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Multi-Material Spreading Strategies for Functionally Graded Material Manufacturing in LPBF

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Abstract. Functionally graded materials (FGMs) offer superior performance due to their gradual property variation. However, traditional manufacturing face challenges with material wastage, geometric complexity, and process control. Laser Powder Bed Fusion (LPBF-AM) enables precise spatial control of material distribution, yet FGM development remains challenging due to complexities in multi-material powder handling and spreading. FGM fabrication in LPBF-AM relies on graded powder spreading before laser interaction with powder. The interaction between multi-material poly-disperse powder introduces uncontrollable mixing, and non-uniform gradation. Predicting powder gradation via modelling is crucial before optimizing laser scanning strategies. This study uses Discrete Element Method (DEM) simulations to analyze polydisperse and multi-material powder spreading. A gradation index quantifies mixing of multi-material, while a novel partitioned dispenser controls deposition, enabling linear and sigmoidal gradation profiles. Experimental LPBF printing validated the method, with Energy Dispersive Spectroscopy (EDS) confirming controlled material transitions and high-quality FGM fabrication.

1 Introduction

Functionally Graded Materials (FGMs) represent an advanced class of materials characterized by a continuous spatial variation in composition or structure, enabling tailored mechanical, thermal, and functional properties within a single component. By integrating multiple materials, FGMs facilitate the development of components with enhanced strength, hardness, flexibility, and thermal conductivity while minimizing assembly complexity. Unlike conventional manufacturing methods, which impose limitations on component size and gradation complexity, additive manufacturing (AM) provides a viable alternative for the cost-effective production of FGMs with controlled compositional transitions in any direction.

Among AM techniques, Laser Powder Bed Fusion (LPBF) is particularly well-suited for fabricating FGMs due to its precise control over microstructure and mechanical properties. LPBF uses layer-by-layer deposition and selective laser melting for the production of complex geometries with engineered material distributions. However, the final component's quality is highly dependent on uniform powder spreading, which remains a considerable difficulty, especially in poly-disperse and multi-material systems. Variations in powder size distribution and material properties can cause defects such as porosity, and heterogeneity in the build, impacting part integrity. Therefore, a fundamental understanding of the physics governing multi-material powder spreading is essential to optimizing FGM fabrication in LPBF. As powder is considered a discontinued media, unlike fluids, the prediction of the behaviour of powder spreading using popular computational methods such as the finite element method and computational fluid dynamics is challenging and not economical in terms of computational cost. Hence, numerical methods like the discrete element method (DEM) are useful in predicting powder spreading in LPBF. Moreover the use of DEM becomes more necessary for multi-material spreading because of its complexity.

The DEM has emerged as a powerful computational technique for studying powder spreading in LPBF, revealing important information about particle interactions, segregation, and gradation. DEM simulations help optimize recoating strategies, improving process reliability and material distribution [1]. Recent studies have explored various recoating mechanisms for FGM fabrication in LPBF. Wen et al. [2] used a vertical hopper (a gravity-based feeder) with partitioned chambers to create an FGM with gradation perpendicular to the spreading direction, which uses gravity and motion to spread the powder on the build platform. However, their study did not investigate the mechanics of particle mixing during spreading. In comparison with the stacking approach which gives step gradation, a partition based approach gives smooth gradation [2]. With the goal of achieving smooth gradation, the current study uses DEM simulations to examine the powder spreading behavior in LPBF for FGM manufacturing. To provide uniform and smooth gradation for high-quality FGM production, a novel partitioned dispenser system is introduced to control material deposition [3]. The research focuses on developing strategies for functionally graded spreading using a partition-based approach, with DEM serving as the primary analytical tool. Two common industrial materials, IN718 and SS17-4PH, which are used extensively in turbine components and other high-

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performance applications, are the subjects of the methodology.

2 Materials and Methods

2.1 DEM simulation of spreading

FGM fabrication begins with particle generation at a fixed dispenser, modelled as virtual boxes. The dispenser is partitioned to separate materials A and B, with particles introduced at distinct locations under gravity. Once filled, the dispenser elevates to accommodate particles by twice the layer thickness in the z-direction (dosage factor 2 [1]), allowing controlled particle spreading on the build platform. The recoater then moves in the x-direction to spread the powder evenly. The motion of the build platform and dispenser, which governs material gradation, is illustrated in fig. 1.

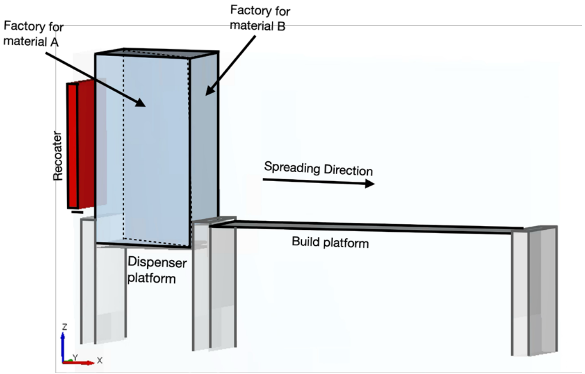

Figure 1. Simulation set up for FGM spreading analysis

The DEM is formulated based on the discrete particle interaction to mimic the particulate behaviours of the powder. The interactions are determined by solving Newton's law of motion for normal and tangential interaction of individual particles of metal powders. The discrete particle interaction with translational and rotational motion can be represented by,

$$m_i \frac{dv_i}{dt} = m_i g + \sum F_{c,i} + f_{\text{external},i} \quad (1)$$

$$I_i \frac{d(\omega_i)}{dt} = \sum T_i \quad (2)$$

where, subscript i represents i^{th} particle; $f_{\text{external},i}$ represents external forces; $F_{c,i}$ represents contact forces; T_i represents torque on the i^{th} particle. The contact forces are determined by using rheological models such as Hertz-Mindlin and Hertz-Mindlin with JKR. The Hertz-Mindlin with JKR model effectively simulates cohesive powder spreading but has notable limitations such as the cohesion force is activated once the particles are in touch. It assumes elastic deformation and spherical particle surfaces, neglecting plasticity. The model in this work is restricted to spherical particles, limiting realism for irregular shapes. It does not account for sintering or melting effects. The Hertz-Mindlin with JKR model incorporates van der Waals forces and is used to describe cohesive interactions among powder particles. The normal contact force in the JKR model and the relationship between the normal overlap ($\delta^{\text{n}}_{\text{ij}}$), contact radius ($\text{r}_\text{c}$), and cutoff overlap ($\delta^{\text{n}}_{\text{cutoff}}$) are defined as

$$F^{\text{n,c}}_{ij} = \frac{4E^*}{3R^*} r_{\text{c}}^3 \hat{n} - \sqrt{8\pi E^* \Gamma}\, r_{\text{c}}^{\frac{3}{2}} \hat{n} \quad (3)$$

$$r_{\text{c}}^4 - 2\delta^n_{ij} R^* r_{\text{c}}^2 - \frac{2\pi\Gamma R^{*2}}{E^*} r_{\text{c}} + \delta^{n2}_{ij} R^{*2} = 0 \quad (4)$$

$$\delta^{\text{n}}_{\text{cutoff}} = -\left(\frac{3\left(F^{\text{n}}_{ij}\right)^2_{\text{pullout}}}{16R^* E^{*2}}\right)^{\frac{1}{3}} \quad (5)$$

where, E^* and R^* denote the effective Young's modulus and effective particle radius, respectively. The work of adhesion determines the cohesive interaction, also known as the interfacial surface energy (Γ), while the maximum cohesive force (pullout force) is given by $(F^n_{ij})_{pullout} = \frac{3}{2}\pi R^* \Gamma$. Simulating metal powder spreading is computationally expensive due to the micron-scale particle size and high Young's modulus. To mitigate this, the Young's modulus was modified following the approach (scaling Young's modulus and surface energy keeping cohesion number constant) by Jaggannagari *et al.* [1]. The Γ value was assumed to be constant for both the material with a value of 0.02 J/m^2. The material properties used in DEM simulations are detailed in table 1. The powders were assumed to be poly-disperse with a median particle diameter (D50) of 40 µm, and all particles were approximated as spheres. The particle size distribution (PSD) was shown in fig. 2. The DEM simulation was carried out using Altair EDEM software. Gradation quality was quantified using the gradation index (GI) [3],

$$\text{GI} = \frac{\text{Material A's particle volume in a grid}}{\text{Total volume of all the particles in the grid}} \quad (6)$$

where, GI value of 1 corresponds to pure SS17-4-PH, while GI value of 0 represents pure IN718. The GI is defined at distributed grid bins (size 0.2 mm) as shown infig. 2.

Table 1. DEM simulation parameters used

Properties used in DEM	IN 718 Material B	SS 17-4-PH Material A	Geometry material
Density kg/m^3	8200	7980	7980
E(in GPa)	195	210	210
E_m (in GPa)[1]	0.0195	0.0210	0.0210
Interaction parameters	Co-efficient of Static friction	Co-efficient of restitution	Co-efficient of Rolling friction
IN718 & IN718	0.64	0.5	0.1
IN718 & SS 17-4-PH	0.64	0.5	0.1
SS 17-4-PH & SS 17-4-PH	0.64	0.5	0.1
SS 17-4-PH & Geometry	0.64	0.5	0.1
IN718 & Geometry	0.64	0.5	0.1

2.2 Experimental methods

The hypothesis proposed in the DEM simulations was implemented in the Laser powder bed fusion machine (Intech additive solution make iFusion SF1 L-PBF machine. The experimental validation of functional gradation was done with line Electron diffraction spectroscopy of Laser

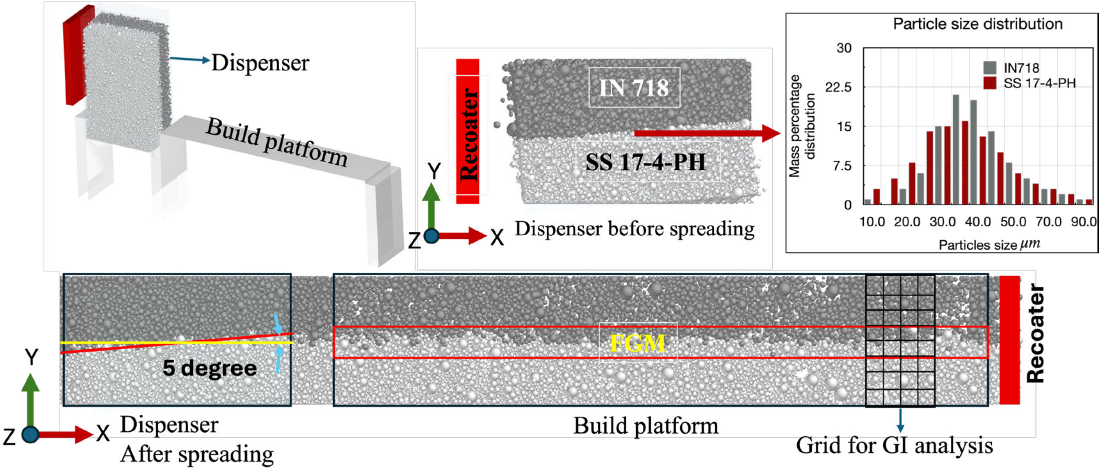

Figure 2. Illustration for FGM spreading via DEM simulation. The figure also shows the particle configuration (for a given PSD) before and after spreading.

powder bed fusion process components. The laser parameters used are as follows by the methods cited by Tiwari *et al.*[4]. The partition-based method used was as followed by Choudhury *et al.*[3], which can be visualised by fig. 3. The laser scanning parameters used are laser scanning speed of 980 m/s in the core of the component with a laser power (80 µm spot diameter) of 295 Watt with hatch spacing of 120 µm. Material A and material B are filled with a temporary partition, which was removed after filling the dispenser as shown in fig. 3. The printed samples were polished for metallography and were etched with Kalling's reagent for the microstructure analysis in a scanning electron microscope (Inspect F).

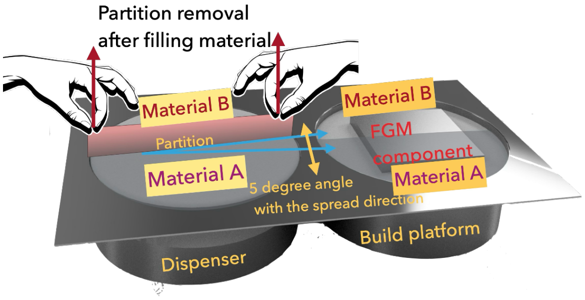

Figure 3. Schematic representation of experimental set up for FGM spreading in LPBF

3 Results

The additive manufacturing of functionally graded material (FGM) parts relies on controlled powder spreading, which is influenced by the recoater's geometry (here linear profile is used) and powder distribution. In this study, a partitioned dual-dispenser system was designed with partitions inclined at 5° relative to the spreading direction. This configuration enables material gradation perpendicular to the spreading direction (along the y-axis), as illustrated in fig. 2. The evolution of GI across the build platform is shown in fig. 4, where the x-axis represents the spreading direction and the y-axis indicates the direction of linear functional gradation. The velocity profile of particles ahead of the recoater, depicted in fig. 5, highlights material circulation driven by velocity variations in the x-z plane. This variation in mixing behavior along the y-axis significantly influences the formation of the gradation profile, as detailed in fig. 6.

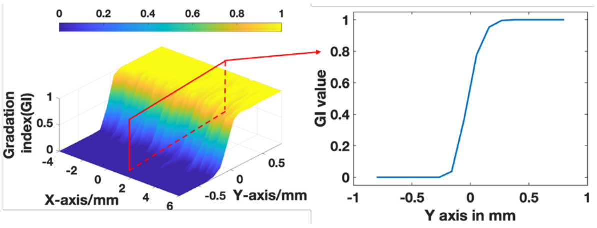

Figure 4. The Gradation index at the build platform to show the effectiveness of FGM spreading

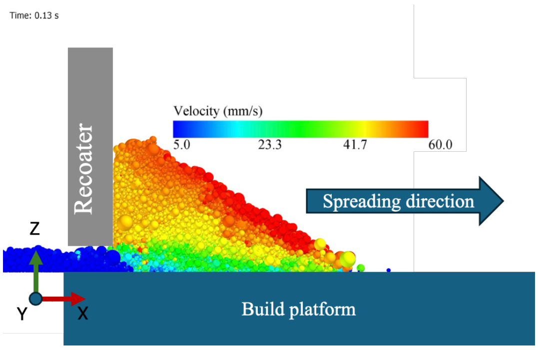

Figure 5. Representation of the velocity variations of powders creating a circulation of materials for mixing and deposition at the build platform

The hypothesis formulated within the discrete element method (DEM) spreading simulation (refer to fig. 2) has been systematically applied to actual part printing, as illustrated in fig. 3.The resultant diffused interface observed in the laser powder bed fusion (LPBF) fabricated part explains the elemental distribution of IN-718 and SS 17-4-PH, characterised by a nickel-rich and an iron-rich matrix, respectively. Qualitative elemental mapping of the printed components was conducted using energy dispersive spectroscopy (EDS), as depicted in fig. 7. Line mapping techniques were employed to describe the elemental gradation achieved within the printed part. Furthermore, fig. 7 presents a comparative analysis of the gradation index (GI) predicted by the DEM model based on volume and the experimentally obtained GI derived from compositional variations of elements, specifically iron and nickel.

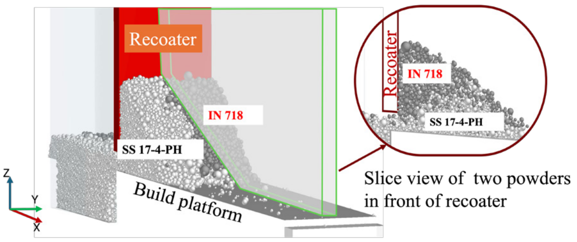

Figure 6. The mixing of two materials in front of the recoater

4 Discussion

The effectiveness of functionally graded material (FGM) spreading on the build platform is evaluated using the gradation index (GI) mapping at specific locations. While material A may appear to stack upon material B at specific locations, the GI calculated as the ratio of particle volume of each material within a given bin provides a quantitative assessment of the spreading quality. During laser interaction, material mixing occurs as the melt pool level penetrates beyond 100 µm, significantly exceeding the layer thickness of 40 µm. The liquid metal mixing and dilution happens due to the Marangoni effect, which is a phenomenon that causes the flow of a liquid due to differences in surface tension [5]. The errors associated with the GI of DEM simulations and GI with composition (from EDS data) of Iron and nickel is a result of diffusion and the mixing of materials during solidification. which leads to change in slope of the GI. However the linear trend is conserved in the real printed parts. Despite differences in composition, both materials exhibit similar melting points, thermal conductivity, and laser interaction characteristics. As a result, no in-plane variation of laser parameters was necessary for achieving controlled material gradation.

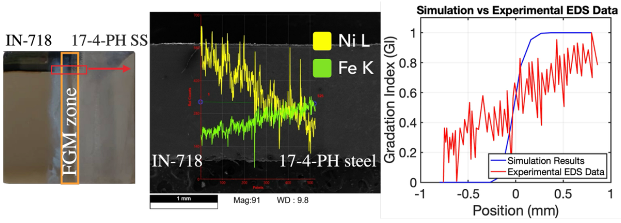

Figure 7. The energy dispersive spectroscopy (EDS) of FGM sample showing linear gradation of element distribution and comparison of GI of simulation and GI of composition

5 Conclusions

1. The successful fabrication of functionally graded materials (FGMs) through Laser Powder Bed Fusion (LPBF) relies on achieving uniform powder spreading with a partition-based approach in the dispenser.
2. DEM simulations provide an insight into powder interaction during multi-material spreading. The spreading of FGM depends on the powder's circulation in front of the recoater.

3. Material composition gradation can be achieved as linear variation as shown in line EDS scan of printed parts.

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