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# Fluid-based removal of inner support structures manufactured by fused deposition modeling: an investigation on factors of influence

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**Abstract**

Additive manufacturing is growing in importance in industrial environments. In this context, a holistic process control is required. The process steps in additive manufacturing are generally data preparation, production, and post-production. If there are overhanging geometric elements in the components to be manufactured, they must be supported. The type of support is technology-specific. In fused deposition modeling, a support structure is simultaneously built to accommodate such geometric elements. The support structure may be mechanically removed in post-processing or in a bath of alkaline solution. For inner support cores with complex geometries, a removal in a liquid bath is preferred for reasons of accessibility. However, sufficient contact with the liquid solution is not always given. Consequently, the removal in these cases is not guaranteed. Information about the duration and quality of removal is currently not precisely quantified. An approach to systemize this process is presented in this paper. Therefore potential factors of influence are listed. Selected parameters and their effects were analyzed in experimental trials. The experiments were designed around removing the support material using injection nozzles. The experimental results show the significant impact of pressure, flow rate, and size of contact area on duration and quality of removal.


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*Keywords:* 3D printing; Support; Removal

## 1. Introduction

In additive manufacturing processes, supporting structures permit the reliable production of overhanging geometries [1]. Since they are only required for production purposes and not part of the component itself, a subsequent removal is necessary [2]. In the case of fused deposition modeling, the support material can be removed mechanically at defined break-away points [3] or dissolved in, e.g., a bath of alkaline solvent [4].

In the latter case, the condition for fluid-based removal is sufficient contact between the dissolving liquid and the support material. This dissolving of support structures is usually done by immersion in a liquid bath.

## 2. Need for action

As is evident from the following examples, the contact condition, however, cannot always be fulfilled:

- According to the Archimedes' principle [5], the additive manufactured part floats on the surface of the liquid bath if its weight ($f_g$) is lower than the buoyancy force ($f_b$). If inlet openings – into which the dissolving liquid should flow – of the part are above the surface of the liquid, internal geometries and thus the support material will experience no contact with the dissolving liquid (Fig. 1).
- Air entrapments within the channels inside the additive manufactured part can lead to insulation. If these entrapments are located unfavorably, i.e., unable to exit during the dissolution process, the contact condition will fail for certain support areas possibly completely (Fig. 2).


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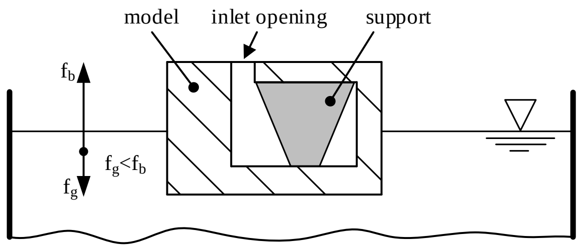


Fig. 1. Contact impeded if inlet opening is not submerged due light weight

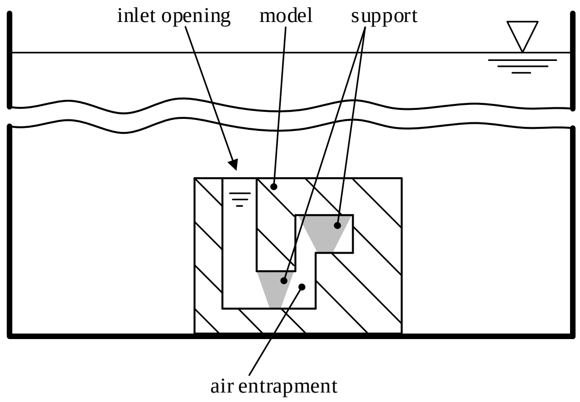


Fig. 2. Contact impeded by air entrapments

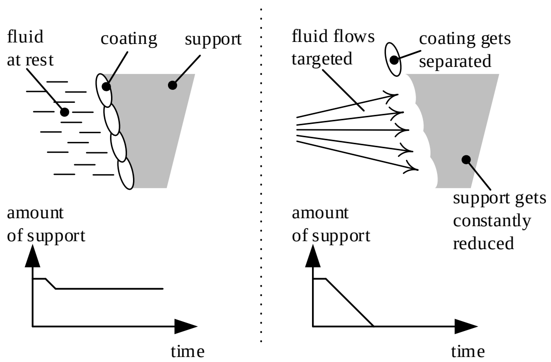


Fig. 3. Contact impeded by quasi-static coating

- The flow force is also of significance. This force removes the evolved quasi-static coating – as a result of the dissolving – on the contact area between the liquid and the support material. If the force is insufficient, the deposited coating with saturated leach interrupts the dissolution process. For that reason, a constant inflow of non-saturated leach at the contact area is necessary (Fig. 3).
- Referring to the examples of Fig. 2 and 3, undercuts and long channel-like geometries required because of mechanical design reasons impede the inflow of the dissolving liquid in terms of its flow speed and force. Hence, the contact between liquid and support material inside the part may not occur or the separating of the coating is insufficient.

Consequently, the leaching process – as a post process – may last longer than the additive deposition of the layers – as the main process – itself (see section 4.2). In the worst case, the support material is not completely dissolved.

As a result, there is a lack of precision in statements concerning the duration and quality of the dissolution process. Since additive manufacturing is of increasing importance in commercial business models, monetary aspects demand quantifiable recommendations for these processes. The work that follows addresses potential influencing factors and their effects on removing the support material fluid-based.

## 3. Factors of influence

In this work, potential influencing factors were investigated. If a model representation is used for this process, there are three fundamental factors of influence that affect the progression of the dissolving process:

- the dissolving liquid
- the object to be dissolved
- the contact between leach and object to be dissolved.

### *3.1. Dissolving liquid*

The solvent used in the experiments is a sodium hydroxide solution with a pH value of 13. The powdered substance *Stratasys WaterWorks Soluble Concentrate P400SC* is mixed in a ratio 1900 gram per 84 liters of water heated to 70°C. The homogeneity of the leach is achieved by the continuous operation of the circulation pump inside the *German Sonic Cleanstation UW90*. By renewing the leach after each series of experiments, a maximum of 200 gr of support material, *Stratasys SR-30 Soluble Support,* is dissolved in 84 liters. Thus saturation and concentration levels can be considered as roughly constant.

### *3.2. Object to be dissolved*

The object to be dissolved is cylinder-shaped with a height of 40 mm and a diameter of 20 mm. It consists of the support material SR-30, which in principle allows a residue-free dissolution in an alkaline bath. The test body designed as a solid material represents the worst case.

All test bodies are based on the same STL file, and have been manufactured with the same extruder nozzle, so that the identical geometrical quality of the test bodies is ensured.

### *3.3. Contact between leach and object to be dissolved*

In the *Cleanstation UW90*, a flow is generated by a circulating pump. However, this is insufficient to dissolve encapsulated cores. The approach in this work is to accelerate the dissolution of the test body by targeted irrigation. The following variations to the contact-condition were included in the test:

- injection position,
- inlet opening,
- nozzle position,
- nozzle diameter,
- injection pressure,
- immersed versus not immersed injection.

## 4. Experimental procedure

### *4.1. Experimental setup*

To analyze the identified relevant parameters, an experimental setup was built (Fig. 4). The above-mentioned parameters were analyzed in the following by means of three trials. Each experiment was performed twice so that an average dissolving time of the test bodies could be calculated. The following listed dissolving periods relate exclusively to these averages.

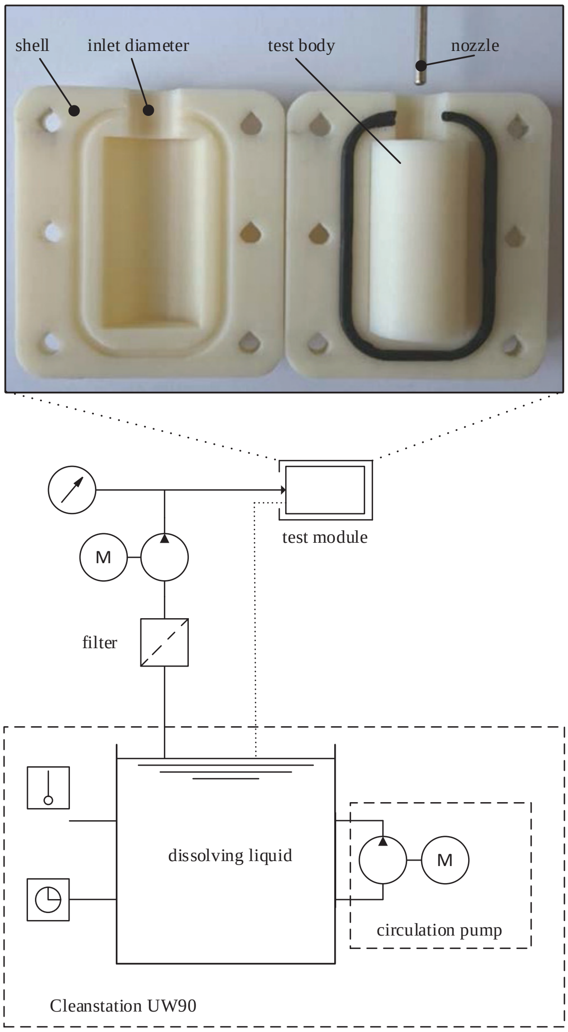


Fig. 4. Experimental setup and test module in detail before the removal process

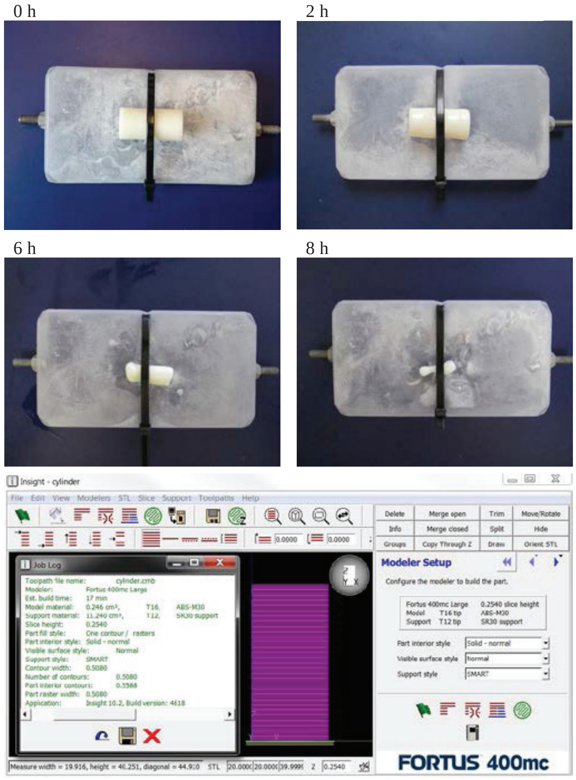


Fig. 5. Progress in basic experiment compared to the estimated build time of the test body

### *4.2. Basic experiment*

First, basic tests were done in order to collect general data on the dissolution behavior of the support material SR-30. The aim of this experiment was to determine a principle value for the behavior of the dissolution. In this context, the dissolution of a test body in the *Cleanstation UW90* is considered. The test body was secured to the bottom of the Cleanstation and dissolved in a bath of tempered, circulating leach. As shown in Fig. 5, the test cylinder was completely dissolved after more than 8 hours. Compared to this, the build-time was about 17 min.

### *4.3. Main experiments*

The three series of main experiments deal with the dissolution behaviour by pressurised irrigation of the test bodies with leach. In test series 1, the test specimen was irrigated from different positions with constant parameter values. The position that resulted in the shortest dissolution time was then taken as the basis for the following test series. In test series 2, the parameter values were varied. The third test series used the parameter-variations from three experiments of series 2 that resulted in the quickest dissolution of the test bodies.

During these three series of experiments, each test body is encased by a shell. This shell has an opening, through which the contact between the leach and the test body may be established. Through this opening, leach flows into the component as well as back out again. Based on these series of experiments, the impact of parameters concerning the dissolution of the support material SR-30 in geometrically confined spaces was investigated.

*4.3.1. Test series 1 – injection position*

The first series consisted of three tests to examine the position of the test body in relation to the injection nozzle during the injection of leach. This test series takes place above the leach surface. The opening in the shell of the test body has a diameter of 10 mm. The nozzle used had a diameter of 1.8 mm and is located directly in line with the opening at a distance of 1 mm. The injection pressure remained constant. The following three injection positions were investigated in terms of dissolution time:

- vertical injection from above
- vertical injection from below
- horizontal injection.

In Table 1 the results of this series of experiments are listed. Based on these results, a horizontal injection is considered to be advantageous. Thus, all subsequent experiments were carried out in the horizontal injection position.

Table 1. Results of test series 1 - position of injection.

| Injection | Average duration of dissolution [min] |
|---|---|
| Vertical from above | 50 |
| Vertical from below | 52.5 |
| Horizontal | 37.5 |

In Fig. 6, an example of the dissolution progress of a test body is shown. The images are from a test of a vertical injection of leach from below.

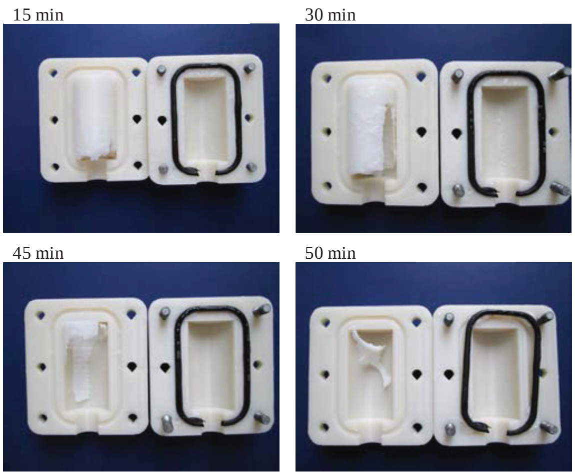


Fig. 6. Selected result of injection vertical from below

*4.3.2. Test series 2 – variation of parameters*

This series consisted of 16 experiments, which also takes place above the leach surface. The following four parameters, which influence the dissolution behavior of the test body, vary here between two defined values:

- Inlet opening ($D_{Inlet}$): the diameter of the inlet opening is set to either 10 mm or 5 mm.
- Position of the injection nozzle: at the nozzle position designated as “external”, the nozzle tip is positioned outside the enclosing shell at a distance of 1 mm. The second nozzle position is named “internal”. During the first 10 minutes it has the same position as “external”. Afterwards the nozzle is moved forward toward the support material. For the remaining period of dissolution, the nozzle tip is located 10 mm within the previously formed hollow in the support material.
- Diameter of the injection nozzle ($D_{Nozzle}$): the two diameters of the injection nozzles were set at 1.8 mm and 1.3 mm.
- Injection pressure ($p_I$): because of the experimental setup, a maximum possible pressure of 2.5 bar and a minimum of 1 bar is derived.

In Table 2, the data from all 16 experiments of this series including varying parameter settings as well as their average dissolution times ($T_{mS}$) are shown.

Table 2. Results of test series 2 - variation of parameters.

| No. | $p_I$ [bar] | $D_{Nozzle}$ [mm] | nozzle position | $D_{Inlet}$ [mm] | $T_{mS}$ [min] |
|---|---|---|---|---|---|
| 1 | 2.5 | 1.8 | external | 10 | 26 |
| 2 | 1 | 1.8 | external | 10 | 41 |
| 3 | 2.5 | 1.3 | external | 10 | 34 |
| 4 | 1 | 1.3 | external | 10 | 50.5 |
| 5 | 2.5 | 1.8 | internal | 10 | 24 |
| 6 | 1 | 1.8 | internal | 10 | 38 |
| 7 | 2.5 | 1.3 | internal | 10 | 36.5 |
| 8 | 1 | 1.3 | internal | 10 | 40.5 |
| 9 | 2.5 | 1.8 | external | 5 | 82 |
| 10 | 1 | 1.8 | external | 5 | 134 |
| 11 | 2.5 | 1.3 | external | 5 | 72 |
| 12 | 1 | 1.3 | external | 5 | 162.5 |
| 13 | 2.5 | 1.8 | internal | 5 | 28.5 |
| 14 | 1 | 1.8 | internal | 5 | 35 |
| 15 | 2.5 | 1.3 | internal | 5 | 35 |
| 16 | 1 | 1.3 | internal | 5 | 48 |

In the following, the effects of the individual adjustable parameters are analyzed in more detail.

*4.3.2.1. Influence of inlet diameter*

In Fig. 7, the average dissolution times of two experiments are compared with each other.

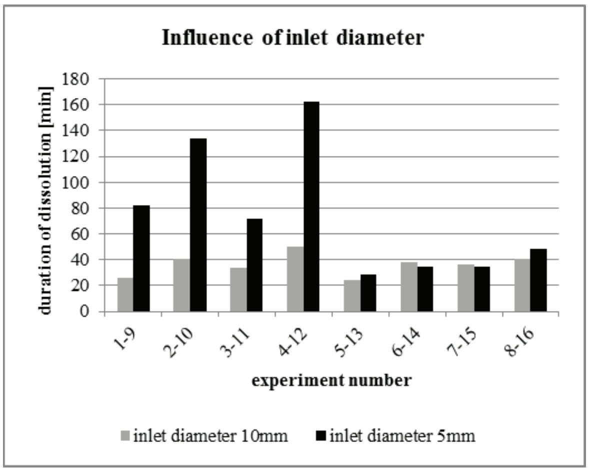


Fig. 7. Influence of inlet diameter

These experiments have identical underlying parameters, only the inlet diameter varies between two values. In the first four pairs of data, there were significant differences in the average dissolution time periods. The common feature of these experiments is the external nozzle position. It can be concluded that the influence of the inlet diameter on the dissolution of the test body is marginal, as soon as the nozzle tip is located inside the component. As the larger inlet diameter usually results in shorter dissolution periods, this is considered positive.

*4.3.2.2. Influence of nozzle position*

In Fig. 8, two experiments are compared, which differ only in the position of the nozzle. For the external nozzle position, the average dissolution times were generally longer. Using an internal nozzle position, especially in experiments with a small inlet diameter, resulted in a significant reduction in times of dissolution.

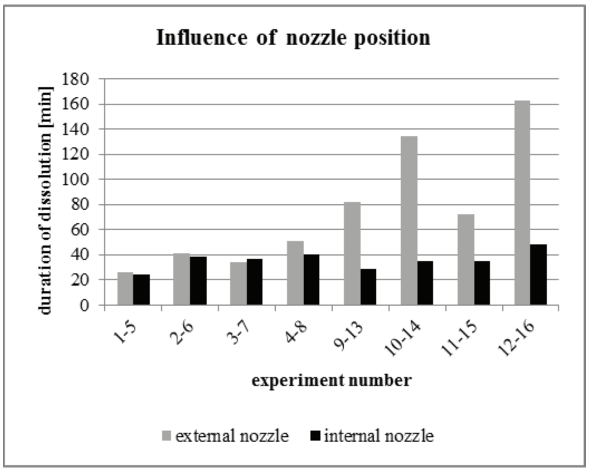


Fig. 8. Influence of nozzle position

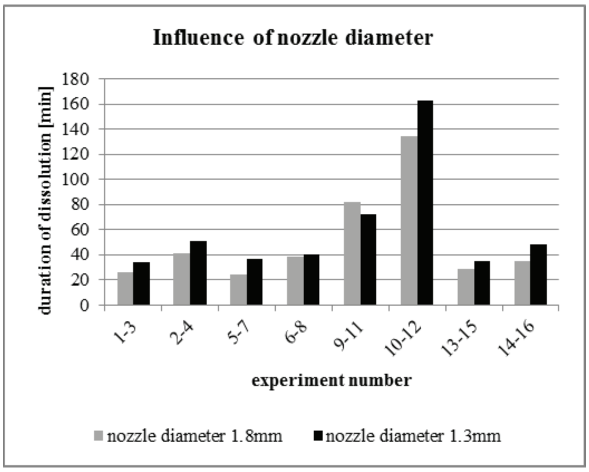


Fig. 9. Influence of nozzle diameter

*4.3.2.3. Influence of nozzle diameter*

For the comparative pairs shown in Fig. 9, only the nozzle diameter was varied. In this way, the influence of flow volume on the dissolution of the test body was analyzed. In these comparative pairs, a larger nozzle diameter and thus a higher flow volume was shown to reduce dissolution times. In contrast to previous analyzed data, in these experiments no connection to other parameters can be detected.

*4.3.2.4. Influence of pressure*

The influence of pressure at approximately constant flow volume was also investigated. There are two changing parameters within a comparison pair to maintain a constant flow rate of 110 l/h. Here, the smaller nozzle in conjunction with the higher pressure is compared to the larger nozzle at reduced pressure. As shown in Fig. 10, a higher pressure always causes a faster dissolution of the test body.

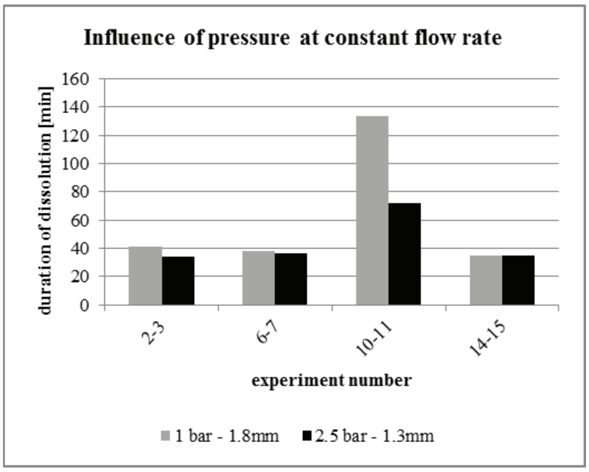


Fig. 10. Influence of pressure at constant flow rate

### 4.3.3. Test series 3 – injection immersed in alkaline solution

The data from the experiments of test series 2 (Table 2) that led to the shortest dissolution duration (No. 1, 5 and 13) were used to investigate the effect of an injection when the test module is fully immersed into the leach. To this end, the entire experimental setup was mounted at the bottom of the Cleanstation. All other parameters correspond to the previous settings of test series 2. The comparison of the experimental series above and below the leach surface shows that the differences in times of dissolution are marginal, see Table 3. Thus, the effect of positioning the injection below or above the leach surface is considered to be small.

Table 3. Results of test series 3 - injection immersed in alkaline solution.

| No. | $p_I$ [bar] | $D_{Nozzle}$ [mm] | nozzle position | $D_{Inlet}$ [mm] | $T_{mS}$ [min] |
|---|---|---|---|---|---|
| 1 | 2.5 | 1.8 | external | 10 | 24.5 |
| 5 | 2.5 | 1.8 | internal | 10 | 25 |
| 13 | 2.5 | 1.8 | internal | 5 | 27 |

## 5. Conclusion and prospects

Basic experiments were designed and performed, in order to establish a well-founded guideline for the dissolution behavior of a test body. The comparison with the main experiments clarifies that the dissolution process using an injection nozzle, is a beneficial approach to remove support material. This is based on the fact that even the longest dissolution period within the framework of the main experiments of about 162.5 minutes (experiment No. 12) is significantly lower than the dissolution duration of the basic experiment of about 8 hours (see section 4.2). This period can be reduced immensely by increasing the injection pressure and the nozzle cross section, and thus the flow rate (experiment No. 9; dissolution time: 82 minutes). Furthermore, if the inlet diameter is enlarged and the nozzle is advanced towards the target support structure, a dissolution time of about 24 minutes (experiment No. 5) can be achieved.

The analysis of test series 2 indicates that the influence of moving the nozzle depends on the inlet diameter. The smaller the inlet diameter, the more influence moving the nozzle has.

Following from this effect, the potential of a higher injection pressure and a higher injected flow volume should be investigated in further studies. However, an increase in pressure is only possible within certain limits, in order not to damage the actual component. The first step therefore is to identify these material-dependent threshold values.

Since, in this work, only the injection by a single nozzle was observed, the flow rate at a given injection pressure may be increased by using a special injecting device that has multiple nozzles. Furthermore, a rotation of the injecting device could be beneficial, as the support material could be removed more uniformly. This is especially important for small inlet openings in basic components with a large volume of support material.

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