SLIP CASTING AS A RAPID TOOLING PROCESS

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ABSTRACT

The paper discusses the slip casting of stainless steel as a method of forming injection moulding tooling. Main steps involved in the precision slip casting of stainless steel and the effects of major parameters such as casting rate have on accuracy are fully discussed. The slip casting process has numerous technical advantages over conventional and rapid tooling processes especially there is strong potential for producing mass production tooling.

INTRODUCTION

The slip casting process has been used for hundreds of years in the ceramic industry for the production of products such as tea pots and toilets. The basic process of slip casting involves the suspension of a powder material in a solution. The powder and solution mixture (slip) is then cast into a porous mould which removes the solution from the powder by capillary action. This then leaves the powder in the form of the mould. This powder part (green part) can then be removed from the mould and then fired in an oven in order to give it strength. The objective of this investigation is to study the possibility of forming injection moulding tools via this method. So raising the concerns of dimensional accuracy, surface finish, and the mechanical / thermal properties of the resulting tool, these are the main factors investigated

The principal reason for undertaking this investigation, was due to the growing industrial demand for low cost tooling, which can be produced in a greatly reduced lead time, to that of conventional tooling methods. The current market for moulds and dies in the USA is about 20 billion dollars [1]. The lead time for the delivery of a injection mould, in the USA ranges from 1200 to 3800 hours [2], depending on the complexity and the size of the mould. For these two reasons there is great interest in the variety of rapid tooling methods that are evolving . This is also the rational for investigating the slip casting method as a potential route to the production of tooling.

The perceived reasons why slip casting has some competitive advantages over conventional and Free Form Fabrication (FFF) tooling methods are:

- The method of production is both suited to that of one-off production and mass production, thus allowing flexibility.
- The process costs are extremely low with very little material wastage and little manual intervention.
- The process is a relatively low skilled in most aspects of the process cycle, this is very different to that of conventional tool making.
- The forming of the porous moulds can be done in a number of ways, such as casting from a FFF model, machining of the mould from a solid block and additionally the material can be carved / sculpted.

- The process has the potential to cross over into other tooling areas such as EDM electrode formation, die casting tools, press tools and possibly, punch tools.
- The process will possibly allow the production of complex composite tools i.e. A tool can be formed with a very hard surface material and a softer backing material, which could be used for either cost or thermal considerations.
- The process has the ability, to allow the production of designer cooling systems [3]. This is where cooling channels for the injection moulding tool, can be designed for that specific cavity and core. The main advantage being that the cooling system will be optimised because of freedom from geometrical constraints imposed by conventional methods.
- The advantages of this process over that of direct tool production on one of the current FFF systems, is that the users are restricted to those systems and their system accuracy. Also, if the tool is produced directly on the FFF machine then, the stair case effect has to be removed from the tool, in what could be a very hard material.
- The process offers greatly reduced lead times to that of the conventional tooling methods, which can be up to 6 months [4]. It is estimated, that tools produced via this routes should take under two weeks to produce, for a given pattern.
- It is also possible that the process will be useful for the production of other products apart from tooling e.g. filters, gears, injection moulding machines reciprocating screws and in general low volume wear resistant parts.

As is apparent from the above points, there are a lot of possible applications of this process, giving advantages over both conventional and FFF injection moulding tool forming methods The main reasons for the investigation into this process is the speed, cost and the range of unconventional tooling materials that the process will possibly allow to be formed via this route.

THE PROCESS

The work carried out into the process of casting Stainless steel was an extension of the work started by Lidaman [5] and then later by Hausner [6]. The basic process route of slip casting is illustrated in figure 1. The steps involved in the in the production of a slip cast part are as follows:

1. Casting of the porous mould on the FFF model. It is important that the FFF model is treated in order to ensure that the model is released from the mould and that bubbles do not form on the surface of the mould.
2. Mixing of the powder and the solution. It is important the two parts are completely mixed and the powder is distributed evenly thought out the solution.
3. Once the two parts are mixed properly, the solution can then be poured into the porous plaster mould. It is important to insure that bubbles are removed from the mixture.
4. Once cast, the part is left to dry in the mould until all the solution is removed from the powder.
5. The part can then be extracted from the mould and any casting features can be removed at this stage. It is important that the part is not removed from the mould unless it is completely dry, as there is some indication that the part can be distorted by the handling of a powder part, if not in the dry state.

6. The part is then place in a oven and fired until the desired density is achieved.
7. Once fired the part is then infiltrated with a lower melting point material, in order to give the part a full density.

After infiltration, the part can be polished for the mounting onto the mould base.

ACHIEVING ACCURATE HIGH QUALITY SLIP CASTINGS

There is an obvious need to produce castings that are accurate, but it is also desirable to have the castings with as high quality possible. The quality is measured in terms of the following criteria:

- Surface reproduction.
- Density. This should be as close to theoretical as possible, i.e. 74 % of solid density for mono sized particles and 79% for bimodal particles sizes [7].
- Particle size distribution. This should be uniform through out the sample.
- Gas entrapment. This should be minimised within the sample.
- The slip should completely fill the mould, which allows complete shape and feature reproduction.
- The part should have a green strength that will allow part processing.

Hausner [6] identified that the basic variables of the process which affected the quality of the parts were:

1.\ Casting rate (Rate of drying in the mould).
2.\ Mould material
3.\ Particle size and shape.
4.\ Solid to liquid ratio.
5.\ Moisture content of the mould
6.\ Air entrapment.
7.\ Type and amount of deflocculant.
8.\ Density of the liquid.
9.\ Reaction of the powder with the liquid.
10.\ Mould porosity
11.\ ph of the solution.
12.\ Temperature of the solution.
13.\ Rate of drying after elimination from the mould.
14.\ Slip viscosity

All these variables were stated to have an effect on the quality of the slip cast parts produced. It has also been shown that some of them affect the accuracy of the parts produced. Of those variables put forward by Hausner [6] there is apparent interplay of the variables with factors such as viscosity being affected by the particle size, particle shape, ph of the solution, liquid to solid ratio, reaction of powder with liquid, type an amount of deflocculant and density of liquid used. Viscosity is also a very important parameter in terms of achieving a good casting. If the viscosity of the mixture is too high it will aggravate air entrapment, give poor detail pick up and possibly will prevent the mould from filling correctly. Therefore it can be seen that achieving a mixture with a low viscosity is important. Of the factors affecting the viscosity, one of the most important is that of the ph of the mixture, as this allows alteration of the viscosity without any detrimental effects on the other variables.

The ph of the mixture can effect the viscosity because the ph is a measurement of the ion content in aqueous solution. Stainless steel with the addition of the correct chemicals, can get the particles to react in such a way by forming a double electric layer around each of the powder particles as illustrated in figure 2. This helps to suspend the particles in the solution, by the forces of repulsion that are generated by these electrically charged layers.

Previous research by Hausner [6] into the optimum ph value of the stainless steel slips, derived a value around 9.8. It is assumed that Hausner [6] made the assumption that the slip acted in a Newtonian manner as there is no information to the contrary. By repeating same experiments using different deflocculant and powder material to that used by Hausner [6], it is considered inappropriate to assume the slip to be Newtonian, as slips using other powders do not act in this manner. The experiments were carried out using a constant stress rheometer and a Philips PW9421 ph meter with a Unicam CE1 glass electrode. The results of the viscosity measurements, of mixtures of the same composition but with different ph values, can be seen in figure 3.

As can be seen from the figure 3 which shows the viscosity's against shear stress for mixtures of the same powder/liquid ratios but at different ph values, the slip acts in a non-Newtonian manner. If we consider the viscosity's at shear rates equivalent to that of pouring, which is in the range of 0.1 to 1 γ/s [8] the slip seams to act in a Newtonian manner. This can be seen in figure 4, which is a plot of viscosity at pour shear rates over the range of ph values, calculated using cross curve fit algorithm.

It is apparent from figure 4, the viscosity is lowest for the slip when the ph value of the solution is about 9.7 which corresponds to the values derived by Hausner[6] The viscosity plays an important role in achieving of a good casting and the control of the ph of the solution allows the solid to liquid ratio to be higher than if ph was not controlled. The reason why this is important is that it allows the process greater control on the casting rate of the slip in the porous mould, which has been shown to affect the accuracy of the casting. This is of extreme importance in this application of this process.

The effect of the casting rate can be seen in figures 5 & 6. These show data derived from an experiment where two solid to liquid ratios were selected. The two selections being the extremes of the workable range. The high solid to liquid ratio gives a very high viscosity solution which is usable on simple shapes for casting. It is important to note that if the ratio was any higher, the slip enters into the region of unusable. At the other end of the range, with a low solid to liquid ratio the slip has a very low viscosity, which makes the production of good castings relatively easy. Further decrease of the solid/liquid ratio does not seem to give large gains in reduction of viscosity.

The mixtures were then cast into plaster moulds which had been soaked in an aqueous solution of release agent for different amounts of time. The purpose of this was to control the moisture content of the porous plaster moulds. Once dry, the resultant casting was then measured using a CNC co-ordinate measuring machine. Figures 5 & 6 show the % shrinkage of the diameter of a cylindrical cast sample. As shown by the data, the faster the casting rate the better in terms of the reduction of shrinkage and increase in repeatability, which is desired in order to achieve an accurate tool. The problem with the casting rate being very high is that it can cause difficulties in terms of the quality of the part after firing. This is assumed to be due to the migration of the smaller particles to the surface of the porous mould, coused by

the high casting rate. This causes the surface of the cast part to be hard and on firing the part will either crack, or will develop a crazy paving effect on its surface.
For this reason, it is important that the casting rate is carefully controlled in order to give the desired effects of accuracy and cast parts which will sinter correctly.

SINTERING OF THE GREEN SLIP CAST PARTS

The firing of the samples has been performed in a tube furnace from temperatures ranging from 1000 to 1300 degrees C. The samples are placed in an alumina boat and then sealed into a Quartz tube into which a gas comprising of 10 % hydrogen and 90 % Argon is pumped in. It is important to note that the gas has to have an extremely low dew point. This is especially important at the low sintering temperatures. The sample was placed on the alumina boat in order to reduce distortion due to friction generated during the sintering process [9]. The quartz tube was used to cope with the massive thermal shock of the process e.g. room temp to 1200 degree C in 20 minutes. It was found that neither alumina or porcelain tubes could tolerate this thermal cycling and would usually crack causing oxidation of the part.

The Sintering of the slip cast samples has many parallels to that of sintering of metal injection moulded (MIM) parts, in terms of the starting green density's and the fact that the particles are spherical. The main variation of the slip cast green parts is that there is a lot less binder in the slip cast parts, with only less than 0.34% (by mass) or 5% vol in comparison to that of MIM which is in the region of 20 - 40 % vol [10]. In terms of sintering, the slip cast parts do not really need to have a debinding stage in the firing process and therefore can be put into the furnace at temperature. In terms of the samples used, it usually reached the temperature of the furnace in under 20 minutes.

The disadvantages of the green slip casting parts in the firing process, is the release agent that sticks to the green parts after extraction from the mould. This generates problems, in terms of pulling particles from the surface of the green part as it burns during the firing process. The problem being that the particles can then stick to the part in the sintering process, causing a rough surface on the sintered part.
The effect of this can be reduced by firstly sintering the part at a relatively low temperature. At this stage the particles can be brushed off by hand and then the part can be resintered at a greater temperature to achieve the desired density. However, it should be noted that this problem usually occurs only when using relatively large powder particles (average particles size of 20 microns). These will usually have a greater casting rate than small particle sizes, so the soak time of the porous moulds needs to be longer thus giving rise to more release agent on the green sample.

The sample once at the maximum density which allows the keeping of the accuracy with low distortions, can then be infiltrated with a lower temperature metal. One of the most common metals for infiltration into the steel parts is copper alloys. Copper alloy also works on stainless steel, but another infiltration alloy under investigation at this point is aluminium. This is not as simple as infiltration of copper alloys but could possibly offer some advantages to the final injection moulding tool.

SUMMARY / CONCLUSIONS

The factor that is important in terms of the accurate slip casting of stainless steel powder is the casting rate, which can effect the shrinkage of the cast part and the shrinkage variation. To achieve accurate parts, the faster the casting rate the better, within the range of casting rates studied in this investigation. However, obtaining the fastest casting rate possible is not always the best solution, as the faster the casting rate, the greater seems to be the migration of the smaller particles towards the surface of the mould, which can cause problems in the sintering process.

The method used in the investigation is not the only method available for the control of the casting rate. Methods such as changing the porosity of the plaster mould (by altering the water to plaster ratio), control of temperature of the slip, changing of the particle size and different casting methods are also believed to have an effect, such as (vacuum casting or centrifugal casting processes). Also under consideration was quality of the casting. It was stated that many variables that can affect the quality of the cast part. One of the most important with regards to the casting process is the viscosity of the slip. The important factor in control of viscosity was the ph of the slip. This can have a large effect on the viscosity and therefore on the quality of the slip cast part.

The sintering stage of the process is not dissimilar to that of the sintering parts produced via the MIM process. The major advantage is that very little binder is used in the process. It is also important to note that the sintering in this application, is only to the stage where accuracy is maintained with very little distortion and that the porosity in the sinter parts are still interconnected. This is to allow the infiltration material to flow into the sintered part and thus give the part full density.

The results obtained so far has given great encouragement that slip casing will be suitable in terms of accuracy. It is also expected that the number of shots that the injection moulding tool produced via this method is estimated to last, to be at least 20,000 shots. Considering that the Keltool process which is similar to, the slip casting, can produce injection moulding tools which can last over 1 million shots [11],. Another comparison which can be taken into consideration is that epoxy resin tools have lasted over 100,000 shots [12]. This is only the start, with super hard composite tools, there is no reason why slip casting method, cannot be used to manufacture injection moulding tools which can be used for mass production.

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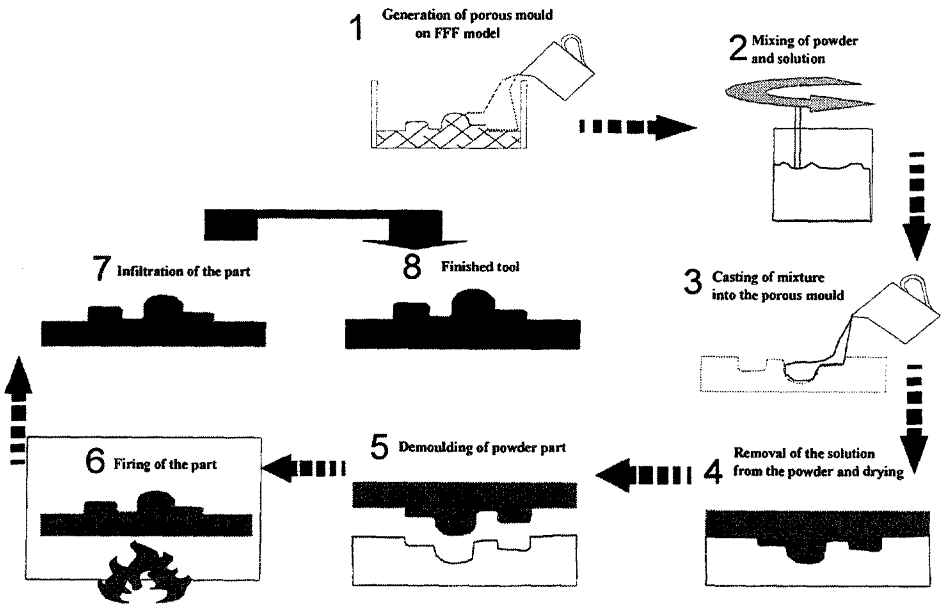

Figure 1 The slip casting process

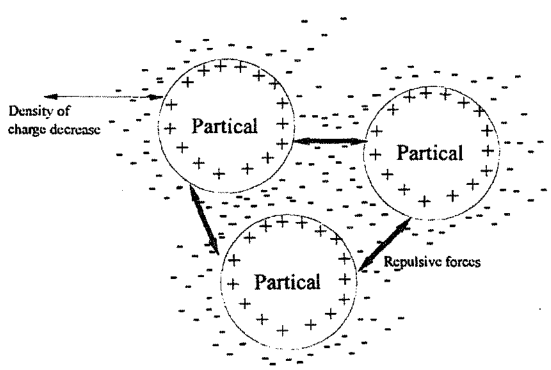

Figure 2 The double electric layer

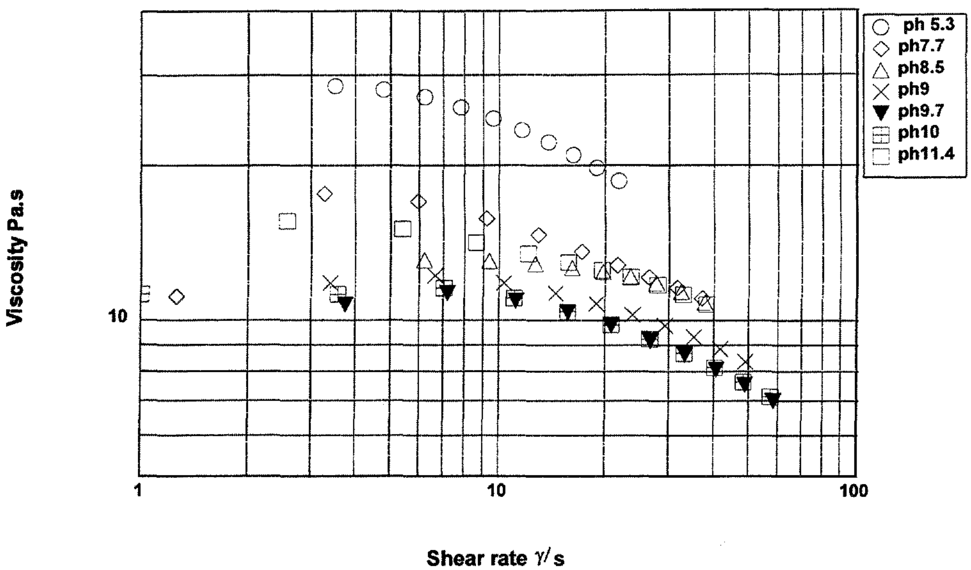

Figure 3 Viscosity against shear rate over a range of ph values

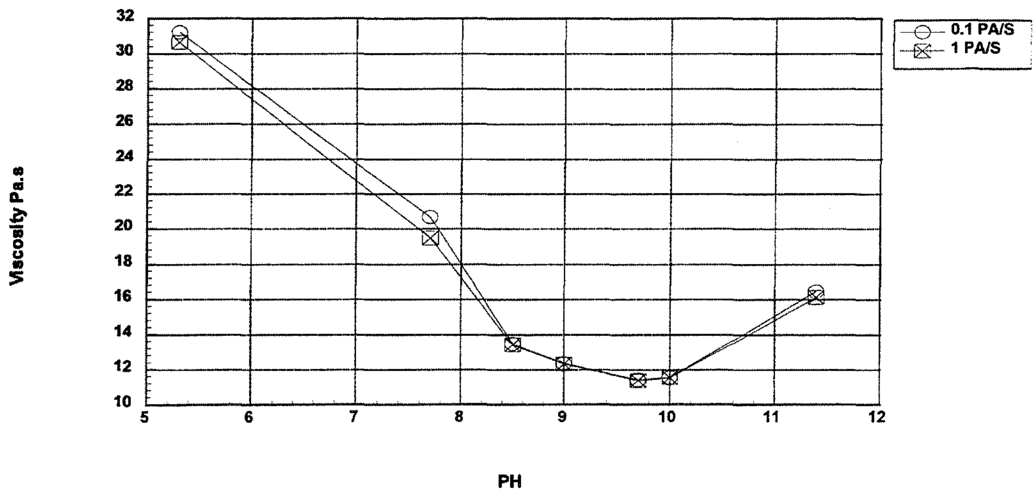

Figure 4 Viscosity against ph for shear rates equivalent to gravity pouring

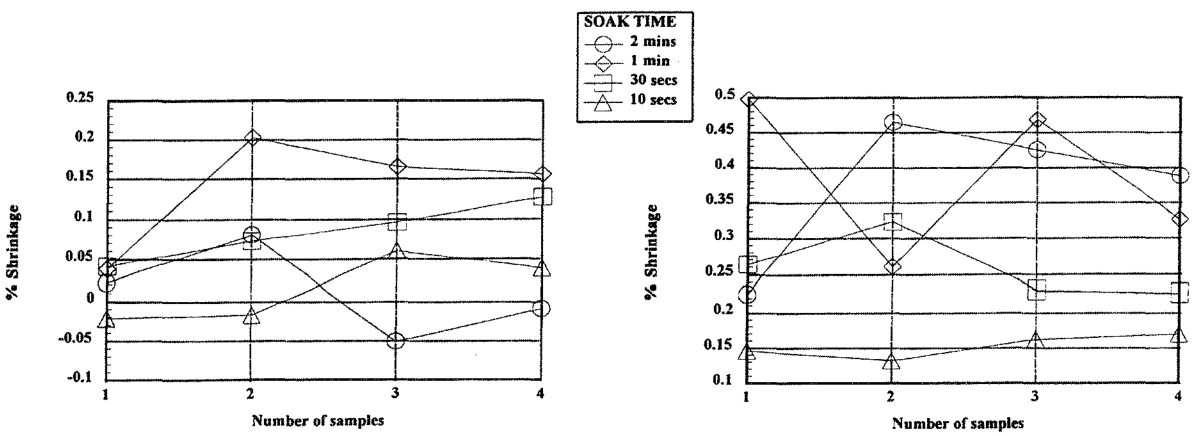

Figure 5 Shrinkage variation with casting rate with high solid to liquid ratio

Figure 6 Shrinkage variation with casting rate with low solid to liquid ratio