# Additive manufacturing of ceramics: Present status and future perspectives

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**Abstract**

At present, fabrication of ceramics using AM-based techniques mainly suffers from two primary limitations, viz: (i) low density and (ii) poor mechanical properties of the finished components. It is worth mentioning that the present state of research in the avenue of AM-based ceramics is focussed mainly on fabricating ceramic and cermet components with enhanced densities and improved mechanical properties. However, to the best of the authors' knowledge, not much is known about the microstructure evolution and its correlation with the mechanical properties of the finished parts. Addressing the aforementioned avenue is highly essential for understanding the utilisation of these components for structural applications. To this end, the present review article is aimed to address the future perspectives in this avenue has been provided with a special emphasis on the need to establish a systematic structure-property correlation in these materials.

**Keywords**: Additive Manufacturing (AM), ceramics, cermets, Correlative characterisation

## 1. Future perspectives

### 1.1 From the viewpoint of fabrication techniques

It appears that there currently exist a number of limitations on the practical applications of AM based ceramics, which mainly includes the lack of microstructural quality control with the fabricated ceramic parts. Besides, a number of defects, particularly ranging from 2-D (surface) defects (such as grain boundaries, interphase boundaries etc.) to various 3D (volume) defects (mainly, porosity) are associated with AM based ceramic parts [1], which require extensive microstructural investigations to be overcome. Moreover, the intrinsic staircase effect associated with AM techniques leads to notch sensitivity issues of final ceramic parts [2]. Besides, the need for post-processing techniques (debinding and sintering), as discussed in the previous sections, signifies that a lot of challenges associated with complex geometry designs for traditional ceramic manufacturing are also applicable for ceramics fabricated using AM based techniques, which primarily include the limitation of thickness of the final part and distortion associated with debinding/sintering.

In the context of indirect (multi-step) AM processes, making use of a binder material, the time-consuming debinding (binder removal) step, renders these processes as unsuitable for a rapid production of ceramics. Although direct (single step) AM processes (Powder bed fusion and Directed energy deposition) do not have this limitation, but however suffer from non-versatility, in terms of producing ceramic parts, unlike that of indirect AM processes [2], [3].

Moreover, during powder bed AM approach, ceramic powder particles tend to exhibit lower flowability [141]. On the other hand, the major problem associated with powder suspension feedstock based AM techniques is the limitation in terms of the content of the ceramic solid, limiting the maximum achievable density of the finished ceramic parts and hence, necessitating optimisation of different process parameters in sintering strategies such as liquid phase sintering (LPS) and Hot Isostatic Pressing (HIP) [4].

Although, a number of reviews on AM of ceramic parts have mentioned about the key factors required for the fabrication of the ceramic pastes during extrusion based shaping processes [141], however the flow of viscous ceramic pastes needs be modeled, in order to prevent cracking in final ceramic parts [142]. Moreover, a textured microstructure may be obtained due to flow-induced alignment of ceramic particles during material extrusion processes [2], [4], [5], necessitating the viscous ceramic paste to be free of large aggregates. In addition, during debinding of green ceramic parts made of powder injection molding (PIM), broad temperature range of binder decomposition leading to an easy escape of the evaporated gas phase from the binder has been reported to minimise the extent of cracking in the debinded parts [1]. In this regard, slow decomposition of the binder has also been reported to be beneficial for retention of the final part shape [6]–[8]. However, the development of new binder and slurry systems for AM based ceramics is an avenue which is presently unexplored and offers huge potential for future investigations.

In the near future, development of piezoelectric ceramic devices (utilising high-piezoelectric coefficient of ceramics) has also been reported to offer a huge potential towards future investigations [9], [10].

**1.2 From the viewpoint of fundamental research**

Although there have been a number of investigations aimed at optimisation of different processing parameters in AM based manufacturing of ceramics [11], however, there still remains a limited understanding on the influence of different processing parameters on the microstructural evolution which is critical to address the major challenges, particularly, (i) low density and (ii) poor mechanical properties which act as major obstacles to a large scale application of these materials in different sectors, such as defence, aerospace, electronics, healthcare etc. Although a number of ways for minimisation of cracking and enhancement of density (of the final part) along with mechanical properties of AM based ceramics have been devised [8], however, these post-processing techniques have failed to render these materials as suitable candidates for high performance applications in the aforementioned sectors, unlike that of conventionally fabricated ceramic parts. This necessitates an understanding of microstructures in AM-based ceramic parts through a systematic structure-property correlation using extensive structural cum chemical characterisation techniques.

As discussed earlier, the onset of "Correlative Microscopy" involving both structural and chemical characterisation from the same region in the microstructure [12], [13], in recent times, has provided a major breakthrough in understanding a number of different properties in different metallic materials [14]. However, at present, there is hardly any report on understanding the mechanical properties of AM-based ceramic parts using the aforementioned technique. In this regard, it becomes highly essential to mention about the role of different 2D interfaces in influencing the mechanical properties of these materials. The simplest of the 2D interfaces in crystalline ceramics are grain boundaries (GBs) and interphase boundaries (IBs) (for multiphase materials). In the context of metallic materials, during plastic deformation, stress concentration at GBs and IBs (both mechanically "weaker" as compared to the lattice) leads to intergranular fracture [15], [16]. This is the most common mode of failure in metallic materials during service [146-151]. Moreover, in the context of metallic materials, it has been reported that by controlling the fraction of different GBs in the microstructure (also reported as "GB engineering" (GBE) in many literatures), it is possible to engineer mechanical properties [17]. However, for AM-based crystalline ceramics with low-symmetry crystal structures, the structure of GBs and IBs tends to be much more complex as compared to those in metallic materials, comprising mostly of high-symmetry crystal structures [18]. This has been the main reason as to why there is hardly any report on GBE of AM-based ceramics.

Thus, in addition to optimisation of different processing parameters, "Correlative microscopy" approach may be utilised for a systematic structure-property correlation combined with tailoring of microstructures in these materials based on GBE, in order to overcome the problem of poor mechanical properties in AM-based ceramics. Moreover, this avenue is presently unexplored and hence, offers a great potential for future investigations.

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