Spin casting characterization: An experimental approach for the definition of runners design guidelines

SPIN CASTING CARACTERISATION: AN EXPERIMENTAL APPROACH

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The actual attention to production cost and time reduction has encouraged many factories to employ some non conventional technologies instead of the conventional one in the moulds realisation.

These specific non conventional manufacturing technologies, able to employ a significant time reduction for tools manufacturing, are commonly called rapid tooling techniques.

Inside these rapid tooling methodologies it is possible to find one of the more direct and flexible technique that with the use of a not cured silicone allows to manually imprint the shape of a physical object, obtaining in this way, with some more handmade refinements directly and simply the mould.

Unfortunately the literature about this technology is very pour and for this reason it is very difficult to know how process parameters drive the final shape of the object cast.

For this reason this work wants to developed a first experimental analysis on the process parameters and mould design variables, in order to estimate a first process characterisation model as guidelines for all the possible users.

Keywords: Rapid Prototyping, Rapid Tooling, Spin Casting

1. Introduction

The moulds realisation represents one of the most expensive phases of the entire product development cycle. For this reason the great competitiveness that characterises the actual manufacturing market has obliged most manufacturing factories to increase the attention on time and cost saving technologies research, expecially for the realisation of limited productions. As a result of this innovation process a lot of factories have introduced inside their design and manufacturing phases the use of the rapid technologies. The use of these layer by layer adding techniques in the design and manufacturing of production tools, as moulds, has given a great advantage mainly in the manufacturing of complex geometries. These specific techniques, better known with the name of **rapid tooling**, could be employed for the realisation of pre-series moulds working directly with a layer by layer technique ***(direct tooling)***, or could be employed for the realisation of the tool master ***(indirect tooling)*** [1]. All these applications are characterised by an high flexibility level in term of complex geometries reachable and by a significant reduction of tool manufacturing time. One of the most interesting indirect rapid tooling techniques, especially in term of cost of the equipment and material employed is "**spin casting"**[2]. This methodology is very simple and characterised by the presence of two fundamental elements: silicone rubber and centrifugal force (Fig.1).

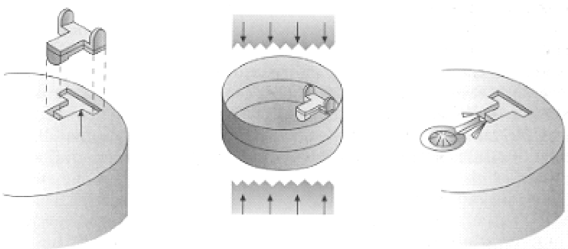
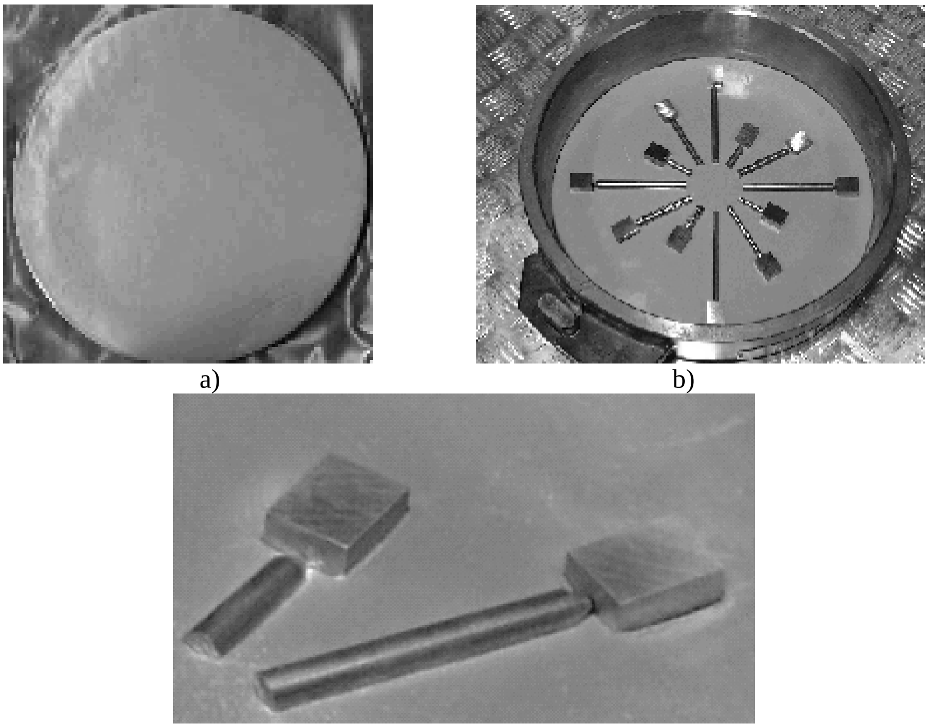


Figure 1: Spin Casting Mould

Just the presence of uncured silicone rubber, that resists to temperature around 550°C and has a plastic behaviour at the beginning of the process, allows a significant flexibility to the process for the manufacturing of very complex geometries (Fig.2).



a) b)

c)

Figure 2: a) Uncured silicone rubber disk b) master imprint c) a particular of master imprint process

2. Spin Casting

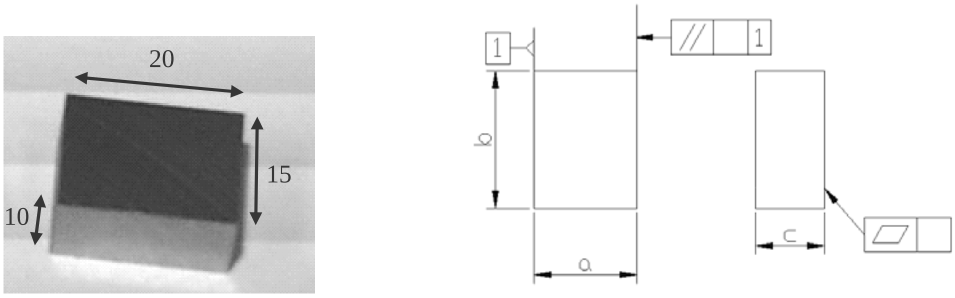
The spin casting process starts with the master models laid out on the disc of uncured silicone rubber. Depending upon model/patter thickness and shape, cavities may be cut or moulded by hand to accommodate the part. The uncured silicone material is soft and pliable like clay. The mould parting line is formed at this stage and can be built up or lowered around any section of the model/pattern. Part of any complexity can handled. Cores and pull-out sections can also be easily incorporated, if required. Mould parting compound is sprayed on the mould and studs are arranged around the edge where (like pins of a die) they precisely position the mould halves to each other. Once located the master models on the silicone disk, normally created with the use of layer by layer techniques (Rapid Prototyping) the mould is ready to be vulcanised in order to modify its plastic behaviour. The mould is in fact placed in a vulcanising frame. This frame is placed in the heated vulcanising press for curing. The combination of heat and pressure forces the silicone into all crevices and around all details of the model/patterns. The heat cross-links and cures the silicone. The resulting mould is tough, resilient, dimensionally accurate, heat and chemically resistant. After vulcanisation the mould is easily fixed to release the patterns (and later, parts) from the cavities. This is true even for patterns with a wide variety of undercuts. In order to complete the realisation of the mould, gates, runner system and air vents are cut into the cured rubber mould with a sharp knife or scalpel. Air vents may also be drilled into the cavity to aid in venting of entrapped air or gasses. Similar gating and venting systems are used for both metals and plastics, so both materials can be cast in the exact same mould for evaluation, if desired.

After these steps the two silicone disks are ready to be located on the spin caster machine (Fig.4), where they are pressed by two disks, in order to avoid fused material escape during the rotation, to be employed for the definitive casting process for a number of time principally related with the: dimension of the disk cavities, generated by the master accommodation in the uncured silicone disk and alloy type. Both these variables are strictly related with the casting process parameters: casting temperature **(T_f)**, disk closing pressure **(p)**, casting time **(t)** and rotational speed **(ω)**. Moreover also the mould design, mainly the runners, influence the efficiency of the casting process. As described before actually this process is manual and iterative, till arriving to a good solution [3].

So starting from these evidences this paper presented a structures experimental analysis of the spin casting process to find out some first guidelines to follow during process design in order to reduce the presence of anomalies in the cast objects

3. Experimental work

Starting from the considerations cited before an experimental analysis about the casting process parameters and the runner typologies has been developed. In order obtain more accurate information about the different parameters influence the rapid prototyped masters have been substituted by steel made ones. Working with simple steel made geometries, parallelepipeds, it is more simple to get reliable information about the dimensional and geometrical tolerances *(parallelism* and *planarity)* provided by the casting process. Moreover the use of steel made masters is also related with the necessity to assure that during the vulcanising process the masters maintain the original shape even under pressure application. With the use o parallelepiped it is possible to measure with a Coordinate Measure Machine (CMM) dimensional and geometrical tolerances (Fig.3).



a) b)

Figure 3: a) Parallelepiped benchmark b) Dimensional and geometrical tolerances analysed

Once choose the tool masters the attention have been moved on the runner design[4]. Before going ahead with their manufacturing it is necessary to consider that normally two different strategies could be followed in their design. It is in fact possible to work with direct runner, that normally take the fused materially directly to the imprints from the disk centre, or with indirect ones, that employ an intermediate grift and secondary littler runner from it to access the master imprints. Moreover a second variable in the runners design is related with the figure imprints access, that could be *top* if the material access is from the figure centre side or *low* on the opposite one. In order to have a more direct control on the dimension of the runners reducing, so the influence of other geometrical aspects given by the presence of intermediate grift and by the presence of more complex runner shapes, the experimental phase has been developed employing a ***direct top*** configuration (Fig.4).

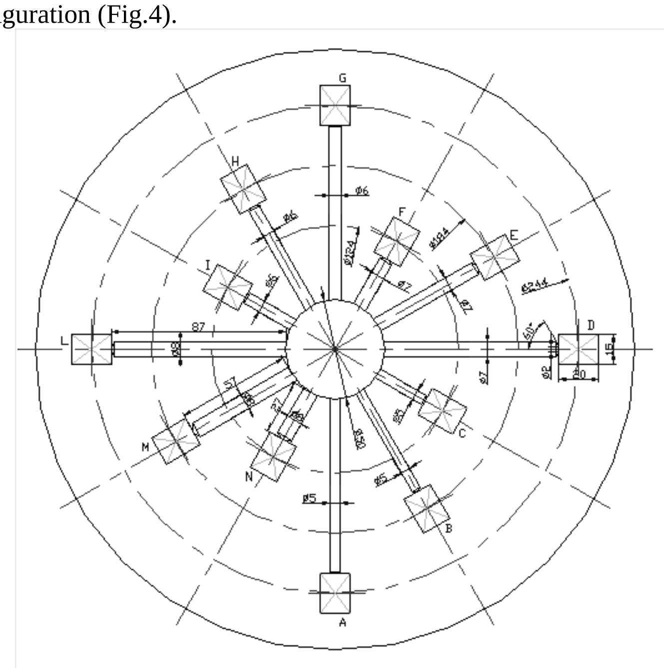


Figure 4: Runners design configuration

Even if normally the runners realisation is developed manually with the use of knifes, in this case, in order to develop a more consistent analysis, they have been obtained during the mould preparation, imprinting them, at the same time of the other masters, on the uncured silicone rubber disk using steel cylinders. In order to evaluate the influence of the figure imprint distance from the centre and the runner diameter a set of different length and diameter cylinder have been selected (Fig.5).

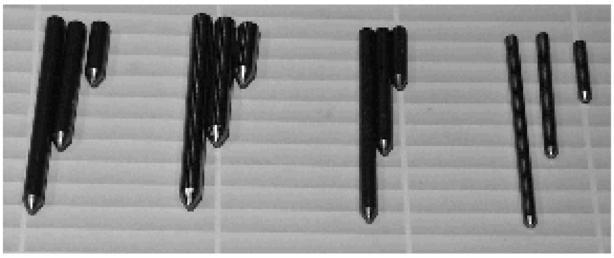


Figure 5: Mould preparation with the use of steel prismatic figures for masters and steel cylinders for runners

Employing twelve benchmarks, in order to complete experimental set, twelve different runners have been chosen varying the diameter with four different values and three different lengths (Tab.1).

Cylinder number	**Length [mm]**	**Diameter [mm]**
1	27	5
2	57	6
3	87	7
4	27	8
5	57	5
6	87	6
7	27	7
8	57	8
9	87	5
10	27	6
11	57	7
12	87	8

Table 1: Dimensions of the cylinder employed for the runners realisation

Moreover in order to grant the balancing of the fused material during the casting process on the whole mould figure, the tool masters have been located on the disk with a central symmetrical configuration (Fig.6)

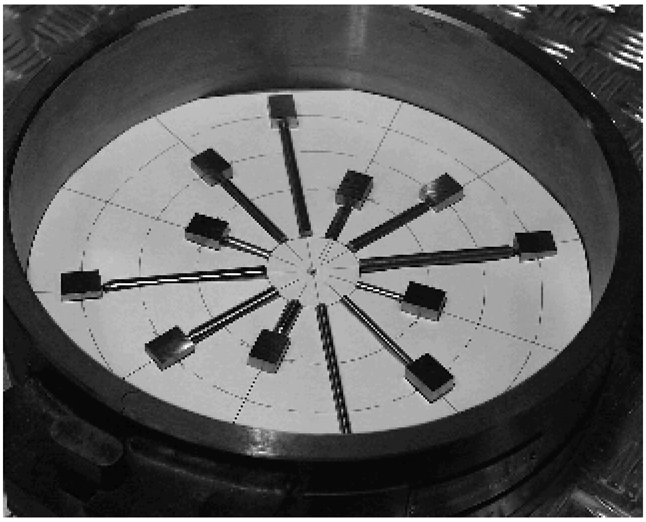


Figure 6: Design of runner and masters locations

For this experimentation has been hypothesized the use of a unique silicone rubber and alloy in order to focus the attention on the process parameters and runner dimensions. The silicone rubber choose, for the entire experimentation set, has been a **BV65HVLD30010** rubber (Tab.2), one of the hardnest actually available, that grant the higest number of cast parts possible. For casting alloy a Zinc based league called ZAMA thank to its low melting properties for the reduced cost and for the good surface roughness reachable (Tab.3).

Name	**Disk Diameter** [mm]	**Disk Thinkness** [mm]	**Shore A Hardness**
BV65HVLD30010	300	10	65

Table 2: Silicone rubber properties

Name	**Density** [Kg/dm^3]	**Specific Heat** [J/kg K]	**Optimal Casting Range** [°C]	**Thermal conductivity** [W/m K]
ZAMA	6,92	382	420-460	113

Table 3: Zinc alloy properties

Starting from the technical information about rubber and alloy given from the producer the set of experiments [5] (Tab.4) has been developed moving in a range of angular speed between 500 and 600 rpm, with pressure from 2 to 3 bar. In order to verify if the variable range has been correctly chosen two tests on the range limits have been run. On 400 rpm the mould show flow problems, the mould is not completely fill, while at 800 rpm and pressure 3 bar the fused material comes out from the mould without completely filling all the figures (Fig.7)

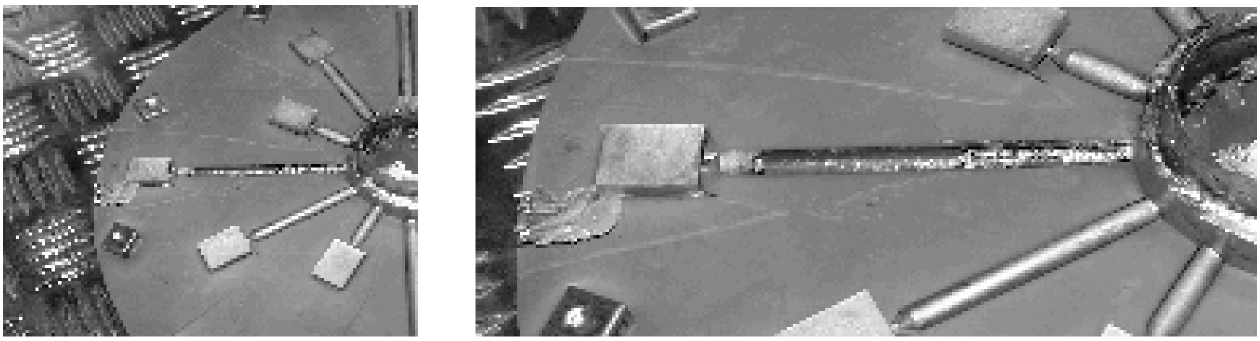


Figure 7: Non controlled material escape and uncompleted figure fill

N° Test	ω [rpm]	p [bar]	t [min]	Tf [°C]
1–2	500	2.5	1’ 20’’	450
3–4	500	3	1’ 20’’	450
5–6	500	2	1’ 20’’	450
7–8	550	2	1’ 20’’	450
9–10	550	2.5	1’ 20’’	450
11–12	550	3	1’ 20’’	450
13–14	600	2	1’ 20’’	450
15-16	600	2.5	1’ 20’’	450
18-19	600	3	1’ 20’’	450
20	700	3	1’ 20’’	450
21	400	3	1’ 20’’	450
22	800	3	1’ 20’’	450

Table 4: Scheme of the Experimental tests developed

In order to allow a successive consistent comparison between the cast parts, a disk integrity evaluation has been developed after every casting step. In particular it has been verified the presence of scorches on the subdivision plane between the two disks, of micro bubbles on the figure surface, of little crevices in the figures, and silicone abrasion inside the master figures, that could modify significantly the results of the successive casting step. While all the tests have been repeated twice the 21,22 and 23 test have been run once because they employ limit conditions.

4. Results Analysis

After the development of the entire experimentations set dimensional information have been obtained with the use of a Coordinate Measure Machine (CMM) working firstly on the vulcanised silicone rubber, on the inferior disk, before the casting process, in order to evaluate the real linear shrinkage of the silicone rubber. Comparing (Tab.5,6) the values on the rubber disk with those on the steel masters, the linear average shrinkage evaluated results less than 1%.

	a [mm]	**b** [mm]	**c** [mm]
A	14,99	19,96	9,99
B	14,98	19,97	9,99
C	14,99	19,98	9,99
D	14,99	19,96	10,00
E	14,99	19,98	9,99
F	14,99	19,95	9,99
G	15,01	19,97	9,97
H	15,00	19,97	9,98
I	14,99	19,97	9,98
L	14,99	19,97	9,97
M	14,99	19,96	9,98
N	14,99	19,96	10,00

Table 5: Dimensions of the steel masters employed for the mould preparation

	a [mm]	**b** [mm]
A	14,99	19,74
B	15,02	19,85
C	15,00	19,77
D	14,99	19,78
E	14,91	19,75
F	14,96	19,75
G	14,92	19,81
H	15,03	19,79
I	15,02	19,92
L	14,98	19,90
M	15,07	19,82
N	15,07	19,88

Table 6: Dimensions of the master imprints after the vulcanising process

After the preliminary measures on the silicone disk, all the cast figures have been measured analysing for each of them dimensions (a, b, c) and evaluating the geometric tolerances in term of parallelism and planarity. (Fig. 8)

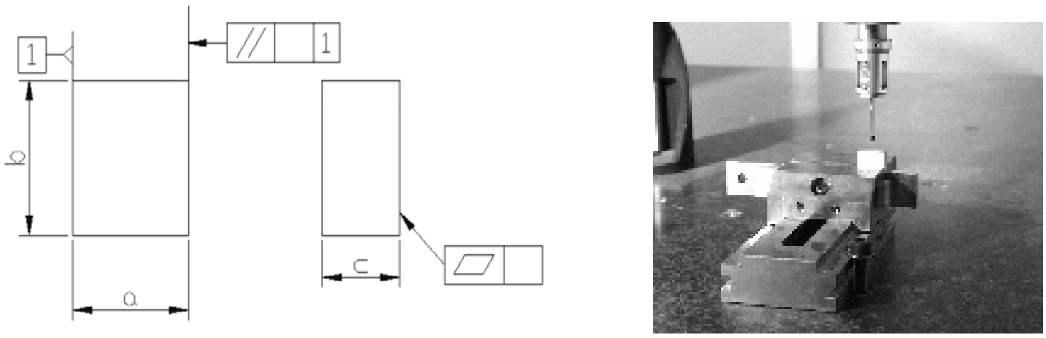


Figure 8: Geometrical and dimensional parameters evaluated on the cast objects with the use of CMM

A big amount of data have been obtained running for all the object cast the measure cited above. Working with the standard deviation analysis [6] and a polynomial regression [7] the experimental results have been analysed in order to understand the process parameters, the runner dimension and the cast objects relations.

$$y = k + x_1 \cdot \omega + x_2 \cdot p + x_3 \cdot d + x_4 \cdot D + x_5 \cdot \omega^2 + x_6 \cdot p^2 + x_7 \cdot d^2 + x_8 \cdot D^2 + x_9 \cdot \omega \cdot p + x_{10} \cdot \omega \cdot d + x_{11} \cdot \omega \cdot D + x_{12} \cdot p \cdot d + x_{13} \cdot p \cdot D + x_{14} \cdot d \cdot D$$

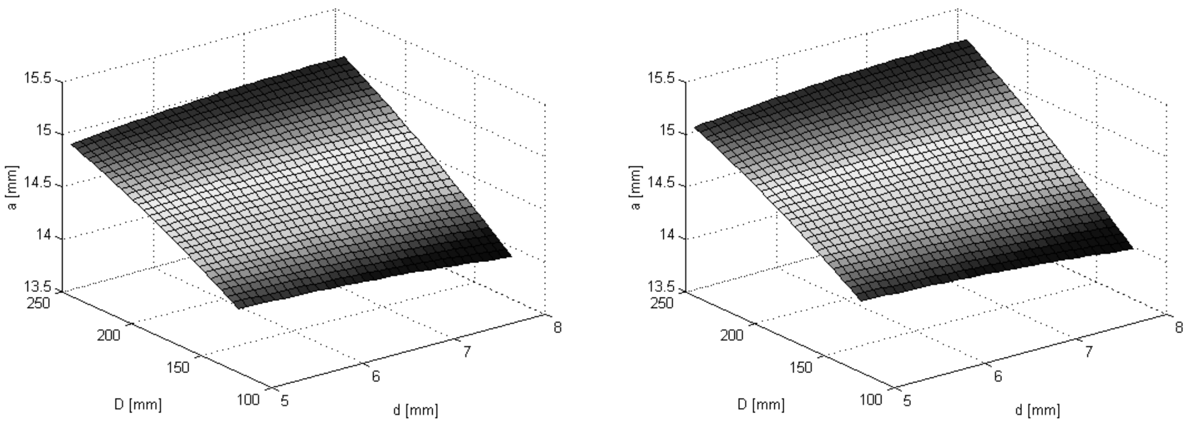
where

k , x_1 , x_2 , x_3 , x_4 , x_5 , x_6 , x_7 , x_8, x_9 , x_{10} , x_{11} , x_{12} , x_{13} , x_{14}	coefficient of the polynomial function
y	dimension of the parallelepiped
w , p , d , D	independent variable

Starting from the results obtained from the experimentations set, a regressive polynomial function has obtained for the dimension **a, b** and **c** of the parallelepiped. The different functions obtained has shown a different reliability values: **a** R^2=0.963, **b** R^2=0,621 and **c** R^2=0,742 . So in order to show only the most significant information, also for limited space allowable, the following data analyse only dimension **a** considering that its polynomial reliable value is the highest one and nearby one.

$$y = 12.12 + 0.970 \cdot p - 0.225 \cdot p^2 - 0.0142 \cdot d^2 - 0.0000144 \cdot D^2 + 0.0000152 \cdot \omega \cdot D + 0.000937 \cdot d \cdot D$$

Working with the polynomial regression some specific consideration have been developed sensitizing graphically the **a** dimension behaviour fixing two variables for every graphs. From the first analysis the function behaviour (Fig.9) shows that moving the master imprint far from the centre of the disk, so incrementing the variable ***D***, that represents the runner length, the cast parallelepiped dimension increases. For the variable ***d***, that represents the runner section diameter, if the master imprint is located nearby the centre, the cast parallelepiped seems to be indirectly proportional to the section variation.

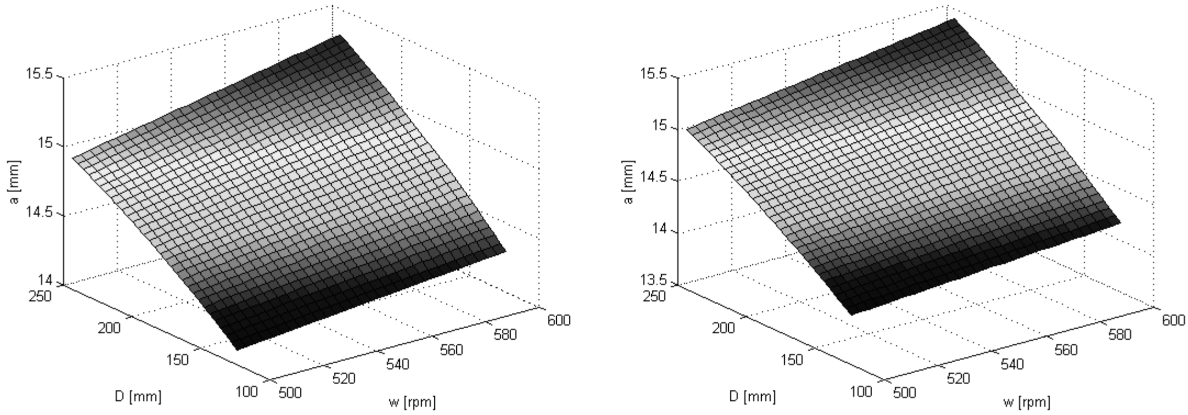


a) **b)**

Figure 9: a) ω = 500 *[rmp]* and p = 2 *[bar]* b) ω = 550 *[rmp]* and p = 2,5 *[bar]*

Moreover from these first results seems that the main effect on the parallelepiped dimension is given by the variable D, so from the radial position of the master imprint on the disk. In fact modifying this value the consequence variation of the parallelepiped dimension seems to be more than 1[mm], while modifying the runner section d, the parallelepiped dimension changes in range between 0,1 – 0,3 [mm].

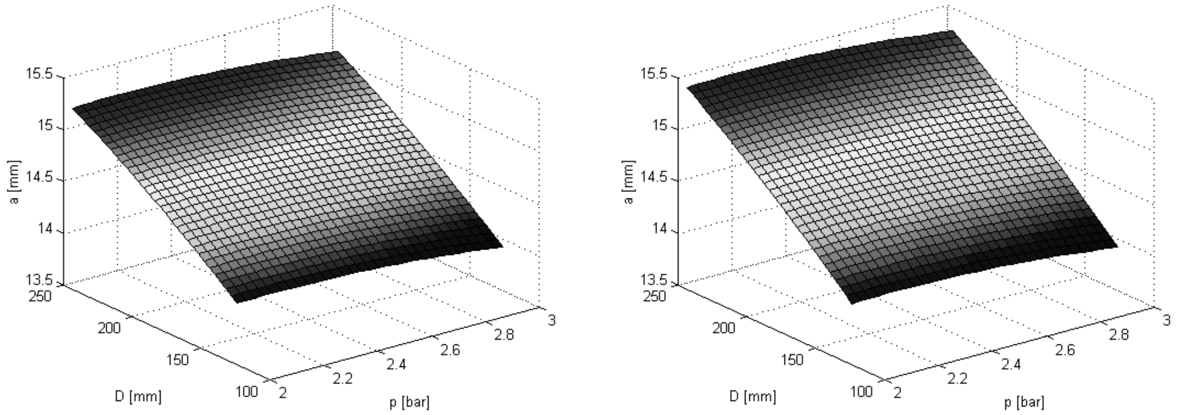
Looking at the graphs it is possible to see that the variable influence on the parallelepiped dimension is linear considering the very reduced curvature shown. Looking for an efficient master location a good solution would be far from the disk centre and with an high runner section. Moving the attention on the influence of w and D, maintaining constant the section d and the pressure p, (Fig.10) the results show how the parallelepiped dimension increases both proportionally with D and ω.



a) **b)**

Figure 10: a) d = 5 *[mm]* and p = 2 *[bar]* b) d = 7 *[mm]* and p = 2,5 *[bar]*

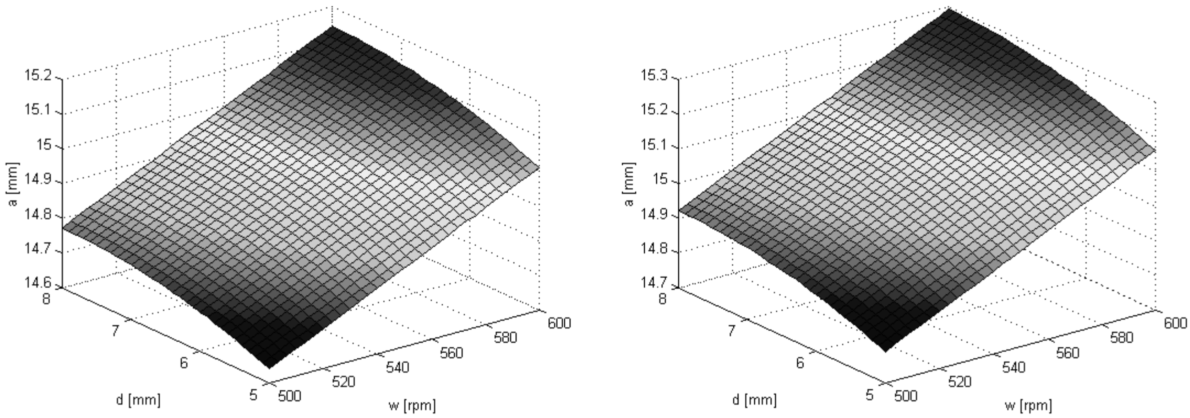
Also maintaining constant ω and d and varying D and p the strong influence between a and D (Fig.11) is again visible and it is also possible to see that increasing p the parallelepiped dimension has a little decreasing.



a) **b)**

Figure 11: a) d = 7 *[mm]* and ω = 550 *[rpm]* b) d = 8 *[mm]* and ω = 600*[rpm]*

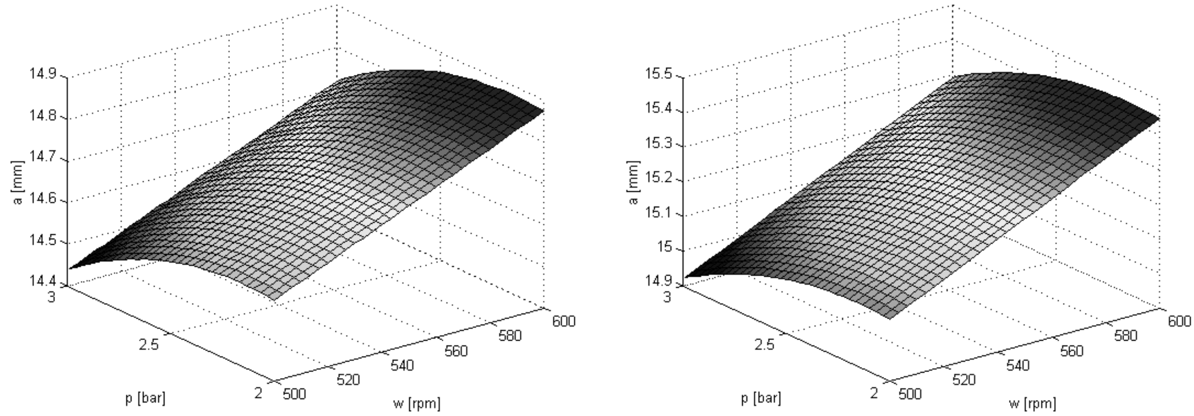
Analysing contemporary the influence of ω and d on the parallelepiped dimension the effect of ω seems to be stronger that the runner section (Fig.12)



a) **b)**

Figure 12: a) D = 184 *[mm]* and p = 2,5*[bar]* b) D= 244 *[mm]* and p = 3 *[bar]*

The results graphs curvature increase varying p and ω at the same time (Fig.13).



a) **b)**

Figure 13: a) D = 184 *[mm]* and d = 6 *[mm]* b) D= 244 *[mm]* and d = 8 *[mm]*

In this case, maintaining the same value for the D and d two opposite effect appear the pressure increasing reduce the parallelepiped dimension while it increase proportionally with the rotational speed. The curvature increase means also that the parallelepiped dimension influence changes with a square behaviour modifying both p and ω.

The last evaluation is related with the geometrical tolerances measured on the different cast models (Tab.7,8) that shows a planarity average value of 0,084 *[mm]* and a standard deviation of +/-0,011, while a parallelism average value between the faces of 0,25 *[mm]* and a standard deviation of +/- 0,065.

A	0,008	0,010	0,012	0,010	0,015	0,002	0,008	0,001	0,004	0,002	0,001	0,002	0,011	0,007	0,009	0,010	0,013	0,014	0,008	0,001	0,009	0,005
B	0,010	0,003	0,014	0,010	0,015	0,006	0,013	0,003	0,003	0,002	0,004	0,002	0,005	0,002	0,003	0,002	0,002	0,006	0,013	0,004	0,004	0,008
C	0,009	0,029	0,008	0,009	0,011	0,002	0,004	0,008	0,004	0,003	0,006	0,001	0,006	0,007	0,005	0,011	0,005	0,005	0,004	0,006	0,004	0,004
D	0,020	0,003	0,003	0,002	0,016	0,002	0,004	0,001	0,003	0,006	0,002	0,009	0,005	0,009	0,009	0,002	0,006	0,011	0,004	0,002	0,004	0,008
E	0,018	0,011	0,031	0,006	0,001	0,003	0,003	0,002	0,004	0,003	0,000	0,002	0,017	0,002	0,013	0,000	0,006	0,007	0,003	0,000	0,009	0,008
F	0,020	0,025	0,006	0,002	0,004	0,001	0,002	0,001	0,000	0,002	0,006	0,009	0,004	0,002	0,006	0,005	0,009	0,005	0,002	0,006	0,005	0,007
G	0,018	0,021	0,032	0,006	0,008	0,000	0,006	0,005	0,002	0,009	0,108	0,013	0,016	0,006	0,007	0,008	0,010	0,008	0,006	0,108	0,016	0,000
H	0,003	0,003	0,036	0,004	0,012	0,001	0,002	0,004	0,001	0,001	0,003	0,001	0,008	0,009	0,006	0,010	0,001	0,004	0,002	0,003	0,009	0,009
I	0,022	0,010	0,032	0,006	0,034	0,000	0,003	0,005	0,006	0,004	0,003	0,002	0,010	0,007	0,007	0,002	0,001	0,004	0,003	0,003	0,008	0,006
L	0,084	0,014	0,001	0,000	0,022	0,004	0,001	0,001	0,008	0,010	0,001	0,008	0,006	0,005	0,008	0,006	0,011	0,004	0,001	0,001	0,006	0,016
M	0,005	0,002	0,033	0,005	0,019	0,007	0,001	0,003	0,008	0,004	0,001	0,005	0,011	0,006	0,010	0,008	0,005	0,016	0,001	0,001	0,013	0,009
N	0,057	0,016	0,067	0,005	0,010	0,005	0,013	0,008	0,000	0,003	0,006	0,008	0,005	0,001	0,005	0,005	0,004	0,007	0,013	0,006	0,001	0,007

Table 7: Planarity values of the cast parallelepiped

A	0,185	0,035	0,234	0,241	0,284	0,209	0,210	0,211	0,238	0,241	0,254	0,267	0,271	0,260	0,242	0,265	0,282	0,313	0,316	0,384	0,035	0,282
B	0,120	0,186	0,240	0,204	0,301	0,205	0,230	0,183	0,185	0,141	0,117	0,154	0,160	0,175	0,224	0,189	0,152	0,111	0,168	0,149	0,186	0,152
C	0,214	0,484	0,348	0,270	0,360	0,253	0,195	0,214	0,251	0,273	0,236	0,252	0,249	0,237	0,234	0,207	0,270	0,282	0,240	0,347	0,484	0,270
D	0,233	0,286	0,266	0,193	0,256	0,191	0,170	0,186	0,184	0,235	0,193	0,226	0,250	0,258	0,232	0,247	0,221	0,288	0,277	0,386	0,286	0,221
E	0,276	0,301	0,448	0,232	0,357	0,230	0,203	0,202	0,237	0,250	0,298	0,256	0,274	0,233	0,247	0,237	0,277	0,317	0,305	0,332	0,301	0,277
F	0,301	0,347	0,533	0,251	0,330	0,294	0,271	0,282	0,237	0,233	0,271	0,292	0,315	0,290	0,316	0,272	0,343	0,378	0,355	0,356	0,347	0,343
G	0,347	0,300	0,238	0,208	0,177	0,200	0,193	0,187	0,222	0,215	0,241	0,262	0,256	0,246	0,203	0,250	0,234	0,294	0,285	0,472	0,300	0,234
H	0,267	0,174	0,377	0,210	0,215	0,213	0,170	0,203	0,222	0,228	0,208	0,244	0,247	0,250	0,230	0,247	0,250	0,294	0,258	0,302	0,174	0,250
I	0,206	0,301	0,268	0,206	0,318	0,250	0,228	0,226	0,206	0,267	0,254	0,293	0,277	0,275	0,279	0,239	0,301	0,307	0,279	0,277	0,301	0,301
L	0,264	0,364	0,034	0,206	0,205	0,178	0,215	0,195	0,198	0,226	0,231	0,259	0,267	0,266	0,227	0,252	0,218	0,280	0,254	0,367	0,364	0,218
M	0,321	0,342	0,364	0,198	0,243	0,228	0,212	0,222	0,256	0,262	0,166	0,247	0,299	0,237	0,262	0,252	0,257	0,299	0,296	0,334	0,342	0,257
N	0,411	0,395	0,435	0,267	0,315	0,243	0,219	0,202	0,293	0,268	0,223	0,257	0,289	0,262	0,268	0,282	0,254	0,338	0,299	0,333	0,395	0,254

Table 8: Parallelism values of the cast parallelepiped

5. Conclusions

Starting from the standard deviation analysis and from the regressive model it is possible to say that the most important variable for the dimension variation is surely the location of the master referred to the centre position. Looking at this variable it is in fact visible that varying this parameter the parallelepiped dimensions are increased of more than 1*[mm]*. The position of the imprints on the side of the disk improve the fill process thank to the presence of an higher centrifugal force entity. The runner diameter is surely less important even if its importance is strongly related with the location of the imprint on the disk. Even if the rotational speed should be maintained with an high value this oblige to increase the disk closing pressure causing, at some values, the disk deformation and consequently the cast object deformation. From this first experimental approach it is possible to say that some more experiments related with the imprints types, shape and volume, have to be run in order to investigate their influence on the mould design and process parameters setting. Considering the verified process parameters sensibility, for every casting project it would be very important to have a first feasibility study in order to reduce any error probability. This could be obtained with the help of simulation tools. Actually there is no commercial tool able to give this help, but it is possible to consider this experimentation as the necessary path or starting point to develop a structured process database for any numerical simulation tools learning.

6. References

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