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A new design for an extensive benchmarking of additive manufacturing machines

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Abstract
This paper focuses on a new methodology for conducting a comprehensive benchmarking of Additive Manufacturing (AM) technologies. The quality of the built products using AM strongly depends on the machine capabilities, and it is thus essential to develop a proper benchmarking design that would allow their comparative evaluation. The benchmarking presented has been designed with the purpose of conducting a comparison between different AM machines, with a particular focus on metal powder-bed AM. The main scope is to make an extensive evaluation of the technologies from multiple points of view, covering: accuracy and precision of the machine, residual stresses on the parts (particularly important in the case of metal AM), homogeneity (in terms of density and residual porosity), build speed, mechanical properties, surface finish and corrosion resistance. For each evaluation criteria, a specific analysis method is employed. The aim of this work is to analyse the current technology capabilities and limitations, in order to assess what different AM machines can deliver in a net-shape process chain scenario. The benchmark is employed for a statistically designed series of experiments to study in detail the AM machine´s real limitations and their working process windows. The design also includes features that represent a challenge for the AM machine, and sometimes exceed the machine´s actual capabilities. Furthermore, the benchmark has been developed to be used as a periodic quality control-job for the operational performance of the AM machines.

Additive Manufacturing, Selective Laser Melting, Powder Bed Fusion, Benchmarking, Technology evaluation, Accuracy, Repeatability, Homogeneity.

1. Introduction

Additive manufacturing (AM) refers to a group of processes that, starting directly from the CAD model, produces parts by building the material layer by layer. These manufacturing techniques are theoretically capable of producing components of any shape in any material [1,2]. The main aim of using AM in industrial environment is to produce parts in a net-shape manner, thus avoiding expensive and time-consuming post-processes. Currently, net-shape fabrication is not possible yet, because of the limiting capabilities of current machines. However, the AM machine that best meets the need can be identified, and the best way for such identification is a benchmarking study [3,4]. An extensive review on benchmarking artefacts has been done by Rebaioli *et al.* [5].

In the following paper a new design is proposed, with the focus on applicability of the metal powder bed fusion AM process named Selective Laser Melting (SLM), for moulds production for injection moulding with the aim to understand what currently can or can not be done.

2. Design

Considering the near impossibility of defining a single standard benchmarking artefact, also in terms of dimensions, that can be used for the evaluation of the newest AM technologies, instead in the following paper the approach towards building such artefacts will be presented. The particular focus is on SLM, specifically to understand the current capabilities and limitations. For this task, a single benchmarking artefact is not enough, as the complexity of these processes makes it difficult to summarise all attributes of interest in the design of a single part, and instead it is necessary to define a whole benchmarking job. The following picture is the Design of Experiment triangle to show the strategy of the benchmarking job presented in this paper (Fig. 1)

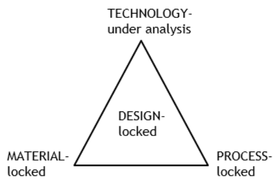

Figure 1. Design of Experiment for the benchmarking.

To limit as much as possible the open variables, the process (SLM), the design (which follows) and the material (a metal alloy) have been locked and will be the same for all the experiments. The only open variable is the technology i.e. the machine under evaluation. Since only the SLM process is evaluated, none of the parts will be post-processed, apart from cutting them from the building platform - and the effects of such support/part removal will be taken into consideration while evaluating the results. The parameters for the design of the benchmarking job, and the best analytical technique for their evaluation, are as follows:

1. Accuracy – dimension: Features as in Fig. 2-3, i.e. holes in different directions, pins, thin walls cross-shaped, unsupported pyramids and a writing, are used to assess what the machines can or can not do. The minimum dimension of the features overpass the publicly acknowledged limits of the current most capable machine, as showed in Table 1. The column "min dim" is the minimum dimension producible from a machine in the market, as declared by the manufacturer. The preferred analysis technique for dimensional accuracy is the 3D scanner, wherein the smallest feature defined on the benchmarking job is still measurable. Capability to build without support structures (i.e. overhangs) will be evaluated through 3 hollow pyramids with 3

inclinations of the sides (45°, 35° and 25°). The example of the artefact is in Fig. 2-3.

2. Accuracy – roughness: The final surface roughness is also very important, considering post-processes, and will be analysed with a contact profilometer as well as contactless equipment depending on the quality of the parts. The measurement will be done in x, y, 45°, and z direction.

Table 1. Minimum dimension of the feature in the artefact.

Feature	Min dim	Min dim in the artefact
Wall thickness	0.15 mm	0.10 mm
Overhang structure	45°	25°
Circular holes (diameter)	0.50 mm	0.20 mm
Circular pins (diameters)	0.50 mm	0.10 mm

3. Precision-repeatability: The same parts will be placed in 5 different positions of the building platform (in the corners and center) and the entire job will be repeated 3 times. The overall job will look like Fig. 4. For tracking repeatability, all the 3D scans of the benchmark artefacts, across the different positions, jobs and machines, will be compared.

4. Homogeneity: The residual porosity in the parts, in terms of density (with Archimedes test on 15x15x10 mm sample) and porosity percentage on a polished surface in x-y and z plane (from a 30x30x20 mm sample), will be used as the indicator.

5. Residual stress: To evaluate the stresses emerging from the manufacturing, two techniques will be used. The first technique is to measure the eventual distortion on a long, unsupported, thin wall (49 mm long, 7 mm high, 0,3 mm width) with the 3D scanner. The second technique is XRD analyses to quantify the surface residual stress of the part.

6. Tensile properties: Four tensile test samples (DS/EN ISO 6892-1:2016) printed in z-direction will be used for comparison.

7. Corrosion resistance (ISO 9227:2006): Tests in artificial atmospheres, using cut-outs from a cylinder (20 mm diameter, 60 mm height), both on the bottom and top of the part, will be performed considering the anisotropy of the building process.

8. Mould features production: Considering a possible final application of interest, tool manufacturing for injection moulding, a feature has been designed to gain insight into the capacity of the machine in building complex shapes. Three hollow spirals, with different internal diameters (1,0 mm, 2,5 mm & 5,0 mm) and constant thickness (1 mm), have been chosen as they resemble conformal cooling channels in moulds. The analysis method are a fluid flow test, a visual evaluation using an endoscope camera, and a surface roughness measurement using computer tomography on the cut parts.

9. Time: Build speeds for the different machines will also be compared.

Simultaneously achieveing excellent results on all chosen parameters is difficult for current machines, and a trade-off chart is an expected outcome from such benchmarking activity. The positions of the parts on the platform (Fig. 4), has been chosen considering the direction of movement of the recoater.

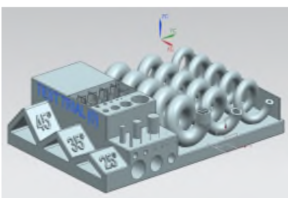

Figure 2. Benchmarking artefact

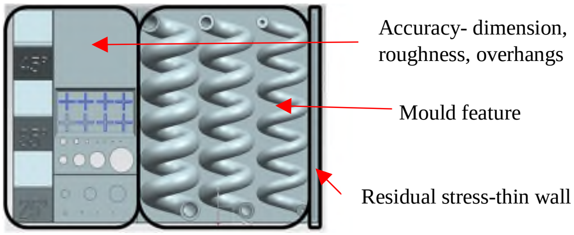

Figure 3. Top view of the artefact identifying the parameters analysed.

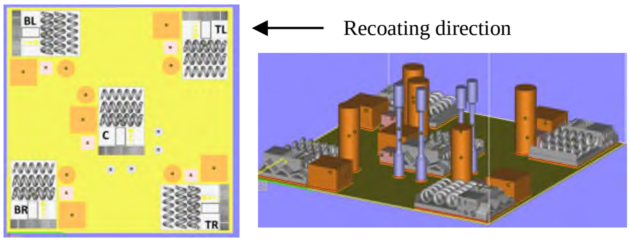

Figure 4. Top view of the benchmarking job containing all the samples.

3. Preliminary results

The proposed benchmarking job has already been successfully built with an EOSM270 in maraging steel grade 300. From a first visual analysis of the artefacts, it was possible to identify clearly the minimum dimension of the features that could be built (Fig. 5) i.e. the smallest thin walls and pins were found missing.

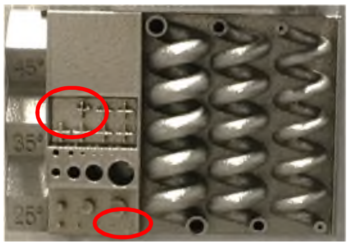

Figure 5. Benchmarking artefact produced in maraging steel.

4. Discussion and conclusion

In this paper, a new approach for performing benchmarking that can be easily adapted to all AM machines has been presented. It consists in a benchmarking sequence of jobs, containing different samples for a global evaluation of the performance of the technology. The main requirement is to adapt the dimension of the feature suggested to the technology under analysis. The results obtained would present the machine capabilities and limitations directly.

The benchmarking job proposed can also be adapted and used as a tool for the periodic check of the machines, to control their performance.

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