wastage, energy consumption, and carbon emission during implant manufacturing.

We developed various nanostructured zirconia-based ceramic components exhibiting vastly superior HTA resistance (>700 times improvement over conventional counterparts) and mechanical performance suitable for use as biomedical implants for dental and hip/knee prosthesis. This will directly impact the >£40B worldwide dental and orthopaedics market through ever-lasting implants and will provide better quality-of-life for the ageing population of around 3 billion people across the globe. The 3D-printed hydrothermally immune dental implants was considered as one of the six best modern technological developments in materials science for shaping the future by a BBC documentary, titled *Materials for the Modern Age: The Secret Story of Stuff.*

Keywords: *3D Printing, Biomedical Implants, Nanostructured Ceramics, Microwave Sintering, Hydrothermal Ageing*

Introduction

From dinner plates to rocket nozzles and aeroengines to electronic packaging, ceramics are ubiquitous in our daily lives. Ceramic materials are classified based on their composition, characteristics, and applications. While ceramics exhibit a wide range of physical and chemical properties that make them suitable for many applications, advanced ceramics that are bio compatible and are specifically developed

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for the biomedical implants are classified as bioceramics. Bioceramic implants are typically used for dental restorations, hip and knee prosthesis, finger joints, and bone tissue engineering/scaffolding and are predominantly made of yttria stabilised zirconia (YSZ) and zirconia-toughened-alumina (ZTA) ceramics. Currently 61% of hip joint replacements are for the 65+ age group and 36% are at 45–64, figures in both age categories are set to rise as people live longer and younger people are increasingly willing to pay for operations that allow them to enjoy sports that place a strain on joints for longer. A closer inspection of the global dental and orthopaedic market data suggests that the USA, Europe, and Japan account for 80% of the market, even though from a population perspective, these regions make up just 20% of the eight billion world population. This illustrates the huge global growth potential in this area: as the standard of living in India, China, Africa, and other regions rise, so will the demand for joint replacement operations. Thus, there is growing demand for bioceramic implants with the ageing population across the globe and any improvement in the development or processing of these bioceramic materials that enhances the quality of the patient life will have tremendous social, economic, and environmental impact.

However, there are two major challenges associated with bioceramic implants manufacturing: (i) complex shaping and (ii) energy intensive sintering. The conventional subtractive implant manufacturing processes involving machining and polishing account for significant material's wastage, amounting to around 90% loss (Figure **1**) in some cases, and these methods also pose an environmental concern (with fine particle debris floating around CNC machining/lathe equipment).

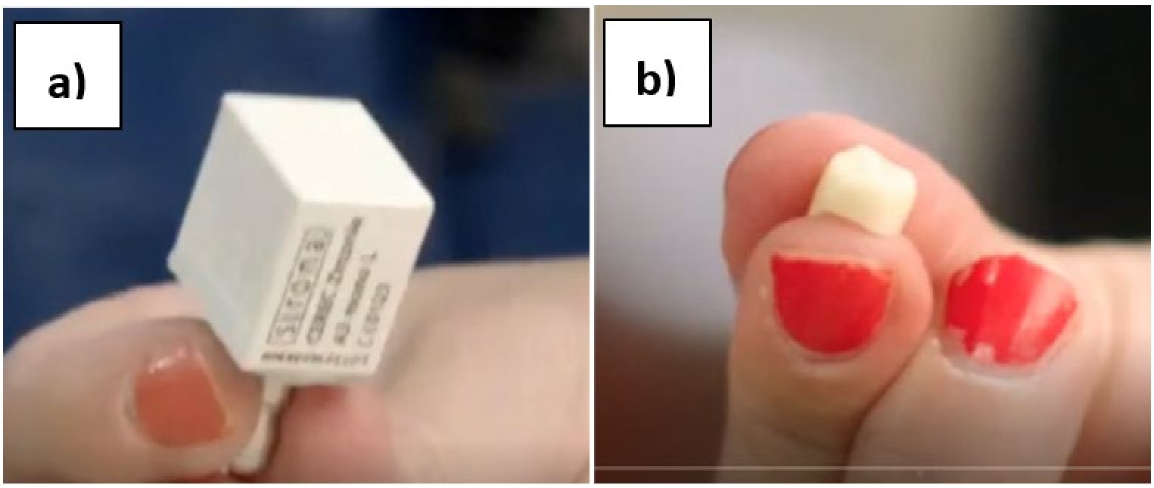

Figure 1: Conventional subtracstive manufacturing of a ceramic dental crown: a) block of zirconia ceramic (15 grams) and b) machined ceramic crown (1.4 grams), resulting in significant material wastage.

Recently at Loughborough University (LU), additive manufacturing (AM, also known as 3D printing) is employed to make these advanced ceramic biomedical implants suitable for personalised healthcare solutions with unparalleled design complexities, allowing for near-net-shaping. Eco-friendly field assisted sintering technologies (FAST) such as microwave and hybrid sintering are used to reduce energy consumption during implant manufacture. A thoughtful combination of AM and FAST resulted in the development of affordable, patient-specific, vastly superior nanostructured ceramic implants with reduced material wastage, energy consumption, and carbon emissions. This forms the subject matter of this article.

Results and Discussion

Various research projects at LU over the years have delivered significant foreground intellectual property[1] and technology know-how related to the fabrication of nanostructured ceramic materials with outstanding properties, surpassing some of the commercial counterparts, relevant to the energy, electronic security and in particular healthcare sectors. Specifically, it has been demonstrated that the hydrothermal ageing (HTA) resistance of zirconia-based ceramics can be enhanced significantly[2] by retaining a nano grain size below 180 nm even at low density components. This is highly relevant to the approximately seven-billion-dollar hip replacement market where concerns about the toxicity/wear debris in metal and polymer components renders all-ceramic solutions increasingly attractive. HTA degradation (the unwanted conversion of tetragonal zirconia to a weaker monoclinic form in an aqueous environment) is the Achilles-heel for the use of zirconia ceramics in the biomedical sector and was the reason behind the well-publicised failure of zirconia hip replacements around the year 2000. Thus, when HTA is countered, new opportunities open. The LU developed technology involve production of novel nano-suspensions with controlled rheology suitable for 3D printing and the microwave-assisted sintering[3] regimes for the manufacturing of zirconia and ZTA ceramics. This holistic powder-to-product approach delivered very small zirconia grain sizes that will assist current compliance (e.g. ISO 13356, ISO 633-3) and open up novel all-ceramic hip replacements via multi-fold enhancement in HTA-resistance of both porous and dense zirconia-based implant structures.

We have demonstrated using many 3D printing platforms like direct ink writing (DIW), digital light projection (DLP), stereolithography (SLA) that near net-zero manufacturing of bioceramic implants can be achieved with almost negligible material wastage, which is a welcoming sustainability trait. Our 3D printing processes use tailored ceramic ink formulations with desirable flow properties to build the complex implant structures directly from the design files (Figure **2**, Figure **3**, and Figure **4**), which significantly reduces material wastage and production costs.

Figure 2: DIW 3D printed nanostructured YSZ dental components.

[1]Annapoorani Ketharam et al. “Deformable granule production.” UK Patent. 2013.
[2]Anish Paul, Bala Vaidhyanathan, and Jon G. P. Binner. “Hydrothermal Aging Behavior of Nanocrystalline Y-TZP Ceramics.” *Journal of the American Ceramic Society* 94, no. 7 (2011): 2146–52. https://doi.org/10.1111/j.1551-2916.2010.04341.x
[3]Jon Binner and Bala Vaidhyanathan. “Processing of Bulk Nanostructured Ceramics.” *Journal of the European Ceramic Society* 28, no. 7 (2008): 1329–39. https://doi.org/10.1016/j.jeurceramsoc.2007.12.024

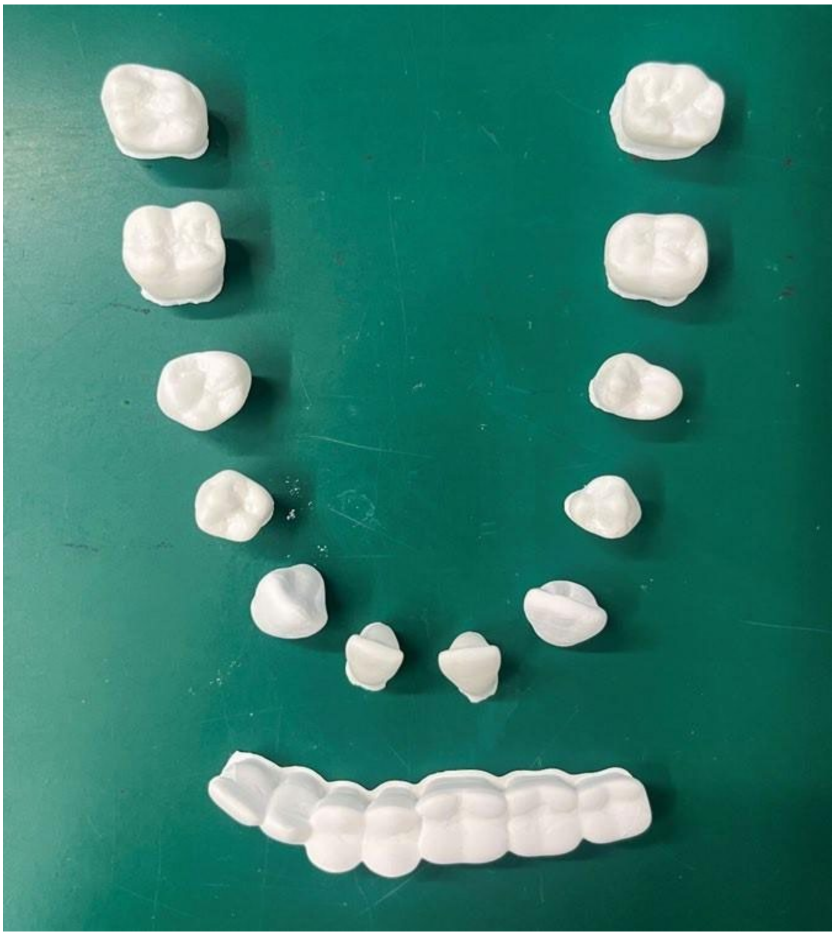

Figure 3: DLP 3D printed ceramic dental components.

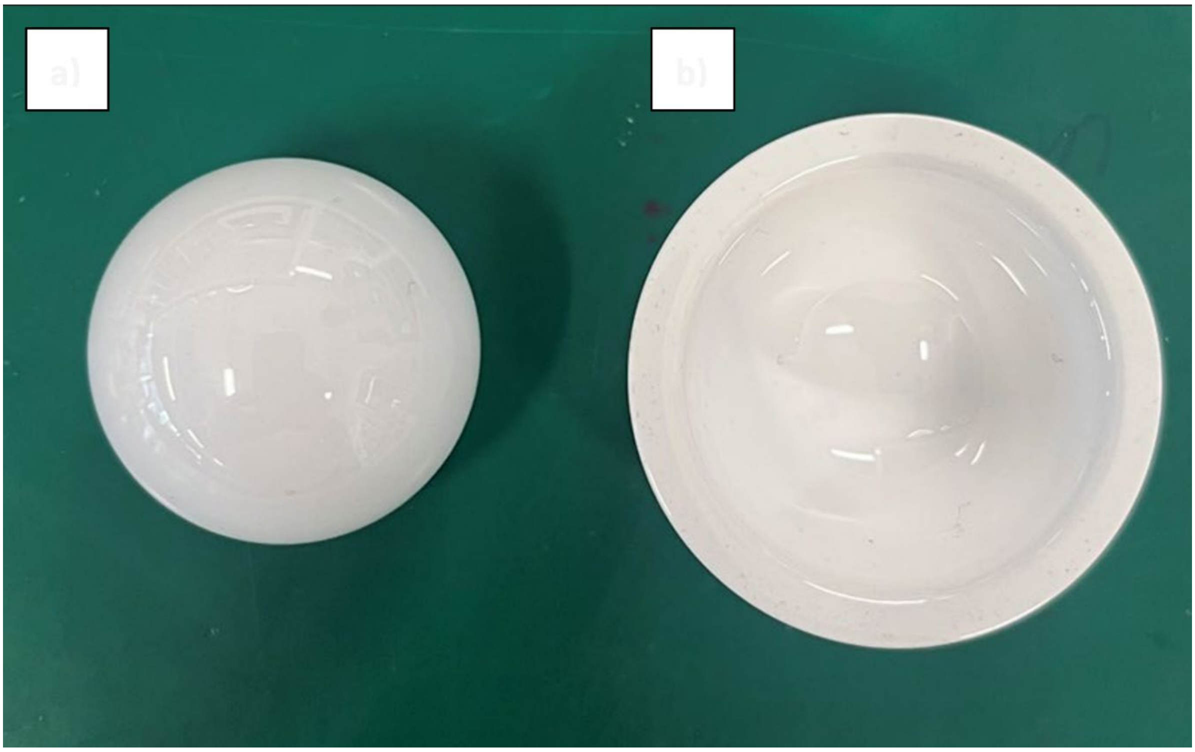

Figure 4: DLP 3D printed cersamic hip implants: a) Femoral Head and b) Acetabular Cup.

The sintering step is the most energy-consuming step in any ceramic filter manufacturing process. Employing FAST like microwave processing at LU, the time and temperature required for sintering have been reduced, which in turn cut down the energy consumption and the associated carbon emission.

Also, a combination of AM and FAST methodologies were employed for the first time to make sustainable ceramic implants with exemplary control on density, nano grain structure, porosity, pore morphology, and novel designed lattices, thus pushing the research boundaries on next generation bioceramic implant manufacturing. This resulted in ceramic implants with extremely fine-grained nanostructure (Figure 5) compared to conventionally processed YSZ ceramics. This exceptional nanostructure, resulted in complete stabilisation of the tetragonal structure for zirconia grains, resulting in total immunity towards HTA[4]. When compared with conventional methods, the 3D-printed YSZ structures also achieved 99.4 ± 0.2 % density and an average Vickers microhardness of $HV_{1/10}$ = 1244.2 ± 98.2 (equivalent to 12.2 ± 0.96 GPa)[5].

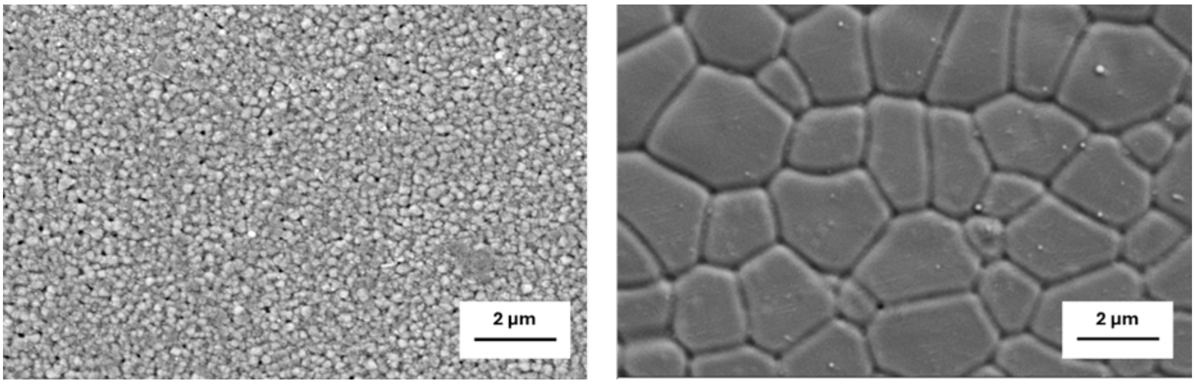

Figure 5: a) Nano grain strucsture using AM and FAST and b) Corresponding conventional micro grain structure of YSZ ceramics.

Further, our cseramic ink formulations are also adaptable for various 3D printing platforms, from cheap and cheerful (£200) desktop printers to the expensive, high throughput (£200,000) printers available to the industry. By adapting the bioceramic resin formulation, this research demonstrates, for the first time, that high-quality ceramic implants/components can be produced using accessible and cost-effective printers[6]. In doing so, it represents a step forward in the democratisation of additive manufacturing for functional ceramics, aiming to reduce barriers to entry and expand the potential for wider adoption of AM in various industrial and research applications. This will help to move the dial on the applicability of ceramic AM from a 'high value – low volume' technology to a 'high volume – low value' viable methodology for producing complex shaped ceramic components. By resorting to a large number of low-end 3D printers (rather than one or two high-end expensive printers), productivity/throughput can be enhanced without compromising on product quality. Such a trait

[4]Paul, Vaidhyanathan, and Binner, "Hydrothermal Aging Behavior of Nanocrystalline Y-TZP Ceramics," March 2, 2011.

[5]Athanasios Goulas et al., "Formulation-driven Additive Manufacturing of 3YSZ Advanced Ceramics via Digital Light Processing," *Open Ceramics* 22 (April 22, 2025): 100785, https://doi.org/10.1016/j.oceram.2025.100785

[6]Athanasios Goulas et al., "Enabling Accessible Additive Manufacturing of Alumina Ceramics Through Formulation Design," *Materials & Design* 258 (August 18, 2025): 114601, https://doi.org/10.1016/j.matdes.2025.114601

augers well for the scale-up manufacturing of biomedical implants via 'low cost – low wastage' additive manufacturing and the industrial take-up of these emerging technologies to make 'affordable' all-ceramic implants.

In addition, 3D printing of biomedical implants also lends itself to remote manufacturing. Further, digitalization of product development and process control can be achieved through AI, neural networks, and machine learning algorithms, paving the way for next-generation implants via IR 4.0/5.0.

Conclusions

Zirconia-based bioceramic resin formulations were designed/developed that are suitable for 3D printing across many accessible and cost-effective DLP printer platforms to produce high-quality ceramic implants/components for healthcare applications. Field assisted sintering techniques were used to achieve fine grained ceramic structures that are totally immune to hydrothermal ageing. Thus, the unique combination of AM and FAST methodology was employed for the first time to make ceramic implants with exemplary control on density, nano grain structure, as well as superior performance, leading to next generation sustainable bioceramic implant manufacturing.

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