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Influence of printing conditions in Binder Jetting on the resin infiltration post-processing

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Abstract: The goal of this work is to study the influence of 3D Binder Jetting process in order to identify the best processing conditions for the resin infiltration post-process. In particular, a dimensional study is carried out to select the most suitable conditions for infiltration in terms of part location in the building bed. Also, the influence of infiltration time on dimensional changes of the processed parts is analysed. The results of this study let us conclude and verify the importance of part location on the bed, especially when it will be exposed to infiltration post-processing. A good choice can improve the final result by shortening the infiltration times, and therefore time and cost of production.

Keywords: Binder Jetting, Dimensional Analysis, Structured Light, Resin Infiltration, Additive Manufacturing.

1. Introduction

Among additive manufacturing techniques, those based on powder have undergone a great relevance in the last two decades. Nowadays, these are the techniques with the best projection. In particular, the Binder Jetting (BJ) technique is one of the most efficient in terms of cost and speed. Despite they have limitations, some applications consider this type of process of great interest. Among these applications, BJ has been shown viable for manufacturing casting moulds [1-3]. Nevertheless, Le Néel et al. [4] explained the necessity of more studies to optimize metal casting applications with BJ processes.

On the other hand, parts printed by BJ with ceramic powder do not reach the mechanical properties to be used as functional parts and, therefore, they are not adequate for using in sand casting moulds. Several authors have shown that post-printing heat treatments of the moulds can help to improve the quality of the mould as well as the casting [5-6]. Post-processes are necessary and among them, infiltration processes could be a suitable option for this improvement [7]. Infiltration process increases the printed parts density and consistency, reducing the typical brittleness of this material. Once the advantages of this post-process are known, it would be interesting to establish the dimensional variations that the infiltrants cause in the parts, in order to consider them in the previous step of design and dimensioning of parts and/or moulds. There are several pending issues to be studied:

- Characterization of infiltrants with low density to improve mechanical and superficial properties of printed parts.
- Characterization of the infiltration process with relation to printing parameters, such as part orientation and position in the building bed. This aspect includes the study of temperature and



infiltration time that may affect to dimensional quality of treated parts.

The goal of this work is to analyse the influence of the printing process itself for the next infiltration post-process with resin. Specifically, a dimensional study is carried out to justify the choice of the position of the part on the building bed.

Several infiltrants recommended by manufacturers are salt water, wax, cyanoacrylate and epoxy resin [8], depending on the final application of the part. In the case of functional models, epoxy resin is recommended for improving the strength. The reason is that its low viscosity leads to deeper infiltration of parts (up to 10 mm applied with a paint brush). However, it is necessary to compare and to look for other more economical, healthier and safer infiltrants, and infiltration processes for applying to industrial moulds.

2. Methodology and equipment

A 3DP machine Project 660Pro (3DSYSTEMS, USA) was used with 600 x 540 dpi resolution, a build area of 254 mm x 381 mm x 203 mm and a build speed of 28 mm/h. In this study, plaster-based powder ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$) with an appropriate water-based binder solution of 2-Pyrrolidone were used as raw materials.

The infiltrating material selected was the Resoltech 1050/1053S resin. This resin has been formulated for manufacturing light structural parts with high mechanical performance using fiberglass, carbon, aramid and basalt as reinforcement, with or without final post-curing. This combination (resin Resoltech 1050+Hardener 1053S) is particularly recommended for infusion due to its low and stable viscosity (205 m.Pa.s according ISO 12058.2) in all working conditions and temperatures [9].

The methodology followed in this work is summarized in figure 1.

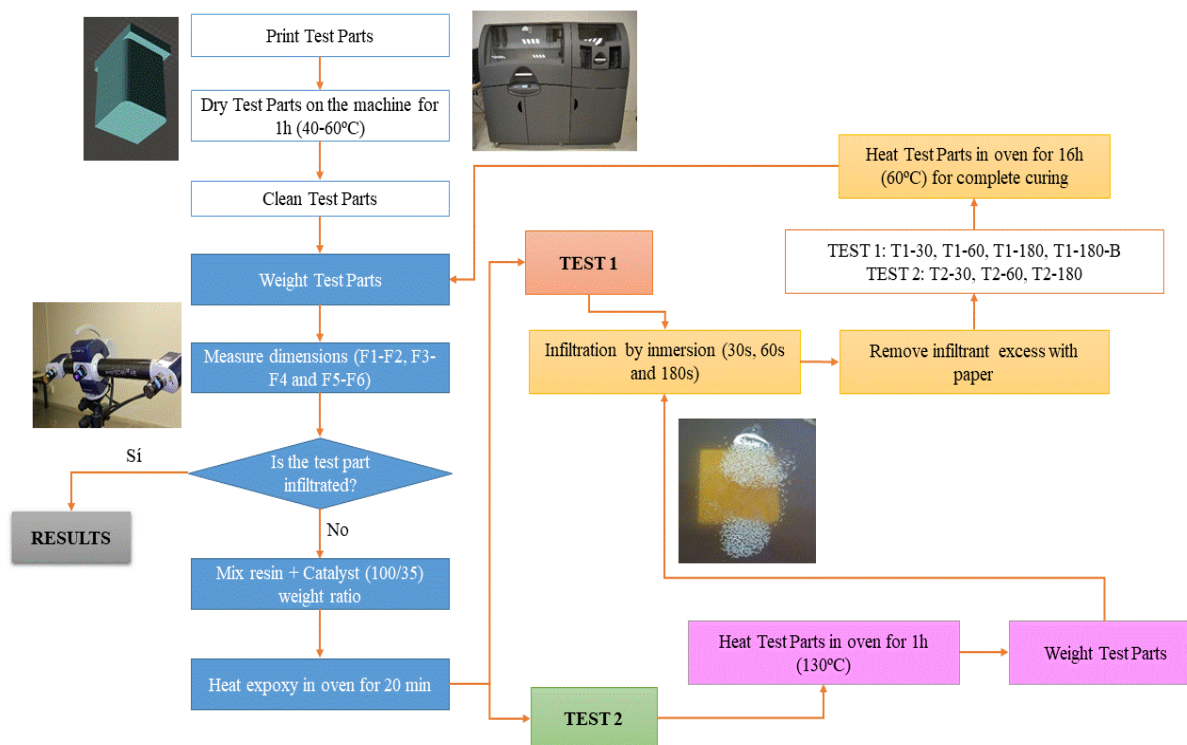


Figure 1. Work methodology.

2.1. Test part design

Figure 2a shows the test part used. The part is 20 mm x 20 mm x 30mm size. It is asymmetric with

specific features such as fillets or flaps, in order to easily identify the printing position as well as to facilitate the scanning with optical systems. Figure 2a, shows the designed test part with the numbering used for each face. Face 1 is the upper printing face and face 2 is the one in contact with the building bed (figure 2b).

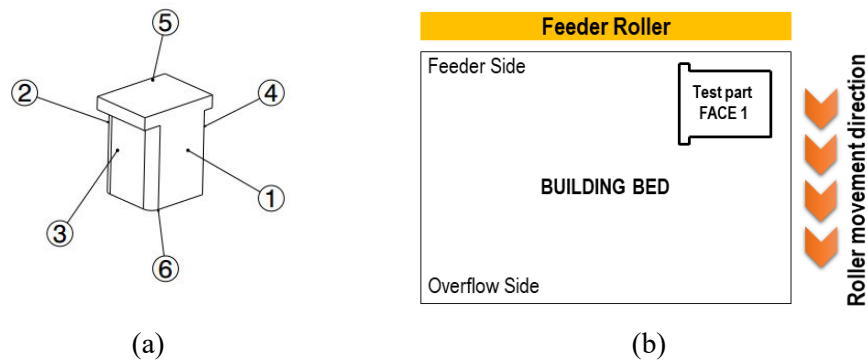


Figure 2. (a) Test part faces. (b) Test part printing orientation on the building bed.

It is important to consider the manufacturer's recommendations when selecting the printing area in the building bed [10]. The greatest densification of the parts is achieved in the upper area (figure 2), near the feeder roller. This is due to the movement of the compaction roller from the Feeder Side to the Overflow Side while spreading the powder on the building bed. For the same reason, the least densification is achieved in the lower area. The different densification of the part, and therefore its porosity, directly affects the later on infiltration process. Thus, these two printing areas were used for printing the parts in order to analyse the influence of the position.

2.2. Design of the infiltration process

Two different infiltration tests were carried out (named Test 1 and Test 2). In both, the weight and dimensions of each test part were measured, before and after the infiltration process to compare its influence.

- Test 1: following the manufacturer's instructions. All the printed parts are kept on the machine for one hour at temperature between 40°C and 60°C. Thus, the parts are dried and a percentage of the interior humidity is removed in order to improve their consistency. The removal of this humidity is also advantageous in the subsequent infiltration process. Parts are then removed from the machine and the excess of powder is removed using a fine brush and pressurized air to avoid damage on the surfaces.
- Test 2: adding a drying stage after cleaning the parts. In theory, an increase in the drying time allows the improvement of the properties of the printed parts and of the subsequent infiltration process, as there is a greater evaporation of the water that increases the internal porosity of the part. Therefore, each test part was exposed to a temperature of 130°C during 2h using a muffle furnace. The temperature was chosen taking in consideration that bibliography indicates that dehydration of the hemihydrate could occur from 110°C [11].

For both tests, the infiltration process was by immersion under atmospheric pressure conditions. First, the resin was heated at 30°C in the furnace during 20 min, in order to increase its fluency. Second, three infiltration times were established (30s, 60s and 180s), in which the part remains submerged in the resin while still hot. The only recommendation in this regard [12] indicates that the adequate dipping time for cyanoacrylate is determined looking for bubbles rising. If bubbles are seen rising up, it is necessary to wait until they are no longer visible, wait 10 s and remove the part from the liquid. In our case, it was observed that bubbles were no visible after 60s of immersion. In order to check the

infiltration differences with a variation of the immersion time and/or to check if infiltrant saturation occurred at some point, two more additional times were established, one shorter (30s) and other longer (180s).

Figure 3 shows the number and position of the printed parts, as well as the nomenclature used for identifying the test and the infiltration time. Each test was repeated three times.

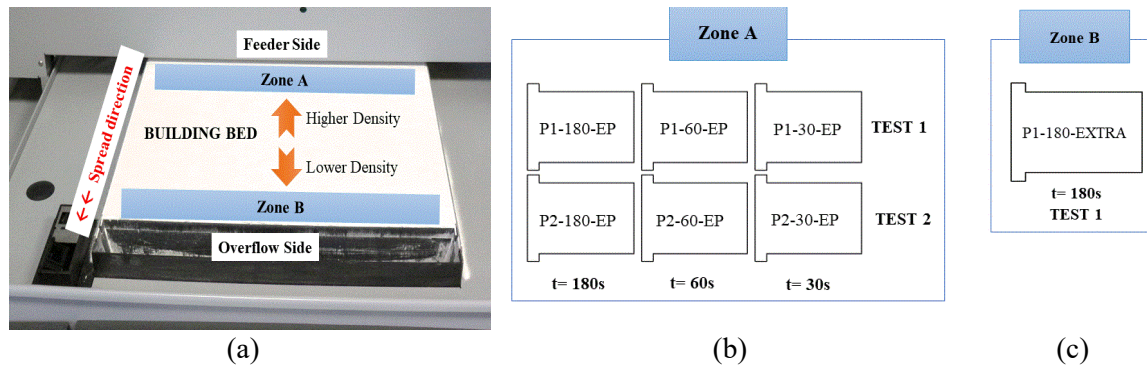


Figure 3. (a) Zones in the building bed. (b) Number and position of the printed parts in zone A. (c) Number and position of the printed parts in zone B.

Finally, the infiltrated parts were placed in a furnace at 60 °C during 16 h to facilitate curing and to obtain the best properties of the resin [9].

2.3. Test parts weighting and scanning

A Mettler AE 240 semi-microanalytical balance (sensitivity $\pm 0.01\text{mg}$) was used for weighing the specimens before and after heat treatment and infiltration process.

Dimensional measurements were made by non-contact technology. A Breuckman smartScan was used. This scanner works by triangulation with blue structured light. Table 1 shows the characteristics of this scanner in the field of view of 125 (FOV125). This field is the one that allows us to obtain the best precision in terms of dimensional measurement [13].

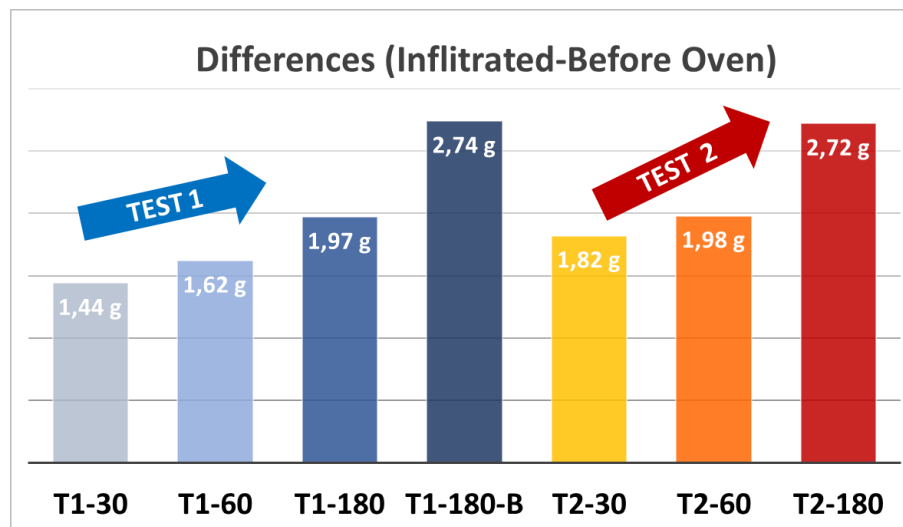
Table 1. Field of view specifications (<http://aicon3d.com>).

FOV	125
FOV size (mm)	95x95
Measuring depth (mm)	60
X,Y resolution (μm)	50
Z resolution (μm)	5
Triangulation angle	32.5°
Working distance (mm)	370

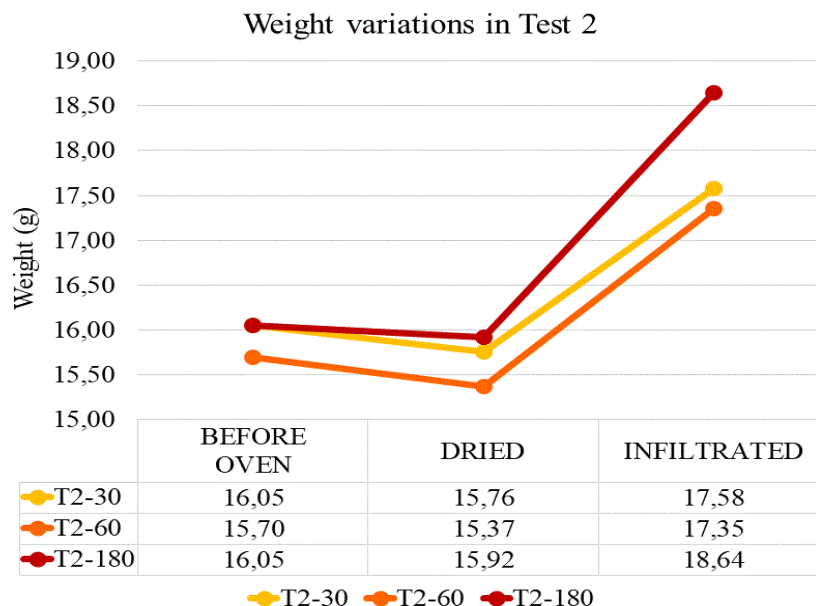
Geomagic Control X software was used for the analysis. Once each part was scanned, three sections were made in X, Y and Z direction to measure the distances between parallel faces. In addition, each part in its final state was 3D-dimensionally compared with respect to the state previous to infiltration.

3. Results and discussion

By weighting the test parts at each stage of the process, it was verified that as longer the infiltration time as higher weight (figure 4a). This behaviour is observed in both Test 1 and Test 2. As expected, the drying process in the furnace for parts in Test 2 causes a higher loss of water by evaporation, and it allows to achieve better infiltration as can be seen in figure 4b.



(a)



(b)

Figure 4. Weight change. **(a)** Differences between the final state and the state previous to apply furnace drying. **(b)** Weight variations in Test 2.

In figure 4 (a) it is also observed that the part manufactured in the bed area with lower density (T1-180-B), without applying a drying process, had a weight gain similar to the best one of Test 2. This could establish a future rule when choosing the printing area on the machine, most suitable for small parts that were to infiltrate.

Several results are obtained during the dimensional analysis with regard to test parts before and after the infiltration process:

- There are not notable 3D differences between each part before and after infiltration. The standard deviations in the 3D comparison is about 30 μm in the worst case. A best fit alignment was used for the comparison. Figure 5 shows a colour map for each comparison, keeping the same scale in the colour bar. As can be seen, the infiltrated test parts according to Test 1 (figures

5a, 5b and 5c) show higher deviations compared to the test parts without infiltration than the parts of Test 2 (figure 5d, 5e and 5f). As the latter have greater increases in weight (figure 4), it shows that the infiltration in Test 2 has been more effective and infiltrant has penetrated deeper in the parts.

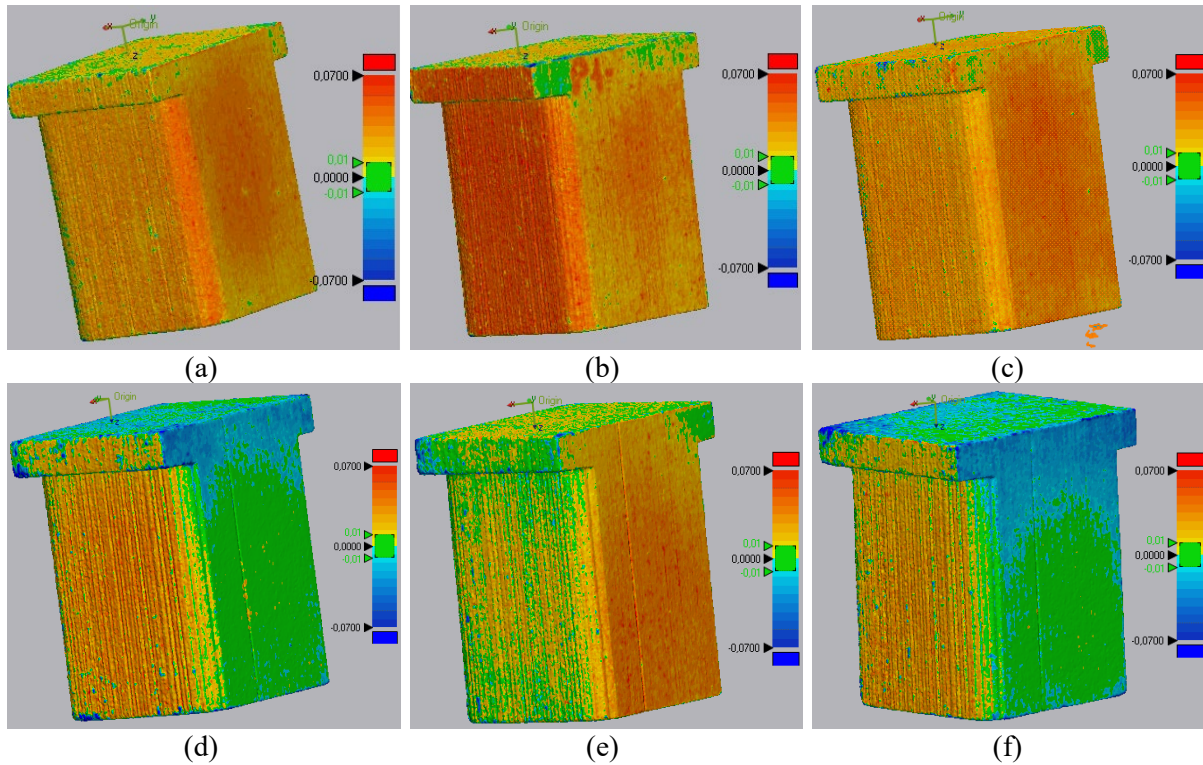


Figure 5. 3D comparison between test parts before and after infiltrating. (a) T1-30. (b) T1-60. (c) T1-180. (d) T2-30. (e) T2-60. (f) T2-180.

- The test part printed in zone B, low density zone, shows a 3D comparison similar to the rest of parts treated according to T1. There is nothing of interest to note in the comparison.

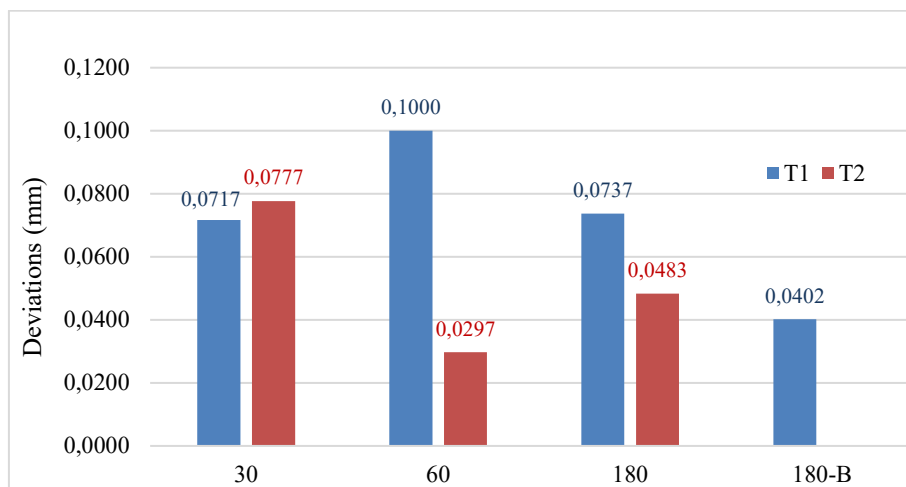


Figure 6. Dimensional deviations between faces 3 and 4, before and after infiltration.

- For both tests, an increase in the dimensions of the infiltrated parts is observed in relation to the same parts before the infiltration process. These deviations are higher for distances between faces 3 and 4, which are the faces resulting from the stacking of layers along the printing axis (figure 6). In the same way as before, it is confirmed that the increase is greater in Test 1, but in any case, the greatest increase is 100 μm .

4. Conclusions

The objective of this study was the analysis of the infiltration process and its effect on the dimensions of the post-processed parts.

- It has been shown that infiltration post-processes improve by adding additional drying stages for the printed parts.
- In addition, it has been seen that the infiltration process does not greatly affect the dimensions of the parts, and that the greatest deviations are found between the faces perpendicular to the printing axis.
- It has been tested that the areas of lower density allow deeper infiltration without additional treatments to promote infiltration. It would be convenient to expand this study in future works.

This work shows the importance of choosing the correct position of the part on the building bed when subsequent infiltration post-processes are carried out.

Destructive tests are considered necessary to verify the mechanical properties of the printed parts depending on the printing area used.

Additional work with vacuum infiltrations is necessary to increase the infiltration speed by extracting the air from the interior of the parts. In addition, the application of subsequent overpressure can improve the results in terms of mechanical properties obtained with the infiltration, but dimensional studies are also necessary in this regard.

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