1. INTRODUCTION

The use of 3D printing has already reached beyond the common uses of creating simple polymeric designs or objects and has expanded into more complex materials like ceramics. In industries like aerospace and automotive, where high-performance materials are crucial, the 3D printing of ceramics offers game changing solutions. The ability to precisely control the composition and microstructure of ceramic components allows for the creation of lightweight yet incredibly strong parts, capable of withstanding extreme temperatures and harsh environments.

Beyond these practical applications lies a realm of boundless research opportunities. Researchers are delving into the intricate science behind 3D printing of advanced ceramics, exploring novel materials, printing techniques, and post-processing methods. Researchers are experimenting with advanced ceramic composites, reinforced with fibers and the addition of nanoparticles, all of this to enhance mechanical properties, thermal stability and other material properties. These efforts hold the promise of revolutionizing design, enabling the creation of more efficient and durable parts for high demanding environments.

The research developed, thanks to the BAYLAT Scholarship, was focused on the topics cited above, more specific on the optimization of 3D printing parameters for advanced ceramics. The development was done between a partnership with BAYLAT, Universidade Federal de Santa Catarina (UFSC) in Brazil and University of Augsburg in Germany. The Institute of Materials Resource Management was the host for all the research and the professors, Dr.-Ing. Suelen Barg and Dr.-Ing. Nils Meyer, of the chairs, Processing of Complex Structured Materials for Demanding Environments and Data-driven Product Engineering and Design, respectively, were the advisors for the project.

2. MATERIALS & METHODS

2.1 Materials

The materials selected for the research were Silicium Carbide (SiC) powder and Pluronic F-127, which when mixed both, create a suitable paste for 3D printing. The use of Silicium Carbide was due to its good thermo-mechanical properties and the subsequent wide application range. SiC features high hardness, wear, temperature and corrosion resistance and high thermal conductivity. As a result, there is a variety of different applications, for example as abrasive, in aerospace, high temperature reactors, wide band-gap semiconductor and in porous form as heat exchangers. However, to create a printable paste several rheological prerequisites have to be fulfilled like yield stress rheology, a shear-thinning behavior and low viscosity, which all of that will allow the extrusion of the paste through fine nozzles at low pressures. That’s where the Pluronic comes in, this is a hydrogel which acts as substrate for the ceramic particles.

2.2 Paste Preparation

The preparation of the paste samples was done by meticulous mixing the ceramic powder with the hydrogel solution, which consisted of adding the Silicium Carbide to the Pluronic and mixing it with a spatula and after speed mixing it in order to achieve a homogenous paste, with the desire rheological properties

2.3 Design of Experiments & Printing Parameter Study

The third step was to design the experiments to create a dataset with high parameter ranges to further use in the data-driven optimization. The experiments consisted in varying printing parameters such as speed, nozzle size, extrusion factor and the concentration of SiC in the printed paste. All of these parameters were adjusted in order to cover a wide range of possible use cases for the paste, and later optimized to achieve the best print quality.

2.4 Print Quality Measurement

The assessment of print quality had been defined earlier by a fellow college within the institute. This assessment methodology involves an evaluation, juxtaposing the anticipated volume against the actual volume of the printed component. For this it was used a point cloud-based alignment process to ensure that both of the shapes were matched.

This process outputs a value ranging from 0 to 1, which relates to the shape accuracy of the sample. 0 being the worst possible, and 1 being the ideal volume fill.

2.5 Optimization

Optimization was done through the modeling of a Gaussian Process, more precisely a Bayesian Optimization model, in order to create an optimization loop, where the model would take as input the current data, evaluate it and output the possible best test candidate, the parameters it expects to perform the best in print quality. The last step was to evaluate the candidate and feed it to the model again and create a loop where the model “feeds” data to it self in order to achieve the best result possible.

3. RESULTS & DISCUSSION

3.1 1st Batch of Printed Samples

The initial dataset of printed samples consisted of approximately 30 samples which were printed with printing parameters ranging from 4 to 24mm/s for Speed, 0.41 to 0.84mm for Tip Size, 0.14 to 0.60 for Extrusion Factor and 33 to 45% of Silicium Carbide content. All these parameters were mixed and tested in order to create a dataset with a high dispersion to further create a more generalized model.

The samples were evaluated by 3D scanning each one of them and comparing the ideal volume against the actual volume. The average quality value for the samples was 0.74 which demonstrated that most of the prints were achieving a shape fidelity close to the ideal. The goal was to achieve the highest possible value, but the group defined that a quality value above 0.8 was considered good enough for the prints.

3.2 Model Optimization

After collecting the initial data, the modeling process began. This process consisted of creating a Python script, due to its versatility, excellent computing capability and the knowledge of this language by the members of the group. We used the Pandas library to organize the tabular data, TensorFlow to work with arrays and tensors, and Botorch to model the Gaussian process and Bayesian optimization steps.

The modeling was done in two parts. One with all the values being treated as continuous and the processing parameters being able to take on any value within the established range, and the other with one of the processing parameters only being able to take on discrete values within the established parameters, a much smaller, more restricted range. Part of the study at this stage was to see if we could find differences between these two models, in order to understand whether the physical limitation of parameters would influence the final result of the optimization.

The results were very similar for both, continuous and discrete models, recommending similar values for the variables we defined in each model, so it wasn't possible to notice the influence on the final result. We were able to notice that, regarding nozzle size, both models always recommended the smallest value possible, probably due to it resulting in a better definition to the final piece and therefore improving the accuracy of the printed material.

With regards to the performance of the models, both were very similar and the expected improvement values were very close. We therefore opted to use the discrete variable model, not only due to physical limitations of the printer, but also because the improvement for the continuous one wasn’t so significant to opt for a model that didn’t represent the reality faced.

3,3 Optimized Printed Samples

Due to time constraints, only one round of optimization was carried out in order to prove the model's ability to represent and optimize a complex process such as the 3D printing of ceramics.

The model validation process was carried out by printing a paste containing 44.5% of SiC and with the following processing parameters: 17.82 mm/s Speed, 0.6 Extrusion Factor and a Nozzle Size of 0.41 mm. Five prints were made with these parameters, but two had equipment failures and were not included in the final analysis.

After the characterization process and final quality measurement, the parts obtained an average quality of 0.78, indicating an increase in overall quality due to the use of optimization techniques.

In addition to the increase in quality measurement, it was possible to notice an increase in the resolution of the piece, so that it became possible to observe the printing lines and the differentiation of the layers of the sample. Although the scope of the research was not linked to the resolution of the printed material, it was promising to see that the optimization improved this aspect as well.

4. CONCLUSION & OUTLOOK

The final conclusions for the project are promising, although the project acted as a proof of concept for the use of Bayesian optimization in 3D ceramic printing, it was possible to see that the modeling is robust enough to abstract the concepts and represent this complex phenomenon.

The use of optimization proved to be very efficient, so that with little data the modeling was able to complete the objective of recommending a next candidate in order to improve the model and optimize the ceramic part production process.

The project in question was restricted to optimizing an objective that is poorly defined in the literature, which is print quality. Little has been published on how to define the quality of printed material, so the method used to compare volumes could be improved.

In addition, the research focused on the study of green ceramics, those before the sintering process, so for a future project there is the possibility of jointly studying the optimization between the production/printing process and the sintering of the material, with a focus on optimizing the final properties of the material.

5. MY OWN EXPERIENCE

I think my experience at the Uni Augsburg was very enriching, both from the point of view of acquiring academic knowledge and personal growth.

I come from a public university in the south of Brazil, the Universidade Federal de Santa Catarina, where I am finishing my degree in materials science & engineering and although it is one of the best universities in the country, the superior facilities and equipment at the University of Augsburg are the first thing that strikes the eye and enchants a student like me who is a technology aficionado.

I was extremely well received and welcomed by the team of professors and colleagues who not only accepted my research proposal, but were always available to guide me through my doubts and show me possible ways out of the difficulties I faced throughout the work.

It's important to note that my area of research is quite new and yet the team of Professor Suelen and Professor Nils embraced the project, encouraging me from the start, so that after this experience at Uni Augsburg my goal for the next few years is to continue in research and as soon as I finish my degree, I intend to return to do the PhD program at this institution.