Investigation of Fluid Intake and Necessary Drying Times of Additive Manufactured Hollow Cylinders for Further Use in Vacuum Casting

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Abstract

Vacuum differential pressure casting belongs to lost mold technique. To produce with the aid of this technology investment models are needed. One possibility is the use of additively produced full body models. The scape is just determined by the outer shell. Therefor the usage of hollow body models can afford a conservation of material and cost cutting. The aim of this paper is the presentation of research results of a practical application of hollow body models.

Keywords: additive manufacturing, drying time, vacuum casting, increase of process reliability

1 Introduction and fundamentals

The modern vacuum differential pressure casting is based on the 4000 years old lost-wax bronze casting. According to the typical manufacturing process this technology allows almost unlimited creativity for the designer. That means complex structures, low wall thicknesses and undercuts are possible. The opportunity of using vacuum differential pressure casting ranges from prototype production to automated mass production. Several masses per piece from a few grams up to 30 kg are possible. The technology is applied in almost every industry e.g. automotive, medical technology or jewelry industry [1], [2].

Melt out pattern are necessary for the production of such molds. For small numbers of products (1 - 5 pieces) additively produced models are used. After printing these models, they are fixed at a gating pattern. This gating pattern will be fixed at a cuvette and cast in investment material under vacuum. Next the casting mold will be burned at 800 C. The mold gets its final strength and the patterns are burned. Afterwards the liquid metal is casted into the still hot ceramic form. The high temperature of the ceramic form slows down the cooling process. An excellent filling of the form is assured by an evacuated mold cavity, shot sleeve and the back pressure of the melt by protection gas. After cooling down and freezing, the ceramic form will be cleaned away by a high pressure water blast. Finally the single parts will be cut of the supply ducts and potential necessary finishing process will be done [1], [2].

2 Initial situation

Especially at small scale production, particular prototype production, the rapid prototyping parts have a significant impact on the total costs of the cast. The following sample calculation shows how effective these solutions are:

A cylinder with 60 mm altitude and 60 mm diameter has a volume of 169.646 mm³. If this cylinder is produced on an Objet Eden 330 with FullCure720 as model material the material costs will be 61.40 € and the manufacturing costs will be 346.67 €. Correspondingly, this leads to production costs of 408.07 € [3].

Justifying of the needs, just the outside form of the molded body is needed to produce a negative cast. That's why it is possible to use hollow bodies for manufacturing the negative. Almost all manufacturers have developed special hollow construction methods. Based on technological restriction of the Polyjet process, there is no possibility to print hollow body models [4]. According to this, the cylinder has to cut in half in a CAD program (for example CATIA V5). Deductively two identical halves of the cylinder are needed to produce one cylinder. In a previous abstract several/different topologies (internal structures) of cylinders were researched [3]. Afterwards the topologies were optimized. See **Fig. 1**, which shows one of the designed and printed cylinders.

Fig. 1 Hollow cylinder with pillar

The usage of hollow bodies has two advantages, a huge conversation of material of nearly 60 % (137 g instead of 331 g) and a reduction of construction time, justified in the reduction of building height by half. The time saving is nearly 50% (302 min instead of 520 min). These savings are inevitably leaving their mark on the costs, the material costs are 20.07€ and the manufacturing costs are 201.33 €. Correspondingly, the production costs are 221.40 € [3].

The casting test was made with four halves of a cylinder (particular two with pillar, the others with two rips), and one solid cylinders as reference, printed with an Objet Eden 330. According to the state of the art technology, the cylinders were cleaned from support material and inlaid in sodium hydroxide. Afterwards they were rinsed out and dried off. After 15 minutes of drying, the cylinders were glued with commercially available glue (one cylinder with three ribs and one cylinder with a pillar). Afterwards the cylinders were assembled to a mounted cluster, each cluster with every kind of cylinders (solid, hollow with 3 rips, hollow with pillar)

As **Fig. 2** illustrates, the hollow cylinders are mounted with wax and the solid one is placed on top of the gate.

Fig. 2 Mounted cluster with hollow cylinder with pillar, solid cylinder, and hollow cylinder having 3 rips (f.l.t.r.)

Subsequently the integration follows into the cuvette. While integrating the cluster a soft dead sound was to be heard. It was not possible to locate the origin of the sound, but it seemed to be insignificant. The processes of melting out the wax, burning of the mold and molding procedure continued. After removing the gypsum, as shown in **Fig. 3**, two intact and one defect cylinders appeared.

The cylinder with pillar was cracked at the bond seam, so that it was not a hollow body any longer. The investment material flowed inside of the cylinder. Solely the additive produced model was casted. That is the reason for the soft dead sound while integrating the cluster into the cuvette. The cylinder busted and the

Fig. 3 Intact cylinder and defect casting

resulting bang could be heard. Both other cylinders were casted correctly.

3 Conduct of test

Normally additive manufactured models are no hollow models and not glued, so there are no rules for environmental conditions, type of glue or other conditions like drying times. According to the material FullCure720, an acrylic resin, the parts of the cylinders were glued with commercially available glue (cyanoacrylate glue). The great diversity of material, which can be fixed with glue, and the quick drying out are advantageous. The low viscosity ensures small connection points. One disadvantage is the reaction performance with water. Cyanoacrylate glue will dry out fast as reaction of water contact or too high humidity. That causes high internal tensions. The result is a brittle gluing. Just a small or no transmission of force is the consequence.

According to the calculations the bonding of the hollow cylinders should resist the strain. In fact this presumption did not become true in the described issue above There is a reason to believe, that the components absorb water off the caustic solution and diffuse slowly. Consequently the focus of research is the time between removing the parts of the caustic solution and the waiting time before gluing them. It should be noted that this paper will not define the optimum waiting time.

The process of the experimental procedure and the expected results with the appropriate consequences are illustrated in **Fig. 4.**

For the tests 10 halves of cylinders with 3 rips, 10 halves of cylinders with pillar and 10 halves of cylinders with optimized topology were printed. They are cleaned with water and inlaid in sodium hydroxide for 2 hours. Next step is the drying in pairs. Starting with 10 minutes till gluing, the waiting time increased step by step over 30 and 60 minutes, till 120 minutes. In this way 4 hollow bodies develop per cylinder type.

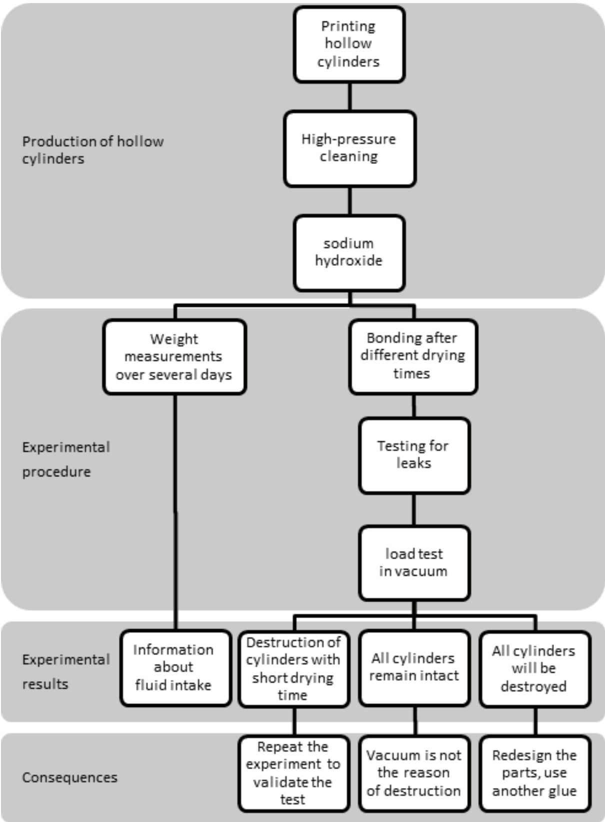

Fig. 4 Process of the experimental procedure and the expected results with the appropriate consequences

Now they are available for the vacuum pressure testing.

According to the manufacturing and technology process the cylinder could be leaky at the bond seam. In this case, nothing will happen, because the inside air will escape and there will be no pressure difference.
To avoid this case, the cylinders were tested by submersion in water. The test environment was the vacuum chamber. After dipping the cylinders the chamber was evacuated. Two different scenarios are expected. The first: If bubbles rise, the cylinder will be leaky. In this case the welding spot has to be glued again, as long as the cylinder passes the test. The second expectant case is that no bubbles are rising. If this happens, the cylinders are ready for the load testing.

Based on limited space conditions in the vacuum chamber is this test divided into two test runs. In the first instance the cylinders with pillar and those with three rips are tested (see **Fig. 5**) and afterwards the test starts again with the cylinders with optimized topology.

As a result of this test, three different scenarios are possible. The first one is that the cylinders show no effect of the vacuum and all cylinders stay complete. If the second expectant case eventuates, it must be assumed, that the vacuum is not the reason for destruction, while the cylinders were embedded in the cuvette. In this instance the research has to focus on another reason. The second case is that all cylinders will be destroyed. Depending on type, shape and position of destruction it is necessary to redesign the parts or search for a new gluing technology/ sort of glue. The third and last case is that only the cylinders with short drying time will crack and at least one pair with longer drying time will not be destroyed.

For the second experimental series the other four cylinders were not glued, just plugged together and weighed periodically with a precision scale at the same time when the others were glued. For data validation purposes weights after 3h and 4h removing the components of the cleaning solution were made.

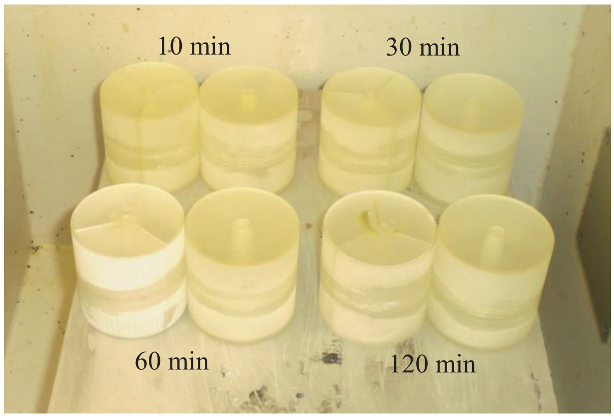

Fig. 5 Cylinders in the vacuum chamber

4 Evaluation

The aim of the scale test is to evaluate how much water the components absorb of the solution. For this one cylinder per hollow cylinder type was weighed at predetermined time intervals. The weights were recorded as a function of time. **Table 1** shows the weight of the components depending on the drying time. The theoretical total volume of the hollow cylinder with pillar is 24.17cm³, the volume of the hollow cylinder with 3 ribs is 32.42 cm³ and with optimized topology 23.75 cm³. With a material density of 1.183g/cm³ [5], this corresponds analogous to weights of 28.593g, 38.547g and 28.096g.

The table shows that the cylinders lose weight continuously, depending on time. After the removal from the cleaning solution the component with pillar starts with 30.812 g, the cylinder with 3 ribs with 40.915 g, and the cylinder with optimized topology with 31.342 g. After 180 min the cylinder with pillar weighs 30.102 g, the cylinder with 3 ribs weighs 39.943 g and the cylinder with optimized topology weights 30.040 g. In addition reference measurements have been done in a two hour rhythm after three days. Both measurements showed a weight of 28.624 g for the cylinder with pillar, a weight of 38.560 g for the component with 3 ribs and a weight of 28.621 g for the cylinder with optimized topology. It can be assumed that this will be the dry weight of both cylinders because there was almost no weight change in this measurement. The slight variance is based on the tolerance (limit) of the printer. In conclusion could be determined that the cylinder with pillar loses 2.188 g, the cylinder with 3 rips loses 2.355 g and the cylinder with optimized topology loses 2.721 g. These are 7.1 % 5.75 % and 8.68 % of their initial weight.

Table 1 Weight of different hollow cylinders depending on drying time

Time [min]	Weight [g] of the cylinder with:		
	pillar	3 rips	optimized topology
0	30.812	40.915	31,342
10	30.692	40.795	31,053
30	30.483	40.684	30,677
60	30.202	40.500	30,265
120	30.117	40.308	30,170
180	30.102	39.943	30,040
240	29.944	39.972	29,864

This test confirmed that the components absorb water from the cleaning solution, which is released continuously to the environment. In order to avoid a reaction between glue and water it is necessary to provide enough drying time.

Therefor the twelve cylinders with different drying times have been placed in the vacuum chamber as follows (**Fig. 5**). On the top left 10 min. drying time, on the top right 30 min. drying time, bottom left 60 min. drying time and bottom right 120 min. drying time. Each pair consists: the cylinder with 3 ribs on the left and the one with the pillar on the right. The array of the cylinders with optimized topology happened on the same way in a second experiment. While evacuating the chamber the cylinders with the pillar cracked first in chronological order: 10 min drying time, 60 min drying time, 30 min drying time. The next ones were the cylinder with the 3 ribs, simultaneously the ones with 10 min and 60 min drying time. The ones which survived are: both cylinders with 120 min drying time and one with 3 ribs and 30 min drying time. Of the topology optimized cylinders cracked those cylinders with 10 minutes and with 30 minutes drying time; those with 60 minutes and 120 minutes drying time withstand the test undamaged.

The result of a closer look to the fragments is that the cylinders cracked at the bond seam and two more or less intact half cylinder survived. The other ones cracked into lots of small pieces, but it is still possible to associate them to only one half cylinder. That means, they busted also at the bond seam. The several broken pieces are shown in **Fig. 6**.

As a result we got the knowledge that the damage of the cylinders is based on the reaction on glue and moisture of the cylinders. The reasons for the different times of fail are manufacturing and process parameter. On the one hand, the gluing was made by hand. That implies mistakes, inaccuracy and leakages. Leaking parts were over glued, this produced a higher strength of the bond seam. On the other hand it is not possible to exclude the fact, that despite of highest degree of diligence, air could escape from the hollow body. In this case, the air from inside the body is evacuated with the air of the chamber and there is no pressure difference, which charges the cylinder.

To exclude that this result is just an accident, the test was repeated with 8 hollow body cylinders with the same parameters. They were glued after 120 min of drying time and all cylinders survived the following test at the vacuum chamber.

Fig. 6 Two more or less intact half cylinder and lots of broken pieces

5 Summary

For the experimental calculation of drying time for additive produced components before gluing a stress test was designed. Before gluing two parts of a cylinder the parts had a drying time of 10, 30, 60, and 120 minutes. After testing for leaks the cylinder were placed in a chamber and this chamber was evacuated. Several cylinders failed this test. Only the hollow cylinders with a drying time of 120 min passed the stress test. The result of the inspection of the failed parts showed that the bond seam is the weakest spot in each case. These facts are evidencing the relation between drying time, or reaction of glue with moisture, inside the components and the damage of the cylinders.

In a second test the loss of weight was determined. The components are losing up to 8.68 % of their original weight. The reason for this effect is evaporating water, which was absorbed while the cleaning process.

By reference to the realized tests/experiments could be proved, that the generative manufactured pieces (by PolyJet procedure) absorb water of the cleaning solution and release it to the environment over a longer period of time. Furthermore was shown that enough drying time is absolutely necessary before the conglutination of both halves of the hollow body, otherwise those will be destroyed in the following process.

The compliance of enough drying time before gluing together generative manufactured (PolyJet procedure) hollow bodies increases the process reliability respectively reduces the defective goods contingent, which contributes to a cost reduction.

It should be noted that the determined values are experimental results which can only be used for cylinders with the same parameter. Other dimensions and specially wall thicknesses may change the result. It is possible that the water take longer for evaporation. On the other hand, the test was not made under constant conditions. The micro climate, specially the humidity has an influence of the drying time. These facts have to be regarded in further tests to optimize the drying time in the future.

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