PARAMETERS AFFECTING SPIN CASTING OF DECORATIVE AND MECHANICAL PARTS

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ABSTRACT

Spin casting is widely used as a batch manufacturing process for decorative products. In the process, moulds are filled by taking advantage of the centrifugal effect, which is used to increase the pressure within the moulds, resulting in more detailed products. In this study, we analyse the different parameters that could affect the casting of mechanical parts through spin casting. Through this study, the user will be guided in the selection of parameters that will result in a certain degree of accuracy. The parameters were determined by performing numerous experiments using zinc alloy and tin-based pewter as casting materials. Results were obtained by casting approximately 15 000 parts in various positions, and at various clamping pressures, rotational speeds and temperatures in both the mould and the material. The experiments were undertaken by varying one parameter at a time, and with each set parameter repeated once, resulting in 100 test pieces per parameter for evaluation. From the results obtained, a series of critical factors and parameters, which are driven by part characteristics or features, has been studied. Contrary to following a modelling approach, the research was conducted following an action-research approach, with planned activities, but where actual results have defined the follow-up procedures. These guidelines will help industrial users ensure the accuracy of parts produced by spin casting. Also, since this project attempted to create a database of results that can be applied in future, it furthermore implies that the data created for the first time can be used in a numerical modelling approach in further/follow-up research. No such data was available from any previous research.

Keywords: Spin casting; decorative parts; mechanical parts; accuracy

1. INTRODUCTION

Spin casting involves the use of a number of master models to create a series of radially spaced cavities in a cylindrical silicone rubber mould. The mould is then cut in two along a plane that intersects all the cavities. The master models are removed, and the mould is reassembled and clamped between two plates. The mould is rotated and molten material is introduced into the centre. The cavities are then filled with the molten material by means of the centrifugal effect. The particular machine used for this study was a series 100A TEKCASTER machine from Tekcast Industries, USA (see Figure 1).

Figure 1: Spin casting machine used for study (www.tekcast.com)

Although spin casting is widely used as a tool for casting decorative articles such as belt buckles, shoe buckles and handles for cupboards [1, 2], there is a limited number of applications that use spin casting as a manufacturing method for end-use mechanical parts. Gatto and Iuliano [3] have reported its use for injection mould tools and Nasser [4] has reported its use for producing after-sales spares. One reason for this limited use is that the accuracy of the parts cast is often inconsistent [5]. In casting decorative articles, dimensional accuracy is not often a critical factor (although surface finish and general appearance play a critical role in the acceptability of parts). However, for mechanical parts it is very important to be able to cast with a certain degree of repeatable accuracy. There are several parameters affecting the accuracy of spin cast parts. These include spin speed, positioning of the parts in the mould, temperatures of the casting material and mould, clamping pressure and rotational direction [6]. The accuracy of the cast parts could be predicted if all the parameters affecting accuracy were understood and controlled. This would ensure more frequent use of spin casting for producing mechanical parts.

The aim of this study was to identify which process parameters have the greatest effect on part accuracy and then to quantify these effects. Particular attention is paid to defining the forces that are at work during spin casting. Having identified angular position, rotational speed, mould temperature and clamping pressure as the parameters with potentially the greatest effect, the results of experiments involving each of these are reported. An attempt is made to explain the trends that were observed and a more general discussion of the importance of the results is provided. Finally, some conclusions are drawn and some areas worthy of further research have been listed.

2. OVERVIEW OF PARAMETERS DETERMINING PART ACCURACY

Three forces play key roles during spin casting: axial, radial and tangential forces. The axial force acts parallel to the axis of rotation, the radial force is the force acting from the centre to the outside of the mould and the tangential force is acting at an angle of 90 to the radial force but opposite to the direction of rotation. The axial force is caused by the top and bottom clamping plates which close the mould while parts are being cast. The axial, radial and tangential forces can be controlled by adjusting clamping pressure, spin speed and part positioning within the mould, respectively.

Owing to the spinning motion used for casting, a rotating reference frame has been used to represent the forces involved. Thus, the centripetal force towards the centre of rotation is replaced with an apparent centrifugal force. This method was chosen as it helps with the intuitive understanding of the problem at hand (i.e. the outwards flow of the material from the centre of the mould). The centrifugal force can be thought of as acting in an outward direction as the parts being cast spin around the centre of rotation. Previous research has shown that this is one of the parameters with the largest effect on part accuracy [7]. The centrifugal force Fc, which each of the cast parts exerts on the mould, is determined by

$$Fc = m\,\omega^2 r \qquad \text{(eqn 1)}$$

where: m is the mass of each part,
ω is the angular velocity and
r is the radial distance from the central axis of the mould.

If the force is too large, the silicone moulds become deformed, thus having an adverse effect upon the shape of the part. For a given shape and casting material, the mass of a part is fixed. Therefore, the magnitude of radial force can be varied by changing either the distance of the part cavities from the central axis or the rotational speed. The radial placement of the parts in the mould can only be varied within certain limits, dependent on the geometry of the parts and the size of the spin casting machine. Normally, parts would be placed as close as practically possible to the outside of the mould. Sufficient rotational speed is needed to form a solid cast part and to ensure that the casting material is forced into all the part features.

Owing to the mass of the molten material used for casting, inertia is present when the material enters the spinning mould. This inertia tries to stop the material from rotating with the mould. Therefore, the spinning mould first needs to accelerate the material, causing a tangential force opposite to the direction of rotation. The tangential force P is given by [7]

$$P = m\left(\frac{k}{r}\right)^2 f \qquad \text{(eqn 2)}$$

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[1] Note: The density of the zinc alloy used was 6.98 g/cm^3 and that of the pewter was 7.35 g/cm^3

where: m is the mass of each part,
k is the radius of gyration used in calculating moment of inertia,
r is the radial distance from the central axis of the mould, and
f is the linear acceleration due to the force P.

The tangential force on the cast part is typically smaller than the radial force (see Figure 2).

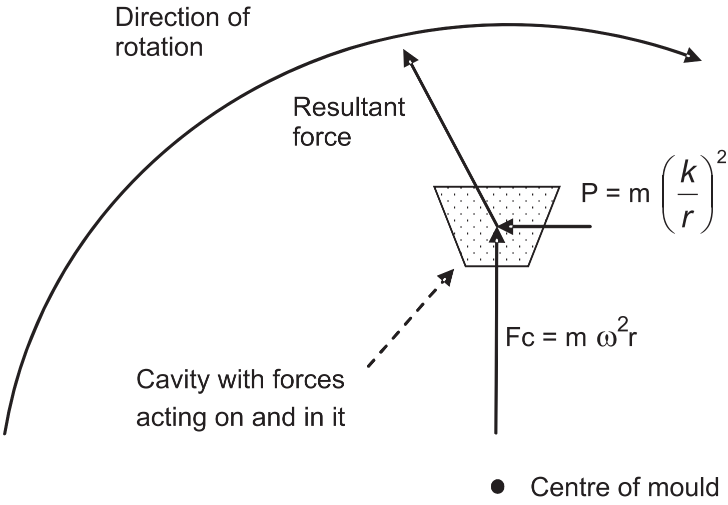

Figure 2: Forces acting on part cast in mould

A flow line is often seen on the surface of objects produced by spin casting. This flow line is in the same direction as the resultant force of the centrifugal and tangential forces. The effect on part accuracy of the flow line direction was deemed worthy of investigation. Therefore, the outcome of varying the angular orientation of the parts was investigated.

The axial force with which the machine clamps the mould between the two plates can also be varied. It must be high enough to ensure that the molten material does not flow out of the split line between the top and bottom moulds. However, if the clamping pressure is too high, the cavity will be deformed, resulting in reduced thickness of the parts. From this, it can be seen that an optimum balance must be achieved. Finding this balance was one of the objectives of the study.

Other parameters playing a role are the temperatures of the molten material and the mould. If the material is not sufficiently hot, its viscosity will be too high to cast the parts. However, if the temperature is too high, the different components of the alloys used can separate. Therefore, the temperature of the material should be kept at 15ºC above the melting temperature of the material [6]. Hence, casting in AZIM 6G zinc alloy [8] was performed at a material temperature of 388C and casting in WM 90 pewter [9] at 280C.

3. INVESTIGATION OF PARAMETERS

Of the numerous parameters identified above, four were identified as critical and selected for further investigation. These were angular positioning of the parts, rotational speed, mould temperature and axial clamping pressure. The effects of these parameters on part accuracy were investigated in several experiments. Some of the parameters were investigated for more than one material.

3.1 Variation in Angular Positioning of Parts

In this investigation, the influence of the angular positioning of the master in the mould was investigated to determine the effect that this parameter has on the accuracy of the cast parts. For this set of experiments, ten cuboid blocks were machined to a nominal length of 40mm, a width of 20mm and a thickness of 10mm (kept within a tolerance of +/- 0.01 mm so that the samples produced could be directly compared with each other). Each of these masters was rotated between 0º and 90º in 10º increments and used to produce a casting mould. The mould was designed so that the distance from the central axis of the mould to the centre of mass for each master was kept constant (see Figure 3). This ensured that the radial distance had no effect on the accuracy of parts for this set of experiments.

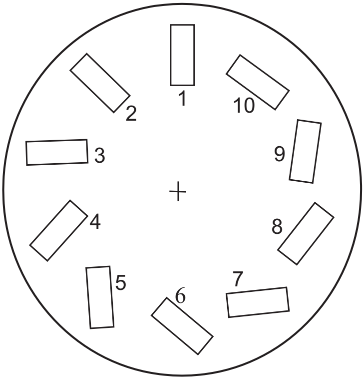

Figure 3: Positioning of ten rectangular masters in mould

Ten sets of parts were cast in zinc alloy using the following parameter values, as suggested by the machine manufacturer, for a specific mould size/diameter of 230mm:

- rotational speed = 450 rpm,
- clamping pressure = 172.3 kPa,
- mould temperature = 35ºC.

All of the 100 parts produced were marked and measured using Vernier callipers along their length, width and thickness directions to determine the deviation from the original dimensions of the master parts. This deviation was expressed as a percentage using

$$\text{Percentage deviation} = 100 - \left(\frac{\text{Cast Size}}{\text{Original Size}}\right) \text{X } 100$$

This meant that a positive deviation indicates a reduction in size. The parts were also evaluated to see if the surface finish and appearance were acceptable. The percentage fill of the cavities was also one of the criteria for evaluation. If a cavity was not filled 100%, then the part was considered a reject and could not be used for measurement. The average results of percentage deviation for length, width and thickness for all 10 positions are shown in Figure 4 together with the average percentage filling of each cavity. There was reasonable repeatability between experiments giving maximum standard deviations of 0.14% for length (at position 1), 0.42% for width (at position 7) and 0.47% for thickness (at position 5).

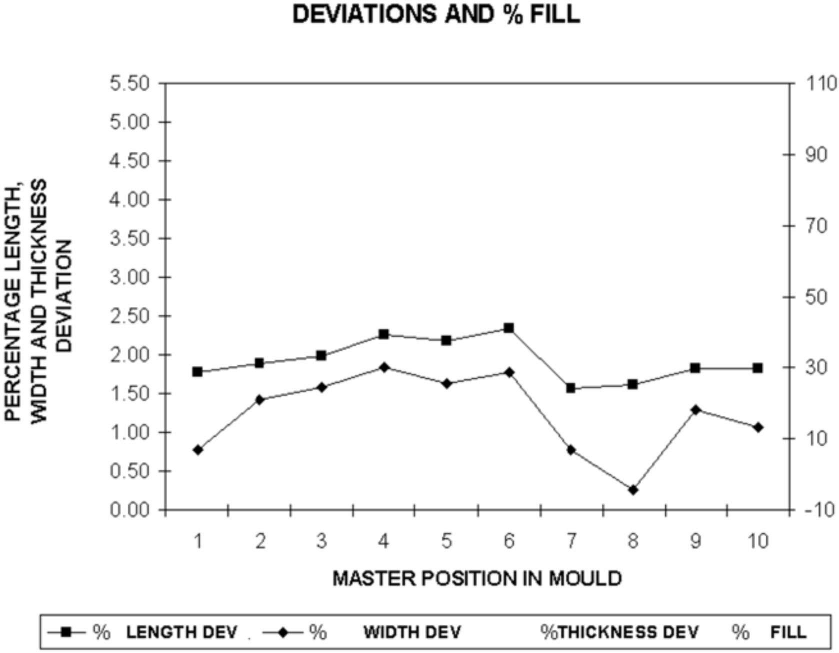

Figure 4: Percentage length, width and thickness deviations and cavity fill

The aim of this investigation was to determine which of the ten positions was optimum in terms of giving the smallest deviation from the master dimensions. From Figure 4 this would appear to be position 8, i.e., the position whose longest dimension is oriented at an angle of 70 to the radial direction. It is likely that this direction correlates with the resultant force direction shown in Figure 2. If this is so, then it would appear that having the initial flow direction of the molten material perpendicular to the longest dimension of the cavity leads to a higher accuracy. During the experiments, only half of the positions (numbers 2, 3, 6, 7 and 10) consistently achieved a 100% cavity fill (as seen in Figure 4). When further experiments were conducted at different rotational speeds, mould temperatures, and clamping pressures, it became clear that the incomplete filling of some of the 10 positions was quite common. Therefore, the most critical factor in choosing the orientation of a part is the ability to achieve a 100% cavity fill. This phenomenon requires further research using more complex shapes.

3.2 Variation in rotational speed

The rotational speed to be used for spin casting must fall within a range recommended by the machine manufacturers. For this experiment, it was varied from 450 rpm to 650 rpm in 50 rpm increments. The parameters of clamping pressure and mould temperature were kept at 172.3 kPa and 50ºC, respectively. Results for average percentage deviation across the 10 positions for parts cast in zinc alloy are shown in Figure 5. It can be seen that the deviations of all three dimensions generally seem to improve as rotational speed increases. Although the plot for thickness deviation is quite erratic, there is a marked improvement when the maximum speed of 650 rpm is reached.

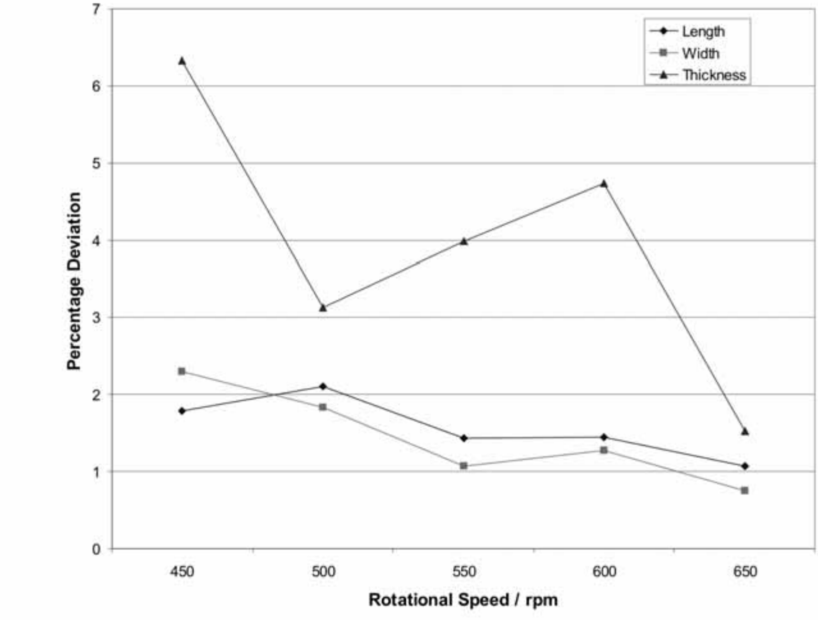

Figure 5: Percentage deviation versus rotational speed (zinc alloy casting)

For the castings made at rotational speeds of 550 rpm and above, the parting line became visible. This is explained by the fact that at higher speeds the two halves of the mould can start to separate as more molten material is forced into the cavities. For this reason, it was decided that 500 rpm would be the optimum rotational speed to consider in all subsequent experiments with zinc alloy.

The experiment was repeated using WM 90 pewter but with a narrower range of rotational speeds, only up to 500 rpm. This was due to the fact that when casting in pewter, the material tends to flow out of the mould split line more easily than for zinc alloy. At 500 rpm, the split line was already visible. The results for the pewter are shown in Figure 6. Once again, clamping pressure and mould temperature were kept constant at values in line with the manufacturer's guidelines.

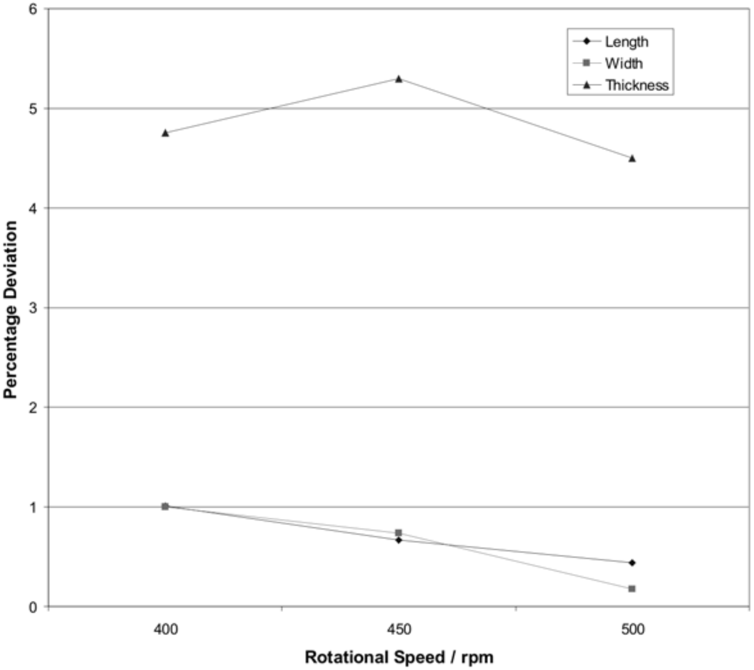

Figure 6: Percentage deviation versus rotational speed (pewter casting)

The length and width deviations for WM 90 pewter once again appear to improve with increasing rotational speed. All the thickness deviations for the pewter are quite similar to each other with no clear trend seen. In comparison with the results seen in the case of the zinc alloy, there is a general trend for lower deviations of length and width (at comparable speeds). For both materials, the percentage thickness deviations are generally much greater than the percentage length and width deviations. This indicates that there is much more shrinkage in the axial direction than in the plane of rotation. This is undoubtedly due to the effect of clamping pressure squeezing the two halves of the mould together. It seems that if rotational speed is increased sufficiently, then this effect can be countered by greater “packing” of the mould. However, the negative aspect of this is the material leakage through the split line.

3.3 Variation of mould temperature

Mould temperature was only varied within the range 20ºC to 60ºC. The reason for this was that if the mould is too cold, the molten material would set in the gate, but if it is too hot, the life of the mould would deteriorate dramatically. Clamping pressure was again kept constant at 172.3 kPa for the casting of the zinc alloy parts and at 206.8 kPa for the pewter parts. The results obtained for zinc alloy are shown in Figure 7 (note that the results for 50ºC were already available from the previous set of experiments). It can be seen that there was no marked trend for the variation in percentage deviation for any of the three dimensions.

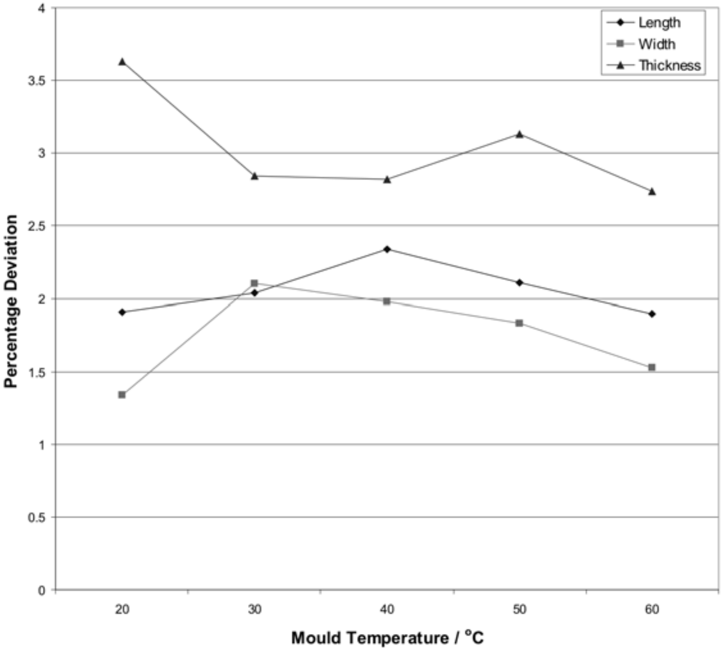

Figure 7: Percentage deviation versus mould temperature (zinc alloy casting)

A similar set of experiments was conducted for WM 90 pewter and the results obtained are shown in Figure 8. In contrast to the results seen in the case of the zinc alloy, it can be seen that there is now a marked trend for percentage deviation to decrease for all three dimensions. The explanation for the difference in deviation trends between pewter and zinc alloy may lie in the fact that the difference between mould temperature and material temperature was approximately 100ºC less than it had been for the zinc alloy.

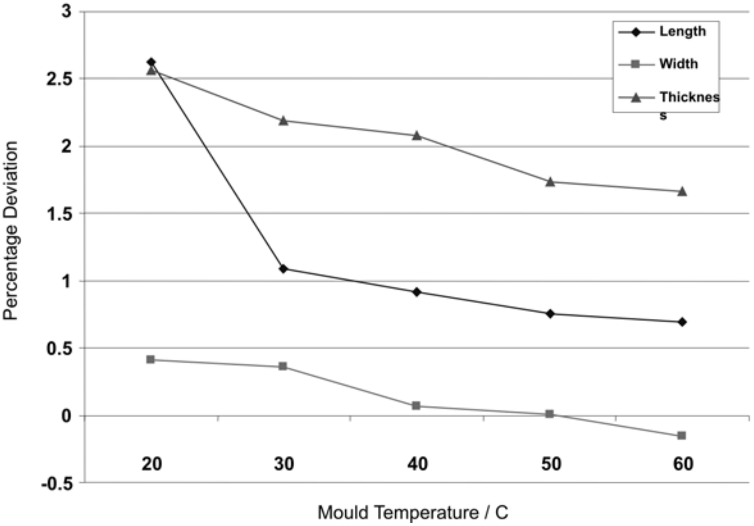

Figure 8: Percentage deviation versus mould temperature (pewter casting)

3.4 Variation in clamping pressure

Clamping pressure was varied from 137.9 kPa to 241.3 kPa and the experiment was repeated for both materials. The rotational speed was 500 rpm and a convenient mould temperature of 30ºC was chosen. The results obtained are shown in Tables 1 and 2. There is no clear overall trend in length and width deviations, but there is a pronounced trend for thickness deviation as shown in Figure 9. In general, across both materials, as clamping pressure is increased, percentage thickness deviation also increases, i.e., the parts are getting thinner. As discussed previously, this was to be expected; however, it is interesting to note the differences in the parameter values between the materials, with the zinc alloy having the highest deviations.

ROTATIONAL SPEED r/min	MATERIAL TEMP. ºC	MOULD TEMP. ºC	CLAMPING PRESSURE kPa	LENGTH % DEV	WIDTH % DEV	THICKNESS % DEV
500	388	30	137.9	2.33	1.78	2.27
500	388	30	172.3	2.37	2.10	2.84
500	388	30	206.8	2.30	2.17	3.91
500	388	30	241.3	1.89	1.60	3.16

Table 1: Experimental results for varying clamping pressure (zinc alloy casting)

ROTATIONAL SPEED r/min	MATERIAL TEMP. ºC	MOULD TEMP. ºC	CLAMPING PRESSURE kPa	LENGTH % DEV	WIDTH % DEV	THICKNESS % DEV
500	280	30	137.9	1.21	0.84	1.52
500	280	30	172.3	1.23	0.87	1.74
500	280	30	206.8	1.21	0.91	2.44
500	280	30	241.3	1.24	0.95	2.29

Table 2: Experimental results for varying clamping pressure (pewter casting)

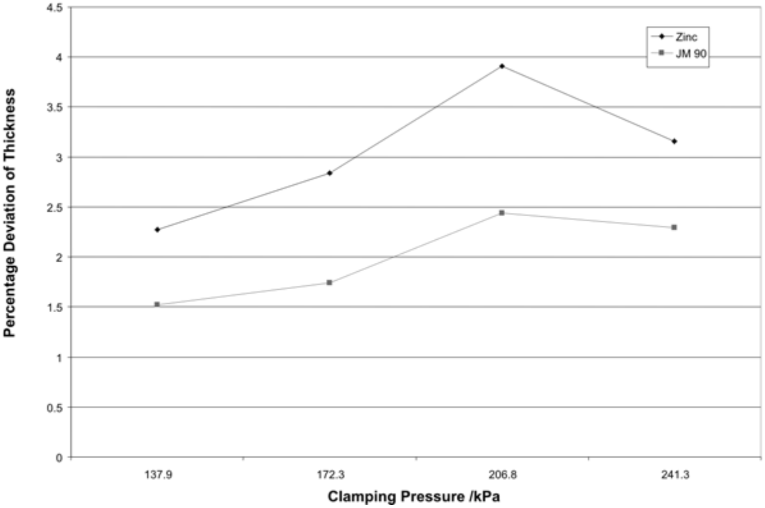

Figure 9: Percentage deviation of thickness versus clamping pressure

4. DISCUSSION OF RESULTS

The experimental results obtained by varying angular position, rotational speed, mould temperature and clamping pressure show the following:

- Angular position affects the ability of spin casting to accurately replicate the geometry of master models. However, a more important issue is the effect that this parameter has on the requirement to have complete cavity filling. With a simple shape like that used in this study, the determination of the optimum orientation to achieve complete filling can probably be deduced from experience. However, more complex shapes may require a more formal approach.

- Increasing the rotational speed affects the "in-plane" accuracy of parts. Higher speed leads to less shrinkage in dimensions that lie perpendicular to the axis of rotation. It seems that more material is being flung into the cavities by the centrifugal force. However, the effect of rotational speed on thickness does not seem to follow a marked trend. This is not so surprising since the thickness dimension is perpendicular to the direction of the centrifugal force. At the highest rotational speed used, there seemed to be some improvement in thickness but it was accompanied by excessive leakage of the molten material through the parting line. Therefore, during spin-casting, rotational speed should be set as high as possible without causing excess leakage of the material. This will ensure that in-plane shrinkage can be maintained at approximately 1% deviation from the master model dimensions (depending on the material used).

- It was observed that mould temperature within the experimental range of 20˚C - 60˚C had no pronounced effect on the accuracy of zinc alloy castings. However, a higher mould temperature can increase the deterioration of the mould and a low temperature can result in scrap formation if mould material sets within the in-gates. Therefore, the mould temperature should be increased from cold, until complete filling of all cavities is achieved, and then held at this temperature.

- The effect of increasing clamping pressure is entirely detrimental to the accuracy of parts. It does nothing to improve the in-plane deviations and causes an increase in thickness deviation. Therefore, the minimum clamping force should be used that will avoid the onset of leakage. An alternative approach would be to accept that there will be a reduction in thickness and to scale the master models accordingly.

- Different materials yield different deviations making it difficult to derive a set of overall “rules of thumb” for how much shrinkage to allow for in different situations. However, a general pattern of deviation has been established that is useful for achieving shrinkages of between 1% and 2% in the X- and Y-directions, and between 3% and 4% in the Z-direction. Pewter showed better shrinkage parameters than zinc alloy, suggesting that this material should be used when duplicating a master pattern for production purposes. However, under normal conditions mechanical parts are cast with zinc alloy and pewter is used for casting decorative parts only.

5. CONCLUSIONS

From this study, it can be seen that the accuracy of spin casting is affected by a number of parameters. Unlike other casting processes, there is no “typical” percentage dimensional deviation that can be quoted, e.g., 0.5% for investment casting and 0.1% for die casting [10]. Clamping pressure, rotational speed, geometry and size of the cavity and casting material all affect part accuracy in different ways and so the percentage deviation will depend on what combination is used. However, this study has identified certain combinations of parameters that have a more predictable impact upon part accuracy. The values given in Tables 1 and 2 can be used as a guideline for selecting spin casting parameters. In general, it is best to cast at the lowest clamping pressure, speed and mould temperature, which will give a consistent cavity fill. The percentage deviations in X, Y and Z are then reasonably predictable, and if greater accuracy is needed the masters can be non-uniformly scaled to make allowance for the different percentage deviations.

Future work should be undertaken to understand more fully the conditions required for consistent cavity fill, particularly for more complex shapes. Also, the recommended technique of non-uniform scaling of the masters should be tested, firstly with regular shapes and then with more complex parts. Finally, it has been noted that pewter tends to give more consistent accuracy results whereas zinc alloy has better mechanical characteristics. Further investigation is needed into other materials that may be suitable for spin casting that can achieve both of these characteristics.

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