I. Introduction of Vacuum Casting

Vacuum casting is currently one of the most popular and flexible forms of rapid tooling for consumer products. It allows the possibility of harnessing the potential of silicone rubber moulds in the batch production, providing cheaper tools and materials. A wide range of resins (wax, plastic, metals) can be cast due to the high chemical resistance of silicone rubber and low interfacial energy of its surface. [1]

The part chosen to be produced by vacuum casting technology is a chess part and is presented in the figure below. The material for the parts is a resin SG95.

Fig. 1.1

The silicon rubber used for these moulds is very advantageous for this technology. It can be easily poured around the master model to obtain a cavity.

These silicon moulds can be used to produce up to 20-40 plastic parts.

The process has a wide range of use from technical industry to the medical system. In the article below it is presented the use of vacuum casting technology for making a biomedical implant.

In the figure below it is presented the 3D part for which the study has been made.

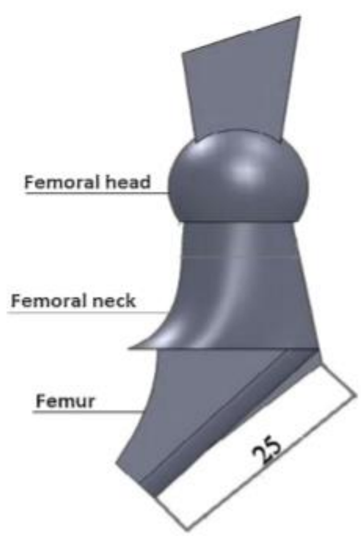

Fig. 1.2.

The hip joint is basically a ball-and-socket joint. During the hip replacement surgery, the damaged hip join is replaced with metal, plastic or ceramic components. The CAD model of the component was made using Solidworks and then converted into .STL file. The master pattern of the hip joint has been produced by FDM (fused deposition modeling) followed by CVS process to enhance the surface finish. After that, multiple replicas from wax were manufactured by vacuum casting. The wax models were then assembled under the form of a tree for producing the metal parts using the vacuum casting technology.

Studies were made on the resulted metal part regarding the surface roughness and the dimensional accuracy. [2]

Fig. 1.3.

In order to prove that very fine geometrical details of the master pattern can be faithfully reproduced in the micro-mould cavities [8] via vacuum casting, in the next article the authors attempt to create both ten micro-moulds and cast micro-gears with the use of an SU8 master pattern.

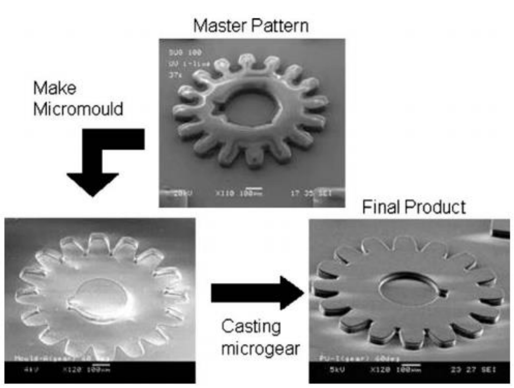

Fig. 1.4.

Micro-moulds are generally produced by lithography methods that often use glass and silicon wafer as substrates, with the exception of the Lithographie Galvanoformung Abformung (LIGA) method, which uses metal substrate. These fabricated moulds are then integrated into the injection moulding machine for mass production. This paper presents the use of vacuum casting methods to produce micromoulds instead of lithography. Silicone rubber is used as the mould material, which is capable of achieving nanometre surface finish. The master pattern of 1-mm diameter micro-gear of 60-μm teeth width and 38-μm thickness was created by standard ultraviolet (UV) lithography using SU8 photoresist. Using the vacuum casting method, ten polyurethane micro-gear specimens of 1-mm diameter and 38-μm thickness using the silicone rubber micro-moulds have been successfully cast under vacuum conditions as a demonstration. Measurement from white-light interferometry (WLI) showed that all of the micro-gear cavities in the micro-moulds were dimensionally accurate and consistent to the master micro-gear, proving that its repeatability is possible.

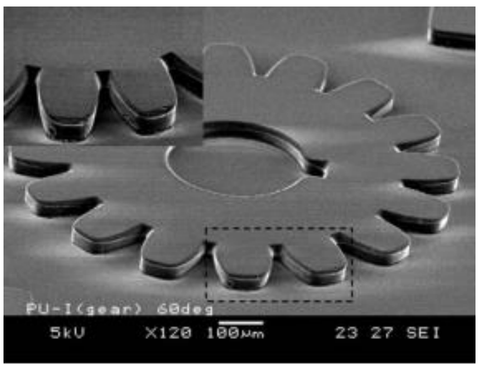

Fig. 1.5.

To evaluate the feasibility of vacuum casting for both micromould and microparts replication, ten silicone rubber micromoulds and ten PU microgears were cast. All were imaged by SEM and measured by WLI for dimensional accuracy and consistency. A set of measurements is defined to describe the microgear and the micromould cavity, the gear diameter, hub diameter and gear height for the microgear. A similar set of definitions is used for the micromould cavity.

Table 1 shows a set of measurements for each micromould specimen (A to J) measured by WLI. It also shows that the standard deviation calculated for accuracy and consistency among the ten specimens is less than 1%, while the maximum and minimum standard deviation between the master pattern and micromould is 1.92% and 0.31%, respectively.

Microgear specimen	Outer diameter (μm)	Hub diameter (μm)	Gear height (μm)	Surface roughness (nm)
A	1,013.7	330.6	38.26	14.54
B	1,012.8	330.8	39.07	18.30
C	1,013.7	330.4	39.33	17.75
D	1,013.1	331.4	38.82	16.29
E	1,011.7	331.8	38.75	11.60
F	1,012.9	331.8	39.29	14.58
G	1,013.8	331.3	39.36	14.59
H	1,013.2	331.5	39.04	8.69
I	1,013.3	331.1	39.29	17.64
J	1,013.9	331.1	39.16	10.03
Average for ten microgears	1,013.2	331.2	39.04	14.40
Average for master pattern	1,012.9	333.4	38.46	9.49
Standard deviation among ten microgear specimens (%)	0.03	0.66	1.51	51.7
Standard deviation between master and microgear specimens (%)	0.660	0.489	0.344	3.337

Fig. 1.6.

The authors have successfully demonstrated the use of the vacuum casting technique in fabricating both micromoulds and microgears of 38-μm thickness and 1-mm diameter. The small deviations between the master pattern and its ten specimens (both micromould cavities and cast microgears) have proven that the proposed method is capable of consistently producing microparts that are dimensionally accurate with respect to the master pattern. In addition, this technique is much faster and cheaper than many existing micromoulding techniques. The authors believe that this technique is suitable for casting real 3D microparts (since the mould is flexible) and the simplicity of this technique would encourage more researchers to use this technique to create microparts.[1]

II. The equipment

A vacuum casting machine has two chamber : the mixing chamber (where the resins are mixed together) and the vacuum chamber. The working parameters are controlled from the electronic panel.

The machines presented in this paper are produced by Renishaw. Renishaw vacuum casting systems can be easily configured to produce parts in polyurethane resins, investment casting wax, filled nylon or soft feel materials, including silicone rubber. This is done simply by exchanging modules on the system.

System configuration options at a glance:

• Vacuum casting module – for plastic prototypes and low volume production in vacuum casting polyurethane resins

• Nylon casting module – for prototypes and production parts in nylon and filled nylon

• Heated cup for wax masters – to create wax master models for investment casting and low melting point alloys for carbon fibre lay-up

• Vario Vac – for prototypes in silicone rubber and highly filled viscous materials

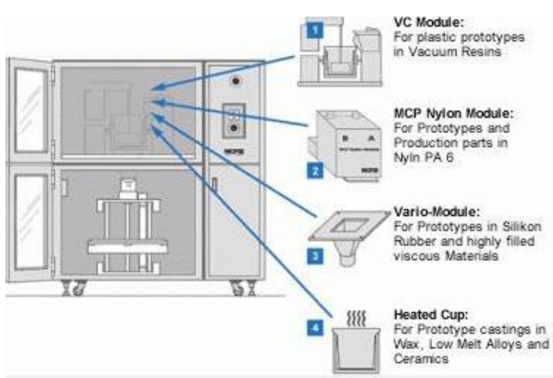

Fig. 2.1.

Renishaw is a leading manufacturer of vacuum casting systems. We provide a full solution for vacuum casting with a range of systems, from manual to high capacity computer automated, for the economic production of short run, end use parts and prototypes.

Vacuum casting system features at a glance:

• Mixing capacities up to 10 L (610 cu/in)

• Controls – PLC touch screen and manual options available

• Mixing and pouring – automatic and semi-automatic options available

• Systems are designed and built in-house, by Renishaw expert engineers with over 25 years of experience in the vacuum casting industry

For plastic vacuum casting, Renishaw has in it’s offer three different machines:

5/01 PLC vacuum casting machine

Fig. 2.2.

Features and benefits

Moulds up to 520 mm × 445 mm × 425 mm.
Small footprint bench-top machine - ideal for small workshops.
Vario Vac differential chamber pressure - suitable for soft-feel materials.
PLC control and automation - ensures consistent casting.
Heated cup - suitable for casting high quality wax masters.

About

The 5/01 PLC is capable of casting the full range of Renishaw polyurethane resins. The system also benefits from Renishaw Vario Vac technology that allows highly viscous materials, such as silicone rubber, to be cast efficiently by applying differential pressure to rapidly force material into the mould.

The 5/01 is smallest PLC* controlled Renishaw vacuum casting system in the range, and benefits from all the process control and user interface features available on the larger 5/04 and 5/06 machines.

*Programmable Logic Controller

VC module

The standard module for production of plastic prototypes and low volume production in vacuum casting polyurethane resins.

Vario Vac module option

Choose between our standard PLC system or the vario vac model, for production of prototypes in silicone rubber and highly filled viscous materials.

Heated cup option

Enables production of wax master models for the investment casting, and low melting point alloys.

5/01 ULC vacuum casting machine

Fig.2.3

Features and benefits

- Mould sizes up to 520 mm × 420 mm × 425 mm
- Small footprint bench top machine - ideal for small workshops
- Manual pouring - minimal maintenance
- Push button operation - simple interface

About

The Renishaw 5/01 ULC is designed as an entry level vacuum casting solution and is particularly well suited to small businesses and educational establishments.

By keeping the control system simple and employing manual control for the resin pouring within the chamber, the 5/01 ULC is incredibly user friendly.

VC module

For plastic prototypes and low volume production in vacuum casting polyurethane resins.

Heated cup option

For creating wax master models for the investment casting process and low melting alloys.

5/04 PLC vacuum casting machine

Features and benefits

- Mould sizes up to 550 mm × 800 mm × 600 mm.
- Nylon Plus casting module - high performance glass or fibre filled polymer.
- Vario Vac differential chamber pressure - suitable for soft-feel materials.
- PLC control and automation - ensures consistent casting.
- Heated cup - suitable for casting high quality wax masters and low melt alloy.
- Dual robot option - for increased casting capacity.

Fig. 2.4.

About

Renishaw's 5/04 vacuum casting system has a casting capacity of up to 5.5 litres.

The system boasts Vario Vac differential pressure casting and comes with the option of a heated cup module.

In addition, the 5/04 benefits from the option of chamber extension, and has been designed to accommodate the Renishaw Nylon Plus casting module for nylon vacuum casting.

VC module

The standard module for plastic prototypes and low volume production in vacuum casting polyurethane resins.

Nylon Plus module option

For prototypes and production parts in nylon and glass filled nylon.

Vario Vac module

Choose between our standard PLC system or the vario vac model, for production of prototypes in silicone rubber and highly filled viscous materials.

Heated cup option

Enables production of wax master models for the investment casting, and low melting point alloys.

Twin robot option

Increases casting capacity from 2.2 L to 5.5 L. [3]

III. Working principle of vacuum casting

Making of prototypes in silicon moulds by Vacuum Casting (VC) is counted among indirect Rapid Tooling (RT) techniques . In that method the silicon mold or matrix is produced on the basis of base models and reflects the prototype geometry through a negative. The base model may be produced with Rapid Prototyping techniques.

The silicon mold is a tool that serves for producing elements of plastics (polyester resins, epoxy polyurethanes) and plastic composites, including nano-composites. Molds made of silicones that have higher resistance to high temperatures may serve for producing single castings of nonferrous metals. Silicon may also be utilized for producing matrices for wax patterns for precision casting. [4]

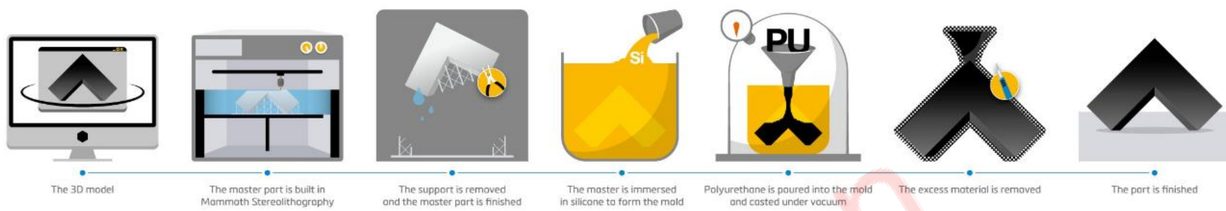

Fig. 3.1.

The vacuum casting process

How does the vacuum casting process work?

1. The master is designed from a three dimensional model (.stl file) and 3D printed. Alternatively a master object can be used is replication is desired.

Fig. 3.2.

2. The master 3D printed model is encased in liquid silicone rubber, and a vacuum is used to remove all remaining air.

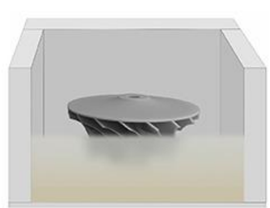

Fig. 3.3

3. The mould is cured in an oven, then cut away from the master.

Fig. 3.4.

4. The Mould is reassembled creating the mould cavity, and holes are made for injecting the resin.

Fig. 3.5.

5. Mould is placed in the bottom compartment of the vacuum casting machine.

Fig. 3.6.

6. Polyurethane consisting of two components A+B casting resins are mixed in top compartment.

Fig. 3.7.

7. After the casting phase the mould is placed in a curing oven to cure.

Fig. 3.8.

8. Post curing the finished part is removed from the mould, which can then be re-used for the next production cycle.

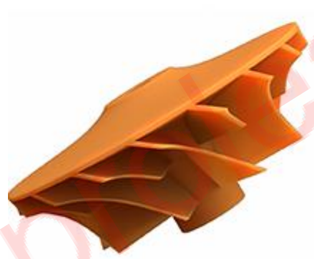

Fig. 3.9. [5]

IV. Vacuum casting working parameters

One of the principal parameter influencing the vacuum casting process is the pressure used.

Vacuum casting technology is a method used in vacuum environment to make the mixed material vacuumed, mixed, bubble-eliminated, then pour the mixed material into the mold cavity, and form a mold eventually. The traditional vacuum casting process depends only on the gravity of the material to cast. In the casting process of the parts especially with a thin wall, complex and large pieces and other characteristics, because of not regulating and controlling casting pressure, so the filling pressure and the filling speed are too low only relying on gravity casting, resulting in material flow-poor and easily giving rise to phenomenon such as insufficient injection or shrink marks (fig. 3.1.a and 3.1.b.).

Fig. 3.1.a Insufficient filling

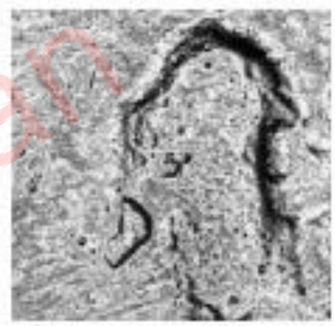

Fig. 3.1.b. Shrink marks

Differential pressure vacuum casting technology is developed base on the traditional vacuum pouring process. In the casting process, make mixing chamber and pouring chamber from a certain differential pressure, and then the mixed material fast fills into the mold cavity fully under the common action of both weight and pressure difference. To some extent, differential pressure vacuum casting avoids the effect of parts with thin wall, complex and large pieces in the casting process caused by insufficient filling, making the casting with high density.

However, differential vacuum casting is a dynamic process with the parameters changing constantly. During the compression process, the air is so difficult to control that the differential pressure between mixing chamber and casting chamber is not constant. If differential pressure is too small, casting easily gives rise to defects such as insufficient injection and shrink-marks (fig. 3.1.a and fig. 3.1.b). If the differential pressure is too great, casting easily gives rise to defects such as spilling and air pocket (fig. 3.2.a and fig. 3.2.b).

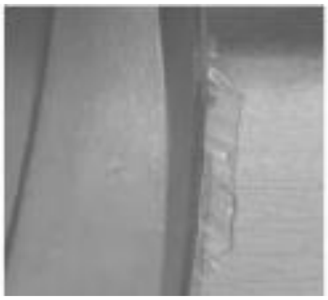

Fig. 3.2.a Spilling

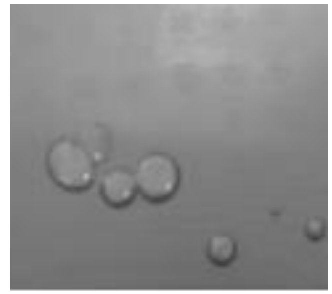

Fig. 3.2.b Air pocket

Another important parameter influencing the process is the pressure time. That is after the separation between mixing chamber and casting chamber because of casting material pouring into funnel, and from the time when gas fills into mixing chamber to the time when a specific differential pressure is formed between mixing chamber and casting chamber.

In the process of differential pressure vacuum casting, the speed of liquid dropping down the funnel and the speed of the mixed material filling into mold cavity are determined by the speed of the gas pressure without considering the action of gravity. The faster the pressurized gas is, the faster the speed of filling is. In the process of differential pressure vacuum casting, the pressure speed should be selected according to casting system design, structure cavity, casting temperature, mold wall thickness, casting cooling velocity, material composition and other specific conditions.

The longer the pressure time is, the smaller the corresponding pressure speed and the filling speed are; conversely, the pressure speed and the filling speed are greater. During the casting and filling process, reasonably controlling the pressure time can control the pressure speed and the filling speed. [6]

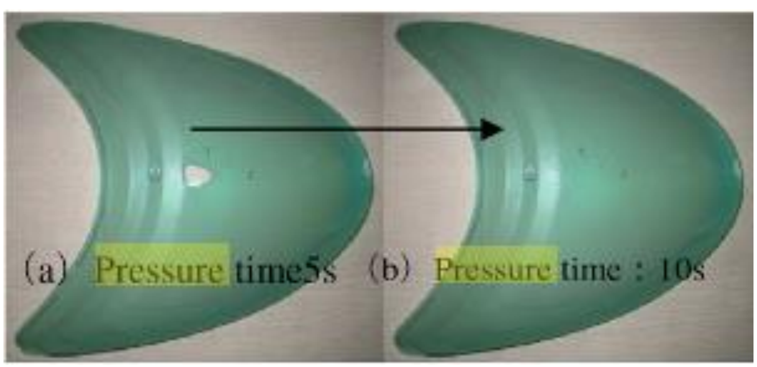

Fig. 3.3 Casting corresponding to differential pressure time

V. Process Efficiency

In the early stages of design when we expect things to change we are looking to produce minimum quantities. An effective prototype will highlight errors or prompt alternative solutions. However, as we progress into the project, the demands grow; quantities start to rise and the methods we use to produce parts have serious cost implications.

Fig. 5.1

When looking at the options for producing a batch of parts, the first decision point relates to aesthetics. If these are important then we can immediately dismiss the direct RP processes as they all involve layers and an associated need to refinish, dress and paint. Whilst technically feasible the costs are non competitive. If aesthetics are important then the contenders are vacuum casting or injection moulding, where process colouring and texturing are conferred by the tooling.

Fig. 5.2

Vacuum casting offers a lower front end cost with a higher unit price, whilst injection moulding demands a higher front end cost, but a significantly lower unit price. Production rates are also significantly different - vacuum casting allows a drip feed of parts whereas injection moulding usually has a longer wait with a fast finish.

Vacuum casting tooling will last between 10 and 25 parts (or lifts) depending upon the geometry of the part and the material being used. After this if the tool hasn't been configured as a multi-cavity tool at the outset it will need replacing. The part unit price remains constant during this time, but the replacement tool will require a second master, costing the same as the first tool, unless you use an early casting or a duplicate master. By comparison, injection moulding costs come from the tooling, the set up on the moulding machine (per batch) and the part price - a combination of material cost and moulding time.

Vacuum casting and injection molding are two of the most popular methods used to process plastics in the rapid prototyping industry. We thought that we would share a brief overview of both manufacturing processes as well as the advantages and disadvantages of both. [7]

What is Vacuum Casting?

Simply put, vacuum casting is a casting process for elastomers using a vacuum to draw the liquid material into the mold. This process is used when air entrapment is a problem, there are intricate details or undercuts, or if the material is fiber or wire reinforced.

What is Injection Molding?

Injection molding is a far more complex manufacturing technique than vacuum casting and requires a good deal of engineering. The process of injection molding begins with either pellets or granules of polymer which are placed in a hopper and then dropped into a barrel. A screw pushes the material into a heater where it melts. Next, the liquid polymer is injected into a steel or aluminum split die through a gate being held in a press under extreme high pressure. After cooling, the die opens and pins eject the finished parts.

A great amount of engineering time and cost is required to fabricate the parts and dies used in injection molding, making vacuum casting the preferred process for many applications where time-to-market and low cost is critical. Still, each method has its own distinct merits and also unique drawbacks.

Fig. 5.3.

Pros of Vacuum Casting

- Ability to create large parts (up to 48” x 96”)
- Relatively fast prototyping and production time frames, sometimes as quickly as 4 weeks
- Lower start up costs — patterns and molds can be made inexpensively from MDF, high density foams and epoxy

- Ideal for repeat jobs — aluminum castings can be made which have virtually unlimited lifetimes
- Good price point on small and medium runs

Cons of Vacuum Casting

- Intricacy of parts is limited — additional details can be added with pressure forming
- Some clear parts will exhibit “mark-off” (i.e., defects or dirt from mold will transfer to parts)
- Consistent wall thickness is not possible — very deep parts can be problematic
- Higher per-piece costs make vacuum forming non-competitive with other automated processes where quantities are larger
- Only one material can be formed at a time
- Finishing costs can be costly and labor intensive

Pros of Injection Molding

- Allows for high production output rates
- Can use inserts within the mold and fillers for added strength
- Close tolerances on small intricate parts are possible
- More than one material can be used at the same time when utilizing co-injection molding
- Typically requires very little post-production work — ejected parts usually have a very finished look
- Very little waste – all scrap can be reground to be reused
- Full automation is possible
- Lower cost-per-part compared to vacuum forming

Cons of Injection Molding

- Extremely high start-up costs
- Requires a great deal of engineering time
- Long time frames necessary to fabricate tooling, making time-to-market a major drawback [8]

VI. Conclusions

Silicone molding results in high-quality parts comparable to injection-molded components. This makes vacuum casted models especially suitable for fit and function testing, marketing purposes or a series of final parts in limited quantities.

Vacuum Casting also lends itself well to a variety of finishing degrees.

The process can be successfully used for prototypes but also for end production of parts in a low volume production reducing costs and manufacturing time.

The wide range of machines also allows the production of a wide range of dimensions.

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