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聚能为笔，化陶成墨，镌刻神笔马良新篇章

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陶瓷，是一种历史悠久且应用广泛的无机非金属材料，在人类文明进程中扮演着至关重要的角色。如今，陶瓷因其优异的物理和化学性能得到大量的研究和使用，结构和功能属性复杂的先进陶瓷材料尤其在机械电子、能源环保、航空航天、生物医疗等高新技术领域占据不可或缺的地位。然而，陶瓷材料固有的高硬度和高脆性，使得在制造高度复杂的三维空间形状或定制化结构与功能产品的时候，传统的模具成形和加工技术往往面临难度高、周期长的技术局限。

增材制造的出现则为突破上述局限提供了全新思路。增材制造技术最早被称为无模制造或快速原型技术，直到 21 世纪才日渐普及并通称为 3D 打印技术。美国在 20 世纪 80 年代发明的适用于有机树脂溶液的“立体光刻-Stereolithography (SL)”光固化增材制造技术，和 90 年代诞生于德国适用于金属粉末的“选区激光熔化-Selective Laser Melting (SLM)”增材制造技术是具有划时代意义且最具代表性的增材制造技术。国际上已经开发了十余种应用于各类材料的增材制造技术。与有机材料和金属材料相比，一般陶瓷材料的物理和化学活性较低且熔点较高，因此部分用于有机和金属材料的增材制造工艺无法直接用于陶瓷增材制造。尽管如此，目前已知的大部分陶瓷增材制造技术仍源自有机材料和金属材料增材制造技术，导致陶瓷材料的增材制造发展困难，且发展历史也相对短暂。增材制造在制造高度复杂结构时所展示的独特灵活性，以及组织与功能的定制化优势，让国内外研究人员趋之若鹜，纷纷投身于陶瓷材料增材制造及其应用研究当中。

近年来，我国在陶瓷增材制造领域涌现出许多优秀的研究团队与企业。根据 2021 年 7 月由深圳大学陈张伟教授等学者创办的“第一届中国陶瓷增材制造前沿科学家论坛(FAME2021)”的初步统计，目前我国已有超过 60 所专门从事陶瓷增材制造与应用探索研究的科研院所，而发展和制造与陶瓷增材制造技术相关的材料、打印工艺装备以及后处理工艺装备的生产商则超过了 20 家。目前，产学界以陶瓷粉末和树脂或黏接剂混合的浆料进行光固化，以 SL 和数字光处理(Digital Light Processing, DLP)或墨水直写(Direct Ink Writing, DIW)增材制造工艺的研究占绝大多数。除此以外，其他研究则以激光选区烧结(Selective Laser Sintering, SLS)和激光定向能量沉积(Laser Directed Energy Deposition, LDED)等采用陶瓷混合粉末及高功率激光的工艺进行直接增材制造为主。在陶瓷材料种类方面，大部分学者围绕氧化物陶瓷材料，如 SiO_2、ZrO_2、Al_2O_3 及其混合或复相材料，以及 PZT、BTO、TCP 等先进陶瓷材料开展研究。主要应用方向包括承重组件或功能性部件，如催化载体、铸型、隔热、压电、传感、人工骨、齿科、超高温部件、精密光学件等。而近年来研究人员也纷纷面向结构功能一体化部件，围绕非氧化物陶瓷如 SiC、Si_3N_4、AlN，甚至更为复杂、可生成多元陶瓷的聚合物前驱体转化陶瓷(Polymer-Derived Ceramics, PDCs)体系等进行增材制造工艺研究，并取得突出进展。

总体而言，陶瓷增材制造过程是以陶瓷基材料为“墨”，以光能、机械能、热能等能源为“笔”，就如同中国神话故事“神笔马良”一样“画出”各种结构功能一体化的复杂陶瓷器件。值得注意的是，“神笔马良”最终练就的是“所画即所得”的效果。笔者认为，这恰恰就是增材制造或 3D 打印追求的终极目标，即“所打(印)即所得”。当然，在陶瓷增材制造领域实现“所打即所得”还需要克服诸多挑战。由于陶瓷具有纷繁复杂的材料性质，在采用各类方法进行增材制造的过程中均涉及材料体系的制备、成形工艺的适配、热处理或后处理工艺的优化等问题。正因如此，在用于成形制造、变形和缺陷抑制、组织和性能调控等方面的材料选取及控制上均需要予以细致全面的考虑和权衡。

2021 年下半年，在 FAME2021 大会召开之际，《无机材料学报》编辑部邀请香港城市大学吕坚院士和深圳大学陈张伟教授担任特邀编辑，以“无机材料增材制造”为主题组织征稿并制作专辑，华中科技大学吴甲民副教授亦参与了这次专辑的组织工作。本专辑收录了我国部分陶瓷增材制造的最新研究成果和综述文章，体现了我国陶瓷增材制造研究的前沿进展。由于时间和篇幅所限，还有一些优秀的研究未能及时收录在本专辑中。希望本专辑能够抛砖引玉，为促进我国陶瓷增材制造研究与应用发展提供有益参考。我们相信在全球学者的不懈努力和推动下，聚能为笔，化陶成墨，陶瓷增材制造一定能够镌刻神笔马良新篇章，完成从“聚沙成塔”的工艺工程研究到“点石成金”的高附加值普及应用的飞跃。

Marking a New Chapter like 'Ma Liang the Magic Brush' with Focused Energies as Pens and Ceramics as Inks

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Ceramics are a series of inorganic nonmetallic materials with a long history and have been extensively used. They have been playing a vital role in the human civilization process. Nowadays, as one of the three pillars in the material systems for modern industry, ceramics with excellent physical and chemical properties have been increasingly used and researched and become indispensable in the high-tech application fields such as machinery and electronics, energy and environmental protection, aerospace and biomedical industries, especially for the advanced ceramics with complex and integrated structural and functional properties. However, due to their inherent high hardness and brittleness, when manufacturing ceramic products with highly complex three-dimensional shapes or customized structures and functions, the traditional molding and machining technologies often face certain technical limitations with great difficulty and long production cycle.

The emergence of additive manufacturing (AM) paves a new way to break through above limitations. AM technology is earliest known as freeform fabrication (FFF) or rapid prototyping (RP) technology, was gradually popular with the general public and is now commonly known as 3D printing technology in this century. 'Stereolithography (SL)' photopolymerization additive manufacturing technology suitable for organic resin solutions and 'Selective Laser Melting (SLM)' additive manufacturing technology for metal powders, were invented in the US and Germany in the 1980s and 1990s, respectively. These two epoch-making technologies are the most significant representatives of all AM technologies. At present, over ten types of additive manufacturing technologies have been developed for various raw materials. However, compared with organic and metallic materials, ceramics generally possess lower physical and chemical activities and higher melting points; some AM processes used for organic and metallic materials cannot be directly applied to ceramic materials. Nevertheless, currently most of the ceramic AM technologies are derived from that made for organic and metallic materials. This makes the development of AM technologies for ceramic materials difficult, and thus its development history is relatively shorter. However, the magic and charm of AM lie in its unique flexibility of manufacturing highly complex shapes, as well as the advantages of customized structures and functions, which extensively attract worldwide researchers to investigate AM of ceramic materials and their applications.

In recent years, a number of excellent research groups and industrial organizations have sprung up in the field of ceramic AM. According to the statistics preliminary generated from the 1st National Forum on Additive Manufacturing of Ceramics (FAME2021) initiated by Prof. CHEN Zhangwei of Shenzhen University in July 2021, there are approximately over 60 institutes in China specializing in the research of ceramic AM and applications, while more than 20 industrial manufacturers are involved in the development and fabrication of materials, printing process equipment, and post-processing equipment that are relevant to ceramic AM technology. Among them, the majority of research focuses on the AM of photopolymerization (including SL and Digital Light Processing (DLP)) or Direct Ink Writing (DIW) using the mixtures of ceramic powders and resins/adhesives. The rest mainly utilizes ceramic powders and high-power lasers such as Selective Laser Sintering (SLS), Laser Directed Energy Deposition (LDED), and other processes for direct AM of ceramics. In terms of the types of ceramic materials involved, most research focuses on oxide ceramic materials, such as SiO_2, ZrO_2, Al_2O_3, and their mixed or multiphase materials, as well as PZT, BTO, TCP, and other advanced ceramics. The main application directions include load-bearing components and functional parts, such as catalytic carriers, casting molds, heat insulation, piezoelectric, sensors, artificial bones, dentistry, ultra-high temperature parts, optics, and other fields. Besides, in recent years, researchers have also turned to AM of non-oxide ceramics such as SiC, Si_3N_4, AlN, and even more complex Polymer-Derived Ceramics (PDCs) that generate polynary ceramics, and substantial progress has been achieved.

In general, the ceramic AM processes take ceramic-based materials as 'inks' and focused energies such as light energy, mechanical energy and heat energy as 'pens', to 'draw' a variety of complex ceramic devices with integrated structures and functions, which is similar with the Chinese fairy tale of 'Ma Liang the Magic Brush'. It is noteworthy that the outcome of 'Ma Liang the Magic Brush' was 'What You Draw Is What You Get'. In our opinion, this is exactly the ultimate goal of AM or 3D printing, namely 'What You Print Is What You Get'. There are still numerous challenges to overcome to achieve 'What You Print Is What You Get' in the field of ceramic AM. Due to the complicated material properties of ceramics, the process of shaping by various AM technologies involves the preparation of the material feedstock systems, the adaptation of forming process, and the optimization of heat treatment and post-treatment process. Therefore, material selection and controls over the forming process, deformation and defect, structures and properties, and other aspects require overall investigation and careful balance.

In the second half of 2021, while the conference of FAME2021 was held, the Editorial Board of the *Journal of Inorganic Materials* invited Prof. LU Jian from the City University of Hong Kong (CUHK) and Prof. CHEN Zhangwei from Shenzhen University (SZU) as guest editors to organize this Special Issue (SI) themed 'Additive Manufacturing of Inorganic Materials'. Prof. WU Jiamin from Huazhong University of Science and Technology (HUST) also contributed to the organization of the SI. This SI focuses on some of the latest research outcomes and review articles in the field of ceramic AM in China, representing the frontier progress of ceramic AM research in China. Due to the limitations of time and space, some excellent work cannot be included in this SI in a timely manner. We hope that the SI can provide a useful reference for promoting the research and application development of ceramic AM in China. With ceramics as inks and focused energies as pens, would ceramic AM mark the new chapter like 'Ma Liang the Magic Brush', manifesting a significant leap from the processing and engineering research of 'Accumulating sands to form a pagoda' to the popularized application of high added value of 'Turning stones into gold by touching'? We believe that with the unremitting efforts and progress made by researchers worldwide, this dream will eventually come true in the near future!

陈张伟，深圳大学长聘教授、增材制造研究所所长、深圳大学优秀学者。英国帝国理工学院哲学博士(2014)、博士后。帝国理工校长奖学金获得者，帝国理工年度唯一 John Kilner Prize 优秀博士论文奖获得者。从事以陶瓷材料为主的增材制造与创新应用研究 10 余年。受邀担任中国机械工程学会增材制造分会委员、中国硅酸盐学会测试技术分会理事、特陶分会青年委员，以及中国医疗器械行业协会 3D 打印医疗器械专业委员会团体标准指导专家；担任 SCI 期刊《Journal of Advanced Ceramics》和 EI 期刊《材料工程》编委、SCI 期刊《无机材料学报》和《Crystals》增材制造专辑特邀编委、《Open Ceramics》客座编辑，以及《SVOA Materials Science and Technology》《Frontiers in Materials and Nanoscience》《精密成形工程》《航空材料学报》期刊编委/青年编委等；参与制定中国机械工程学会《中国机械工程技术路线图（2021 版）》陶瓷增材制造相关内容。作为创始主席发起创办了“第一届中国陶瓷增材制造前沿科学家论坛 FAME2021”，该论坛入选“2021 年度中国科协重要学术会议指南”。受邀担任国内外重要增材制造会议共同主席并做大会报告/特邀报告近 20 次。担任《Nature Communications》《Materials Horizons》等三十余本高水平期刊审稿人，以及中国国家自然科学基金、加拿大工程和自然科学研究基金 NSERC、新加坡 A STAR 政府基金、新西兰政府 Marsden Fund 基金以及广东、北京、陕西、深圳等多个省市项目评审专家。2017 至今主持和参与陶瓷增材制造相关的国家和省市级项目 20 余项，并与华为等知名企业开展合作研究。在《Acta Materialia》《Additive Manufacturing》《Virtual and Rapid Prototyping》《Materials Research Letter》《Journal of Advanced Ceramics》《Journal of the European Ceramic Society》《无机材料学报》《机械工程学报》《硅酸盐学报》等国内外期刊发表高水平论文 70 余篇，单篇最高被引超 600 次，入选 ESI 高被引和热点论文 1 篇。申请和授权发明专利 10 余项。研究成果获中央主流媒体《科技日报》的长篇专访报道以及新华网、人民网、环球网等知名媒体平台的转载报道。2017 年至今共指导博士后 8 名、博士生 3 名、硕士生近 20 名。
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吕坚，香港城市大学机械工程学系及材料科学与工程系讲座教授，法国国家技术科学院院士。香港材料研究会理事长，香港创新科技及再工业化委员会委员，广东省大湾区激光与增材制造产业技术创新联盟副理事长，中国增材制造联盟专家委员会副主任委员，中国力学学会特邀理事，广东省松山湖材料实验室战略咨询委员会及学术委员会委员。2006 年获法国国家荣誉骑士勋章，2011 年当选法国国家技术科学院院士；2017 年获法国国家荣誉军团骑士勋章；2018 年获中国工程院第十二届光华工程科技奖。曾先后担任法国机械工业技术中心(CETIM)高级研究工程师和实验室负责人，法国特鲁瓦技术大学机械系统工程系系主任，法国教育部与法国国家科学中心(CNRS)机械系统与并行工程实验室主任，香港理工大学机械工程系系主任、副院长，香港城市大学科学与工程学院院长，香港城市大学副校长(研究与科技)兼周亦卿研究生院院长，香港力学学会理事长，香港研究资助局(RGC)委员等职。目前担任《Nano Materials Science》《Science China Technological Sciences》等高水平期刊的主编或编委。研究方向涉及 3D/4D 打印材料、工艺与性能，先进结构与功能纳米材料的制备与物理及化学性能；生物与仿生材料；实验力学与塑性力学；以及结构材料预应力工程等。研究团队在《Nature》 (封面文章), 《Science》《Nature Materials》《Science Advances》《Advanced Materials》《Materials Today》《Nature Communications》等知名期刊上发表论文 450 余篇，引用 30700 余次(Google Scholar)。取得 51 项国内外专利授权，其中 4D 打印陶瓷技术已经获得美国专利局授权 3 项专利，并被欧盟委员会选为 100 项可能对全球经济产生重大影响的颠覆性技术(100 Radical Innovation Breakthroughs for the future)之一。

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深圳大学增材制造研究所简介

深圳大学增材制造研究所(Additive Manufacturing Institute, Shenzhen University (AMI-SZU))成立于 2016 年，是深圳大学目前唯一专门从事各类增材制造技术研究的校一级研究机构，依托深圳大学机电与控制工程学院。

研究所现有教师 5 名，专职副研究员 2 名，博士后研究人员 8 人，博士研究生 3 人，硕士研究生 50 余人，均从事面向科学基础和工程应用的增材制造研究，涵盖了材料、工艺、装备和应用等各个方面。目前开展的增材制造工艺方面的研究包括：用于有机物和陶瓷增材制造的光固化技术(包括 SL 和 DLP)、用于陶瓷等无机材料增材制造的挤出直写技术(DIW)、用于无机材料增材制造的喷墨打印技术(IJP)、用于金属增材制造的激光选区熔化(SLM)和用于金属和陶瓷材料增材制造的激光能量沉积技术(LMD)等。研究的应用方向包括：固态氧化物燃料电池和锂电池等能源器件；面向尾气净化环保及核聚变堆的催化剂载体部件；面向航空航天的轻质高强陶瓷结构件和高性能金属部件等。

深圳大学增材制造研究所成立 4 年以来，获批国家自然科学基金面上项目(3 项)、青年项目(4 项)、广东激光与增材制造重点研发项目/课题(2 项)，以及广东省自然科学基金面上项目、广东教育厅青年创新人才项目、深圳市科创委项目及华为公司等各级纵向和横向科研项目 30 余项，累计科研经费和固定资产近 3000 万元。近年来在陶瓷和金属材料增材制造等领域顶级期刊发表高水平研究论文和综述性论文近 60 篇。培养的学生多人次获得国家奖学金、腾讯创始人奖学金、深圳大学一等学业奖学金、优秀科研奖、优秀毕业生、深圳大学百篇优秀毕业论文等奖励和荣誉。

深圳大学增材制造研究所与国内外相关高校和企业建立了良好的合作关系，同时热忱欢迎各界人士莅临考察指导并探讨交流合作。此外，研究所长期招聘和招考具有相关背景且能力优秀的博士后和研究生。

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