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Optimal Machining Parameters Determination of Polymers-Ceramic Composite for Hybrid Manufacturing

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Abstract

The use of technical ceramics is growing thanks to their high mechanical properties. To attain the tolerances and surface finish, operations including machining or grinding are performed. Due to the risk of fracture, they are limited to low material removal rates.
One promising option is to rely on the hybridization of manufacturing process. This paper is linked to the project HyProPAM that combines additive and substractive techniques. An experimental methodology to determine the optimal milling parameters parts in Zirconia is proposed. Cutting forces and surface topography are used as indicator to determine the quality of the operation.

Keywords: hybrid manufacturing; milling; ceramic; additive manufacturing

1. Introduction

Additive manufacturing (AM) allows the production of mechanical parts with complex geometry without requiring heavy investments in tooling [1, 2]. Its flexibility m akes it naturally integrable in an 'industry 4.0' production approach [3, 4]. Extrusion processes are techniques with a high development potential due to their relatively low capital expenditure (CAPEX), even for metal or ceramic manufacturing [3]. The production of ceramic parts by FDM techniques is challenging because of the brittleness of the filament [5]. T he Pellet Additive Manufacturing (PAM) technology is a promising alternative for the 3D printing of ceramics. Its production cycle is similar to conventional fused deposition modelling (FDM), but it uses injection molding pellets as feedstock, suppressing the problems linked to the filament h andling. I n a ddition, it offers a more important range of material industrially available because it can used pellets initially developed for ceramic injection moulding (CIM).

However, the major drawback of FDM and related techniques such as PAM lies in the high surface roughness of the parts at the end of the process (sometimes of the order of 40 μm Ra [6]). This roughness negatively impacts, among others, the static and fatigue strength of the components, its corrosion resistance, its tribological properties. It also impacts the aesthetics of the part. The improvement of surface conditions by mechanical reworking at the end of the AM process can be difficult because complex geometries are generally targeted and some areas of the part, such as cavities are not accessible anymore. A global treatment of the part by non-contact techniques (such as electrochemical machining or tribofinishing) is possible but presents questions from an environmental point of view and does not always allow to reach the requirements of functional parts [7] (for example $R_a = 1.6\ \mu m$ for contact applications).
In this context, developing hybrid manufacturing strategies (combination of different manufacturing technique [8, 9]) is a promising way of gathering the advantages of additive and substractive manufacturing. For example, machining can be performed to reduce the external roughness of the part after its printing (this approach is called alternate hybridization, figure

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1). By stopping periodically the printing of the part, is is possible to access zones that are not accessible on the final parts such as internal zones using the full capacity of the hybridization (figure 2). One remaining challenge is the definition of the operational parameters for the finishing operations.

Fig. 1. Reduction of external roughness by machining using sequential hybridization

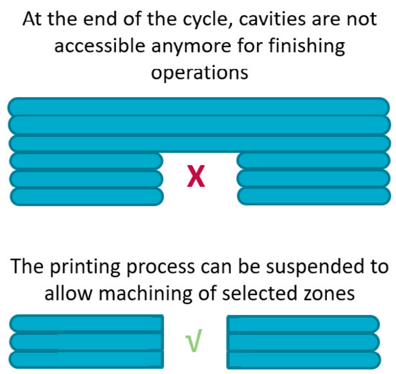

Fig. 2. Reduction of internal roughness by machining using alternate hybridization

2. Objective of the paper

To lower production costs, the choice of a cutting tool dedicated to the machining of polymers can be considered rather than a tool dedicated to ceramic materials. In this case, it there is no reference for the choice of the cutting parameters for the polymers/ceramic composite used for the additive manufacturing step. This paper presents a methodology to select the optimal cutting parameters in order to finish parts produced by additive manufacturing using PAM technique and milling operations with such tools. It intends to answer four research questions:

- **Q1**: Is it possible to machine ceramic parts produced with PAM process with a milling tool adapted to the (thermoplastic polymer) binder ?
- **Q2**: Is it possible to use the couple tool-material standard [10] to determine the optimal parameter range for this particular couple tool-material ?
- **Q3**: Is it possible to achieve surface finish compatible with contact application ($R_a \leq 1.6\ \mu m$ eg) ?
- **Q4**: Does the tool support those machining operations with acceptable wear behaviour ?

3. Material and methods

A standard test consists in the machining of three passes with the same cutting parameters on a part manufactured by PAM technique while constantly recording the cutting forces. After those three passes, roughness measurement is performed on the machined surface and microscope imaging of the tool and the machined surface are taken. Prior to those tests, the raw AM part has been shaped using lateral and face milling to provide neat surfaces, so the cutting parameters (axial and radial depth of cut) can be measured precisely. The results are then analysed using the framework of NF E 66-520 standard.

3.1. Additive manufacturing

The sample parts were manufactured on a Pollen PAM series MC using raw material with commercial name INMAFLOW K2015 (supplier INMATEC). It is composed of a black zirconia powder (ZrO_2, 94,5%, Y_2O_3 partially stabilized) and a thermoplastic binder based on polyamide (PA). The density of this raw material is 6000 kg/m^3. There is 85% of ceramic and 15% of binder in mass. The geometry of the samples (figure 3) consists in a cylindrical zone (15 mm height and 15 mm diameter) and a cubic one (side of 20 mm). The build direction is aligned with the axis of the cylindrical part. The cube is in contact with the build plate on the AM machine. The material is added in layers of 350 μm. Printing parameters remains constant for this study, they are selected as the values proposed by the supplier of the material. The main ones are a nozzle temperature of 165 $°C$, extruder temperature of 130 $°C$, build plate temperature of 35 $°C$, printing speed of 20 mm/s. Using these printing parameters, the arithmetic roughness of the faces parallel to the build direction is $38,0 \pm 4,6\ \mu m$. The surface in contact with the build plate has an arithmetic roughness of $4,2 \pm 0,6\ \mu m$.

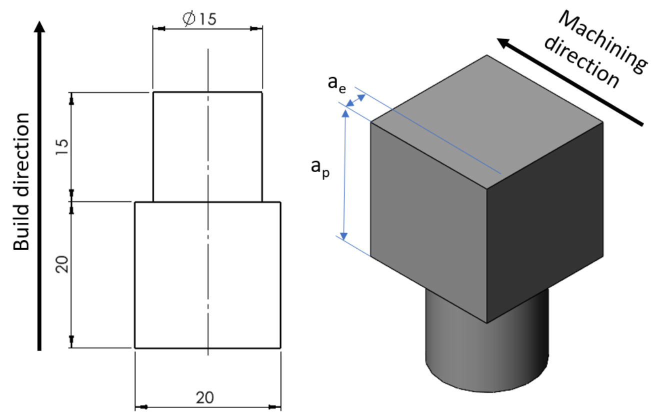

Fig. 3. Geometry of the samples parts

3.2. Machining

Machining operations are performed using a Stäubli TX200 robotic arm confined in a secure cell equipped with a Teknomotor spindle (7.8 kW, 24000 rpm max.). The cylindrical zone of the sample parts are clamped on a three jaw chuck (figure 4) which is linked to a Kistler 9256C dynamometer measuring the forces in all directions. Acquisition chain is composed of the multichannel charge amplifier (Kistler 5070A), the data acquisition system (Kistler 5697A2) and DynoWare software for recording.

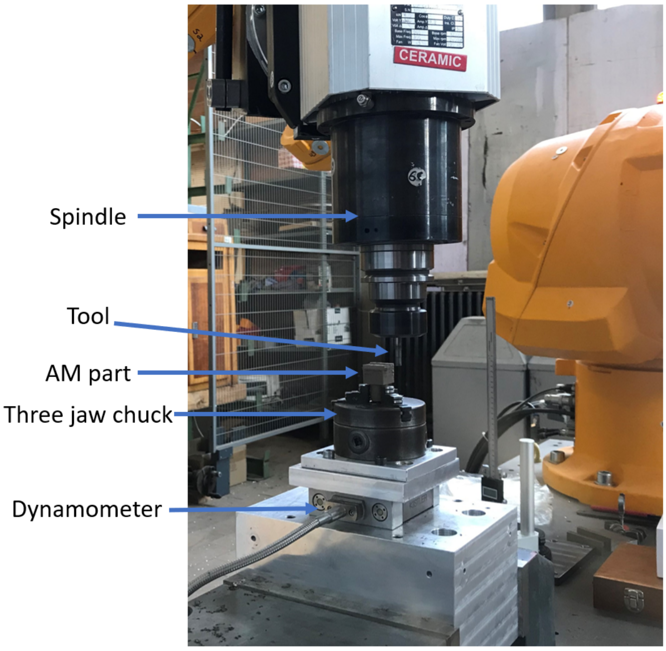

Fig. 4. Experimental setup

The milling tool is provided by the company Hoffmann Group (reference 209425 6). It is a 6 mm cylindrical endmill with three cutting edges having a double helix angle. This carbide uncoated tool is dedicated to the machining of thermoplastic polymers. The reference cutting parameters proposed by the supplier for polymers are a cutting speed of 150 m/min, a feed per tooth in the range of 0.12 mm/tooth (for PEEK) to 0.18 mm/tooth (for POM). The tool is adapted to any radial depth of cut, maximum axial depth of cut is 19 mm.

3.3. Surface topography evaluation

The surface topography is evaluated following the prescriptions of ISO4288 standard[11] by measuring the arithmetic and total roughness with a roughness measurement machine DH-6 from Diavite using a 5 μm diameter probe. The surface generated and the wear of the tool are also qualitatively evaluated using a microscope AM7013MZT from Dino-lite.

3.4. Couple tool-material

The couple tool-material [10] proposes a standardized methodology to experimentally determine the optimal range of cutting parameters for a given cutting tool on a metallic material. Previous studies [12] showed that, even if the standard is dedicated to metallic materials, it can be partly applied to white ceramic material. The current paper investigates if those conclusions can also be valid for the green body produced by AM.

The global approach is based on the analysis of the specific cutting energy and the roughness of the part during a series of experimental tests. The standard defines several sets of tests aiming at first to determine a reference point. The specific cutting energy represents the ratio of the power needed for the cutting operation by the material removal rate. This quantity is equivalent to the specific pressure determined by the ratio of the cutting force by the uncut chip section. The standard focus both on the mean value of the specific cutting energy during several tests and on its standard deviation. Indeed, a good choice of cutting parameters may lead to a reproducible behaviour, so a small dispersion of the results.

A reference point is a set of cutting parameters allowing to machine the part with acceptable results qualitatively speaking. The stability of the results is evaluated by adding some experimental points around the reference (small variation of cutting speed, feed per tooth, axial or radial depth of cut) and checking if the machining is still successful.

If such a point is found, the minimal value of the cutting speed producing acceptable results is searched prior to the definition of an acceptable range for the other cutting parameters. The procedure can then be extended to the definition of an analytical model to predict torque, power and force for the whole range of parameters tested and a study of the wear of the tool.

Even though all these steps may not be successfully achieved for the couple tool-material considered in this paper, the methodology is used as a guideline for a systematic approach of the problem.

4. Results analysis

4.1. Qualification test

The cutting parameters for the first candidate as qualification test were defined as follow:

- The feed per tooth (f_z) of 0.15 mm/tooth was selected as the mean value proposed by the supplier for the machining of polymers;
- The axial depth of cut (a_p) of 3 mm was selected to have a machined surface large enough to be inspected with the roughness measurement machine;

- The radial depth of cut (a_e) of 0.5 mm was selected as a reasonable value for a finishing operation as expected for the hybrid manufacturing scheme.

Different cutting speed (v_c) allowed by the spindle (from 2000 to 22000 RPM) were selected, using up and downmilling. The main conclusions are as follow:

- While using downmilling, the roughness of the part is systematically poor with the presence of craters on the machined surface (see figure 5). The darker zones in 5 are places where the material has been stripped, creating craters) while upmilling gives good results (see figure 6);
- Some cutting conditions in downmilling allows the production of a part free of damage with an arithmetic roughness lower than the target of 1.6 μm (so research question **Q1** can be considered as valid);
- There is a significant variation of the specific cutting energy during a given test (high standard deviation), but also a significant difference between two repetitions of the same test on different part but also using the same part (figure 7). This evolution is rather different than the graphs provided in the standard. In addition to the poor repeatability, the conclusion is thus that this indicator is not well suited for the current study(so the answer to research question **Q2** is negative);
- However, for a spindle speed of 12 kRPM, there is a good repeatability of the results, so this point can be a good candidate for a reference point.

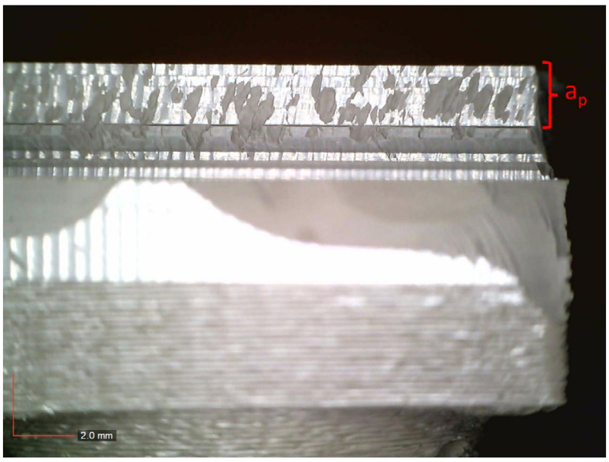

Fig. 5. Typical surface topography using downmilling cutting conditions

By repeating five tests with this spindle speed of 12 kRPM, it can be seen that ll roughness measurement, including their respective uncertainty range remains in the same roughness class, so the results are repeatable (figure 9). The roughness remains lower than the target of 1.6 μm, so the answer to research question **Q3** is positive.

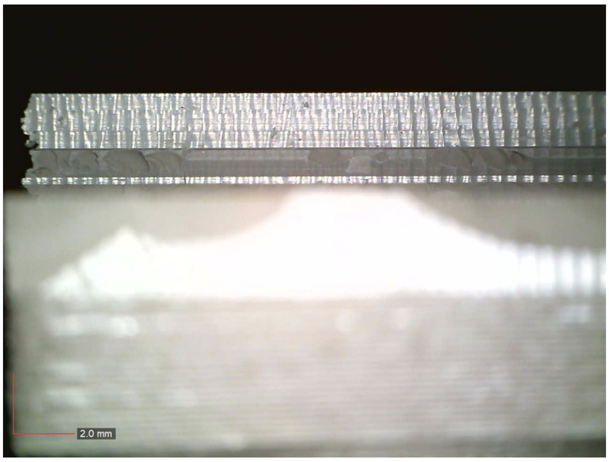

Fig. 6. Typical surface topography using upmilling cutting conditions

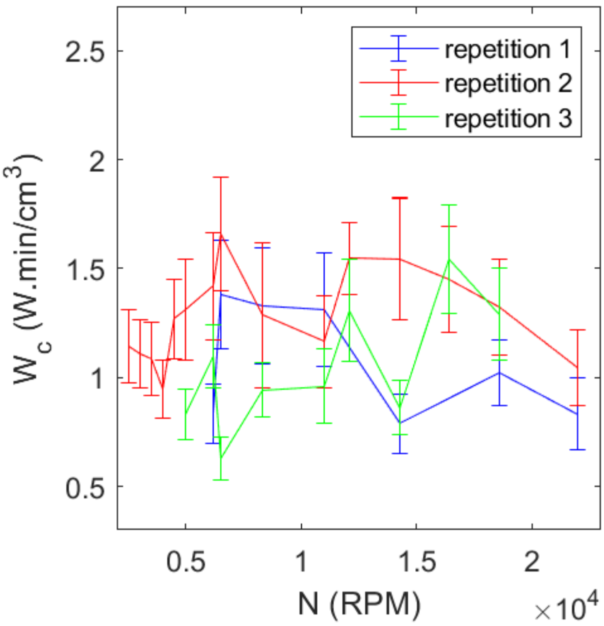

Fig. 7. Evolution of the specific energy with respect to the spindle speed / cutting speed (each point is associated with an error bar of $\pm\sigma$ computed for the three repetitions of the test in the same conditions)

The specific cutting energy (figure 8) experience significant variation of about 40% from the lower mean to the higher mean value (figure 8). These results confirms that the use of the couple tool-material standard based on the specific cutting energy is not appropriate for the tool selected for the study.

In order to check the use of these cutting parameters as a reference point, a variation of the cutting parameters around their default value was performed using a range of 20% (see table 1).

The surface finish of the part is below the threshold of 1,6 μm for all those measurements. The reference point can be validated using this surface quality criteria.

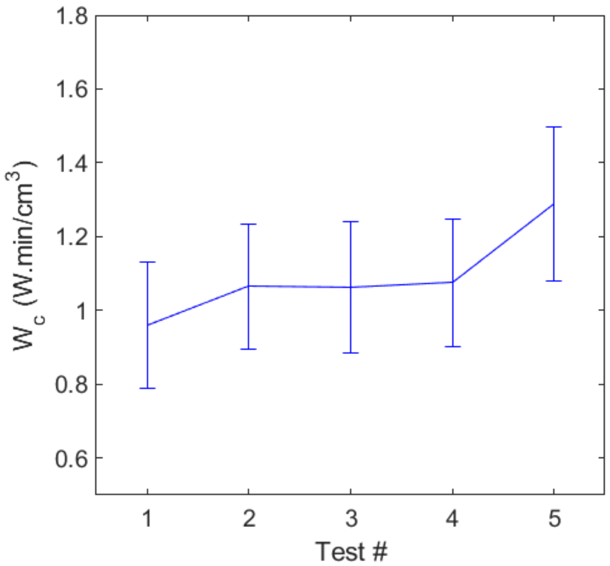

Fig. 8. Evolution of the specific cutting energy over five repetition of the reference point

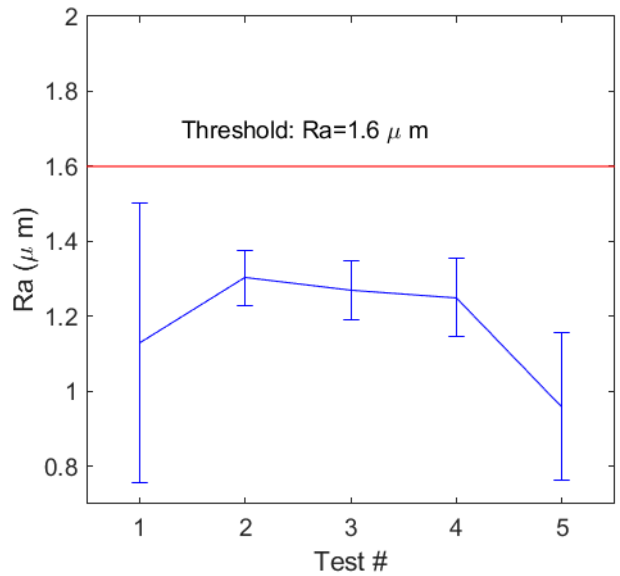

Fig. 9. Evolution of roughness over five repetitions of the reference point

4.2. Tool wear

Even though a complete tool wear analysis was not performed for the paper, the analysis of the picture of the tool at different stage of the project can lead to preliminary conclusions. Indeed, as compared to its initial condition (figure 11), the edges of the cutting tool that were used for the experimental plan (45 seconds of effective cutting time) shows no visible sign of wear (figure 12). It can be noted that some small areas have changed of color, this may be an indicator that some of the polymer has melt during the machining and the solidified on

test	f_z (mm/tooth)	a_p (mm)	a_e (mm)	R_a (μm)
1	0.15	3	0.5	1.09
2	0.13	3	0.5	1.34
3	0.17	3	0.5	1.42
4	0.15	3	0.4	0.79
5	0.15	3	0.6	1.42
6	0.15	3,6	0.5	1.19
7	0.15	2,4	0.5	0.76

Table 1. Variation of the cutting parameters around the reference values

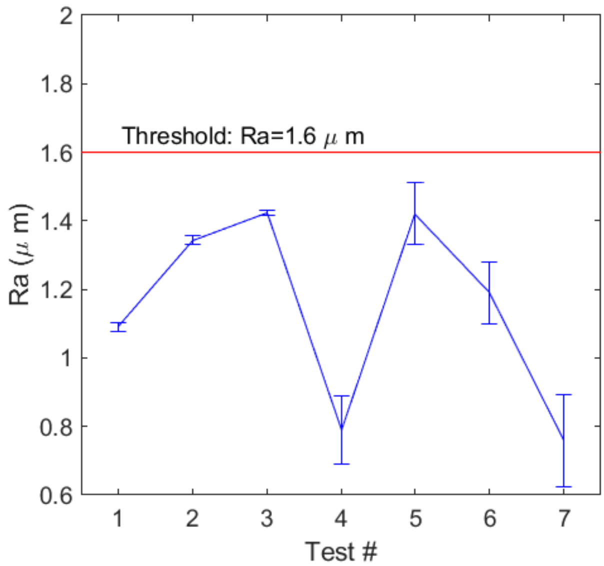

Fig. 10. Roughness for the different cutting parameters around the reference point.

the cutting tool. At this stage, research question **Q4** cannot be concluded, but the absence of catastrophic wear is promising.

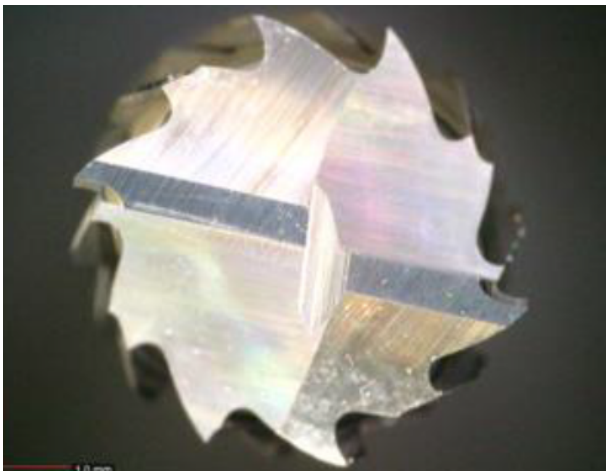

Fig. 11. Picture of the tool after the first machining operation

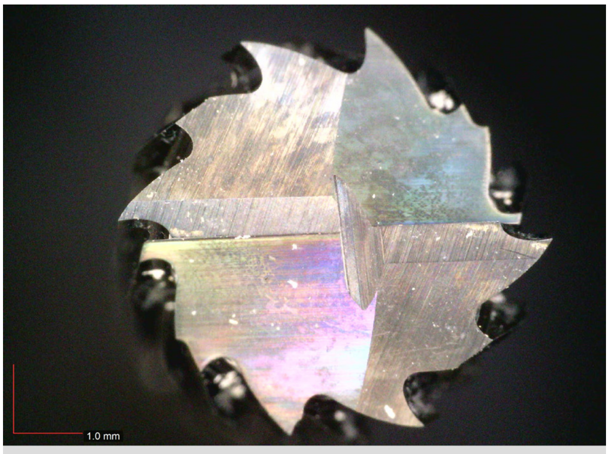

Fig. 12. Picture of the tool after the end of the experimental plan

5. Conclusion and perspectives

In this paper, the framework of the couple tool-material standard is tested to determine the acceptable range of cutting parameters for a milling tool finishing a zirconia green part obtained by PAM . Several research questions were addressed, the main conclusions are as follow:

- **Q1**: Is it possible to machine ceramic parts produced with PAM process with a milling tool adapted to the (polymer) binder ? Yes, some cutting conditions were found for which the parts were machined without catastrophic damages, the technological choice is thus valid.
- **Q2**: Is it possible to use the couple tool-material standard to determine the optimal parameter range for this particular coupl tool-material ? No, the shape of the curves showing the evolution of the specific cutting energy and the cutting speed (or spindle speed) have no similarities with the examples shown in the standard. However, the systematic methodology proposed in the standard allows to find a stable point (spindle speed 12 kRPM, feed 0.15 mm/tooth, axial depth of cut 3 mm and radial depth of cut 0.5 mm) that gives satisfactory results.
- **Q3**: Is it possible to achieve surface finish compatible with contact application ($R_a \leq 1.6\mu m$ eg) ? Yes, by repeating several tests with the cutting parameters considered as the reference point, it was shown that all roughness measurements were below the threshold of 1.6 μm.
- **Q4**: Does the tool support those machining operations with acceptable wear behaviour. The machining time for all the tests was less than one minute, it is thus insufficient to conclude on the tool wear behaviour. However, the absence of wear marks after this first step is an encouraging sign for the use of this tool.

The three main perspectives of the work are:

- using the same methodology on the same material with different type of milling tool to check if more steps the couple tool-material standard can be applied and provide a comparison in terms of performance between the different tools considered;
- using the cutting tool presented in the paper in a fully hybrid approach (machining a layer of material right after it was printed eg) to check if the identified cutting parameters remain valid in these conditions
- assessing the quality of the part after the cycles of unbinding and sintering necessary to obtain the final properties of the part.

Acknowledgements

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