VACUUM CASTING AS A RAPID MANUFACTURING AND PROTOTYPING OPTION

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Abstract

This article looks at the role that vacuum casting plays in the rapid prototyping and rapid manufacturing process. The accuracy to which components can be reproduced, by looking at the controllable factors in the casting process and the different types of materials that are available, were investigated and the process was also compared to other rapid prototyping and manufacturing processes in terms of cost effectiveness. Castings were made from a typical component under different operating conditions and the characteristics of the cast component, dimensions strength and surface hardness, were measured and plotted to determine the characteristics and accuracy of the process.

Key words: Vacuum Casting, Rapid Prototyping and Rapid Manufacturing.

1. INTRODUCTION

As a result of increased competition between manufacturers worldwide, different processes and techniques are investigated to make the manufacturing process more time- and cost efficient. The vacuum casting process is used world wide as a relative low cost rapid prototyping or rapid tooling and manufacturing option with a high degree of dimensional accuracy as far as the reproduced components are concerned.

2. PURPOSE OF INVESTIGATION

The purpose of the project was to evaluate the vacuum casting process in terms of:

- The cost efficiency of vacuum casting as a rapid manufacturing option with reference to the cost of casting materials and equipment.

- The type of components that can be reproduced as far as degree of complexity and size is concerned.

- The effect of the available different types of thermoset plastics and silicones on the dimensional accuracy, strength and surface finish (in the vacuum casting process).

- The accuracy that can be obtained in the reproduction process and the factors that influence the accuracy of the casting process.

3. CASTING MATERIAL

3.1 Vacuum grade thermoplastics

The material manufacturer Huntsman, has 9 Vacuum Grade Thermoset Plastics that are available on the South African market. All these vacuum grade polyurethanes have been specially formulated for the vacuum casting process. Processing of the plastics can only be done with the necessary application equipment. The components are degassed, mixed and cast into silicone moulds that have been preheated at a temperature range of between 30 - 70 ^{0}C. The compatibility of the polyurethane with the silicone needs to be checked. The compatibility between the silicone mould and the plastic can be checked by casting a small amount of the plastic over a piece of silicone to verify whether the plastic releases clearly from the silicone after it has vulcanized [3].

3.2 Coloring agents

Coloring agents are soluble or insoluble materials, that are used to obtain required colors within plastics. Soluble coloring agents are known as dyes and the insoluble ones as pigments. Normally pigments have a particle size of 0,01 to 1 µm. Pigments are furthermore classified as either organic or inorganic. Usually inorganic pigments have a high light and heat stability, and high opacity, but do not have a high tinting strength. Examples of inorganic pigments are:

White	:	Titanium dioxide, zinc oxide,
Yellow	:	Chrome yellow, nickel titanium yellow,
Red	:	Molybdenum red, red iron oxide,
Blue	:	Ultramarine blue, cobalt blue, manganese purple,
Green	:	Chrome green, cobalt green,
Brown	:	Brown iron oxide,
Black	:	Black iron oxide, carbon black.

Organic pigments have a high tinting strength and low opacity. For this reason an admixture of inorganic and organic pigments is quite often used for coloring [1],[2], [6], [8].

3.3 Typical mould material

All the experiments were conducted with M4640 silicone from Wacker which has following characteristics.

Description
A silicone rubber, that vulcanises at room temperature (RTV) after the addition of a pasty or liquid catalyst.

Key properties
A pourable transparent product

- Moderately hard
- High mechanical strength
- High resistance to polyurethanes and epoxy resins
- Linear shrinkage after 7 days : < 0,1 %
- Mixing ratio : 1 : 10 (by weight)
- Potlife at 23 ^{0}C & 50 % Relative Humidity (RH) : 90 min
- Demoulding time at 23 ^{0}C : 15h
- Demoulding time at 70 ^{0}C : 30h

Fig 3.1 A typical silicone mould.

4 EXPERIMENTAL WORK

4.1 Part chosen for the experiential work

To conduct the experiments on the material characteristics, a normal tensile test specimen, as shown in figure 4.1, was chosen because it can be used to determine the influence of the controllable factors on several dimensions of the specimen; the tensile strength can be measured accurately in the tensile test and the surface hardness can also be determined accurately. The figure below shows the critical dimensions on the specimen against which the cast components were compared.

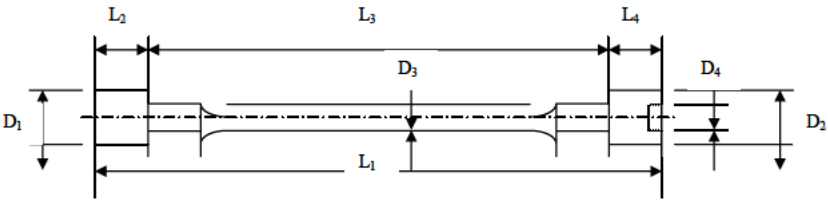

Fig 4.1 : Dimensions of specimen

A digital micrometer, able to measure to 10 µm, was used to measure the specimen. For each dimension, ten measurements were taken around the circumference of the specimen, as shown in the table 4.1. The same method was used to measure the cast components. The average value were calculated and used as the correct value for the dimension. The standard deviation gives an indication of how accurate the measurements are [5],[6],[7],[9].

Table 4.1: Measurements of Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

4.2 Casting of the PU specimens

Three similar silicone moulds were made from the steel specimen. During each casting, three PU specimen were cast. Ten measurements for each dimension were taken, and the average value for the three castings were taken as the correct value, to be compared to the dimensions of the steel specimen. Table 4.2 gives an example of how the measurements were taken, and the average value calculated.

4.3 Layout of the experiential work

During the casting process three temperatures can be varied to obtain different results in the cast component. That is the mould temperature (the temperature to which the silicone mould is preheated before the cast is made), the curing temperature (the temperature at which the cast component is cured inside the mould) and the resin temperature (the temperature at which the resin is stored). One of the purposes of this project was to determine what influence each of these temperatures would have on the physical characteristics of the cast component. Silicone moulds are normally preheated at temperatures ranging from 30 to 70 ^{o}C. A decision was made to preheat the silicone mould to 30, 50 and 70 ^{o}C for the evaluation. The preheating temperatures were limited to three to limit the amount of castings necessary to make any significant conclusions. The curing temperatures were taken the same as the preheating temperatures.

The resin temperature was kept at 30 ^{0}C, because the resin is normally stored at 30 ^{o}C to avoid crystallization. During the degassing of the resin in the vacuum chamber, the surrounding temperature drops considerably inside because there is a constant volume of which the pressure is reduced from 1 Atm to 5 mBar. It would therefore be difficult to keep the resin at an elevated temperature during degassing.

Table 4.2: Measurements on a typical PU specimen

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	**1**	170.00	15.85	139.23	15.46	28.60	28 89	9.43	3 36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3 31
	3	170.50	16.06	138.76	15.58	28.28	28 55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3 24
	5	170.55	16.00	138.79	15.68	28.65	28 88	9.55	3 23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3 36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3 34
	8	170.10	15.97	139.02	15.48	28.36	28 57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3 23
	10	170.50	15.93	139.34	15.57	28.42	28 89	9.43	3 25
Cast2	**1**	171.00	16.26	139.97	15.57	28.70	28 58	9.50	3 35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3 36
	3	171.00	16.26	139.75	15.71	28.56	28 84	9.61	3 32
	4	171.10	16.04	139.67	15.56	28.62	28 97	9.60	3 28
	5	171.40	15.97	139.72	15.65	28.70	28 99	9.56	3 35
	6	171.20	16.10	139.99	15.63	28.67	28 84	9.53	3 37
	7	171.00	16.09	139.96	15.72	28.59	28 56	9.60	3 36
	8	171.10	16.13	139.92	15.56	28.49	28 84	9.58	3 37
	9	171.00	16.09	139.85	15.61	28.59	28 92	9.52	3 37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	**1**	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3 39
	3	170.50	15.70	139.82	15.53	28.37	28 94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3 37
	5	170.60	15.75	139.70	15.44	28.70	28 88	9.59	3 37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3 38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3 39
	9	170.50	15.76	139.72	15.54	28.68	28 93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3 38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3 34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0 08

The normal processing temperature for resin is 30 ^{o}C and it was therefore decided to keep the resin at that temperature and determine the influence of the mould temperature on the cast components. The castings were made in a matrix as shown in the Table 4.3

Table 4.3: Layout of experimental work.

Experiment	Mould Temperature °C	Curing Temperature °C	Resin Temperature °C
1.1	30	30	30
	30	50	30
	30	70	30
1.2	50	30	30
	50	50	30
	50	70	30
1.3	70	30	30
	70	50	30
	70	70	30
2.1	30	30	30
	50	30	30
	70	30	30
2.2	30	50	30
	50	50	30
	70	50	30
2.3	30	70	30
	50	70	30
	70	70	30

5. EVALUATION OF EXPERIMENTAL WORK

5.1 Summary

Each of the following subsections gives a short description of the conditions under which each casting was made as well a summary of the conclusion that can be made from the results obtained.

5.2 Experiment 1.1: Altered curing temperature, mould temperature at 30 °C

During this experiment, the mould was preheated to 30 °C, the resin kept at 30 °C and the curing temperature varied from 30 to 50 to 70 °C. At least two hours were allowed for curing the part inside the mould. The graph, as presented figure 5.1, gives an indication of how the dimension L_1 has changed with a change in curing temperature. The dimension has changed from 171,25 to 171,50 mm, with an increase in the curing temperature, while the shrinkage has decreased from 0,8 % to 0,4 %.

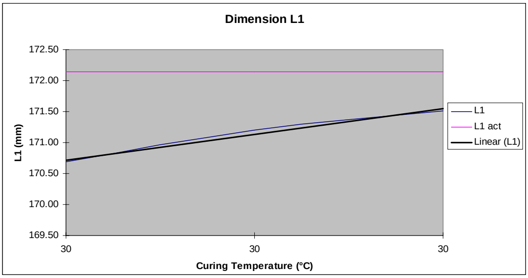

Fig. 5.1: Change in dimension L_1.

Most dimensions showed a change in shrinkage ranging from 0,2 to 0,6%, with some increases and some decreases. It is interesting to note that all the length's showed an increase in shrinkage and all the diameters showed a decrease in shrinkage. The biggest change in dimension was in dimensions L_3 and L_1. One would expect the change in L_3 to be reflected in L_1, because L_3 is part of L_1. Because L_3 is a long thin section, one would expect it to reflect the biggest change. The change in shrinkage of dimension L_1 is presented in the figure 5.2.

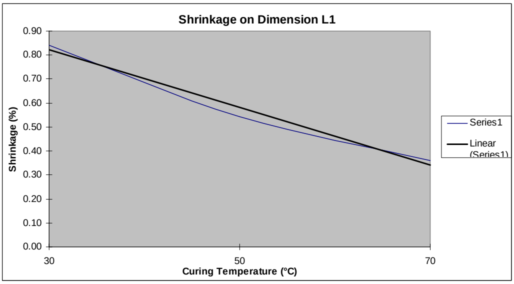

Fig. 5.2: Change in the shrinkage of dimension L_1.

From the data obtained in this experiment it is clear that the change in curing temperature did not have a clear noticeable change in the dimensions of the cast component.

The results from the tensile test are presented in the figure 5.3. The material showed some increase in strength when cured at 70 ^{0}C.

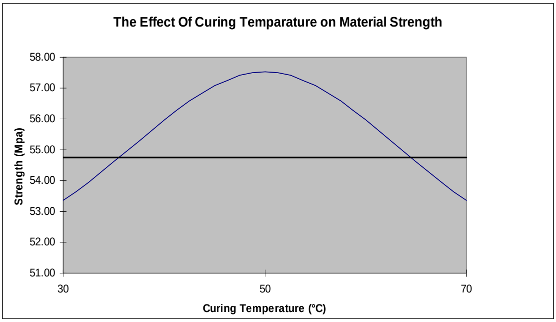

Fig. 5.3: Change in strength of component.

The change in the surface hardness is presented in the figure 5.4. The last measurement showed a decline in the surface hardness of the component.

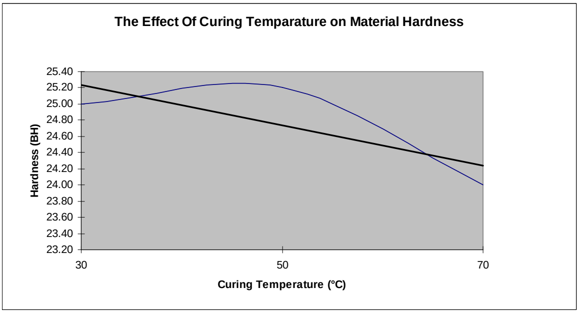

Fig. 5.4: Change in the surface hardness of the component.

5.3 Experiment 1.2: Altered curing temperature, mould temperature at 50 ^{0}C.

During this experiment the mould was preheated to 50 ^{0}C, the resin kept at 30 ^{0}C and the curing temperature varied from 30 to 50 to 70 ^{0}C.

Once again it is interesting to note that all the length's shows an increase with an increase in curing temperature and all the diameters shows a decrease with an increase in curing temperature. All the length's moved closer to the required dimension (0 % shrinkage) and the diameters moved further away from the required dimensions. On the length's the shrinkage decreased in the order of 0,5% and on the diameters the shrinkage increased from 0,2 to 0,3%. The material strength decreased constantly with an increase in curing temperature while the surface hardness increased.

5.4 Experiment 1.3: Altered curing temperature, mould temperature at 70 ^{0}C.

During this experiment the mould was preheated to 70 ^{0}C, the resin kept at 30 ^{0}C and the curing temperature varied from 30 to 50 to 70 ^{0}C.

The shrinkage of dimensions L_1 to L_4 showed similar changes, with a slight increase at a curing temperature of 50 ^{0}C and a decrease again at a curing temperature of 70 ^{0}C. The shrinkage of the diameters showed constant increases with an increase in the curing temperature.

The material strength shows a decrease from 66 Mpa to 62 Mpa with an increase in the curing temperature, while the surface hardness stays fairly constant at approximately 24 to 25 BH.

5.5 Experiment 2.1: Altered mould temperature, mould and resin temperature at 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin and the curing temperature kept at 30 ^{0}C.

All the length's showed a slight increase in value while some of the diameters showed an increase and some showed a decrease. The shrinkage in the length's decreased from 0,3 to 0,7 %, while that of the diameters varied with 0,2 %, some positive and some negative. It can clearly be seen from all the dimensions that the shrinkage stayed constant with a mould temperature increase from 30 to 50 ^{0}C, but started to vary when the mould temperature was increased above 50 ^{0}C. For most dimensions the variation was positive since the shrinkage decreased.

5.6 Experiment 2.2: Altered mould temperature, curing at 50 ^{0}C and resin temperature at 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin temperature kept at 30 ^{0}C and the curing temperature kept at 50 ^{0}C. Dimension L_1 decreased with an increase in the mould temperature, while dimensions L_2, L_3 and L_4 increased. This seems impossible because $L_1 = L_2 + L_3 + L_4$. The values used for these dimensions are the combined average for three specimen, where ten readings were taken per specimen. If one compares the dimensions taken from three specimen, as presented in table 6.1 and compare that with the measurements taken from the original specimen, as presented in table 6.2, it can be seen that the deviation in values are much bigger in the cast component than it is in the original machined steel specimen. For such a deviation in the dimensions of the cast component, it is clear that the accuracy of the dimension on the cast component cannot be measured to two decimal places [5],[6],[7]. In general the shrinkage of the length's decrease with an increase in the mould temperature while the shrinkage of the diameters increased.

The material strength increased from 54 MPa to 60 MPa with the increase in mould temperature, while the surface hardness varied little from 24 to 25 BH.

5.7 Experiment 2.3: Altered mould temperature, curing at 70 ^{0}C and resin temperature at 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin temperature kept at 30 ^{0}C and the curing temperature kept at 70 ^{0}C. No clear trend in the change of the dimensions was seen from this experiment. The shrinkage of some of the dimensions increased while others decreased. The material strength decreased from 64 to 61 MPa, while the surface hardness stayed constant at 25 to 26 BH.

6. CONCLUSION

During this research project a vacuum casting machine was constructed in order to evaluate the vacuum casting process in terms of the conditions as set out in section 2. The sections that follows presents a summarized conclusion on all those elements.

6.1 The cost efficiency of vacuum casting

Vacuum casting is a relative expensive rapid manufacturing option if compared to gravity and RIM casting. The resins that are used for vacuum casting ranges from R 400 to R450 per kilogram at the time the experiments were conducted, while those for gravity and RIM casting were in the order of R 80 per kilogram. At the time the experiments were conducted a small vacuum casting facility (able to handle 1000cc of plastic in a casting chamber of 450 * 450 *350 mm high) ranged from R 200k for a manually operated machine to R 300k for an automatically operated machine. A RIM casting machine cost approximately R 80k at that stage. It can thus be concluded that vacuum casting is one of the more expensive rapid manufacturing options however, less expensive than RP, and should only be applied if the specific characteristics that can be obtained with the process are required [9].

6.2 The type of components that can be reproduced

Vacuum casting can reproduce components in a range of vacuum grade plastics as well as melted wax (an add-on to the machine). The size of components that can be reproduced is limited by the size of the casting chamber. The wall thickness is limited by specific material specifications. Shrinkage up to 0,1 % is obtainable by varying the factors that control the casting process, eg. the mould temperature, the curing temperature etc. To achieve complete mould filling with different types of plastics is an trial and error process by playing around with the controllable factors. Components with undercuts can be reproduced as long as they can be released from the flexible silicone mould, or by splitting the mould into more than two sections.

6.3 Different types of plastics and silicones available

A very wide range of silicones and plastics are available from different manufacturers. New materials especially developed for vacuum casting as well as those not specifically developed for vacuum casting, appear on the market quite often. The availability of those materials on the South African market is a problem because of the limited shelf life of the products and the volumes that are being sold. At this stage all vacuum grade plastics are imported on request only. If the materials are urgently needed they are flown into the country which makes them more expensive.

6.4 The accuracy that can be obtained

Vacuum casting is quite an accurate casting process but still a casting process. A lot of factors influence the casting process, like the controllable factors (the mould temperature, the curing temperature, the resin temperature, the hardness of the silicone mould, the ultimate vacuum and the mixing time allowed), as well as the uncontrollable factors (the ambient temperature, the relative humidity, and the viscosity of the mixed thermoset plastics). The silicone that was used in the experiments had a relative low shore hardness, resulting in clear parting lines being created on the cast component which in return influenced the average dimension that could be determined. At the stage at which the experiments were conducted that was the only silicone available. Silicones with a higher shore hardness appeared on the market later and would certainly have made a difference to the results that were obtained. The experiments that were conducted showed that no clear pattern in the dimensional accuracy could be observed. Certain dimensions increased while others decreased when a specific operating condition was altered. The material strength and surface hardness stayed fairly constant with a change in operating conditions.

It can be concluded that vacuum casting is a relative accurate rapid manufacturing option, which sometimes requires a lot of trial and error to create a part that can resemble the original part as close as possible in a range of plastics and wax. Shrinkage in the order of 0,1% is quite obtainable. If compared to other RP and RM technologies, vacuum casting is more expensive than RIM casting but less expensive than the SLS process.

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