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Dimensional variations of castings and moulds in the ceramic mould casting process

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Abstract

Ceramic mould casting process produces high precision castings at a relatively low cost for the production of small number of parts, making it particularly suitable for producing moulds and dies. There is a constant demand for improving the process capabilities including dimensional accuracy and consistency. In this study, dimensional changes and variability of ceramic moulds and steel castings (P20) have been investigated using a pyramid-shaped part. It was shown that the accuracy of the ceramic mould plays a dominant role in obtaining tight casting tolerances. It was also shown that the dimension, location and orientation of a feature on the part had significant effects on the overall linear dimensional changes as well as the dimensional variability of the ceramic mould and the casting. The complex dependence of dimensional variations on feature orientation and location on the part has been discussed on the basis of asynchronous burning on the mould cavity surface at different locations during the burning-out process.

Key words: ceramic mould casting, dimensional changes / variability, accuracy of castings and moulds, burning-out process

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1. Introduction

As a precision casting process, ceramic mould casting has several unique features. It yields the type of tolerances equivalent to lost wax precision casting, but at a significantly lower cost for casting small number of parts. At the same time, high precision parts can be produced at much larger sizes (up to 5000 kg) than using the lost wax investment casting (up to 120 kg) [1]. Thus, this process is particularly suitable for the production of moulds and dies for various applications [2-8]. Recent developments have shown that combining the ceramic mould casting process with rapid prototyping (RP) technologies provides an effective way of making quality tools rapidly and inexpensively for both short runs and production applications [9]. This new rapid tooling (RT) route complements the existing RT methods, most of which are only suitable for fabricating small tools for either prototyping or short-run productions.

Considering the stringent tolerance requirements for the tooling applications, there is a constant demand for better understanding and further improvement in the ceramic mould casting process in terms of casting accuracy and consistency. In previous studies [10-12], dimensional changes of specimens made according to the ceramic mould casting process have been systematically investigated under various processing conditions. Very useful information has been generated that helps to better understand the dimensional changes of ceramic moulds and to improve the quality of castings using the ceramic mould casting process. However, in these studies, simple bar-shaped specimens were used with a thickness of only 12 mm, which are considerably thinner than production casting moulds

and do not reflect the effects of interactions/restrictions between different parts of a production mould with complex structures. In order to obtain more realistic and quantitative results, it is desirable and beneficial to use moulds with thicknesses and structures comparable to those used in production.

In this study, a stepped pyramid-shaped part has been used to investigate the dimensional changes and the variability of ceramic moulds and steel castings as a function of feature dimension and orientation. The observed experimental results are explained based on the asynchronous burning on the mould cavity surface at different locations during the burning-out process.

2. Experimental methods

2.1 The test part

A pyramid-shaped part with stacked square plates was designed and used in the assessment of dimensional variations of moulds and castings. The nominal dimensions of the part are shown in Figure 1. No draft (i.e., a zero draft angle) was applied to any of the surfaces. A pattern was CNC machined out of aluminium to a surface finish of Ra 0.2 μm .

2.2 Ceramic mould fabrication and processing conditions

The slurry used in this study is composed of a mixture of coarse and fine refractory powders and a prehydrolysed ethyl silicate binder (with a solid SiO_2 content of approximately 20%). 10% ammonium carbonate aqueous solution was used as the gelling agent. The amount of gelling agent used in the slurry was so adjusted that the gelling time

was approximately 12 min after the addition of the gelling agent (1.5 ml per 100 ml binder in the current conditions).

The fabrication of the ceramic mould starts with the formation of the slurry by mixing the refractory ingredients and the binder. Then the gelling agent (10% ammonium carbonate aqueous solution) was added to the slurry and further mixed for one minute before pouring into the flask enclosing the pattern. The slurry was allowed to gel and harden for 30 min before stripping the pattern. The gelled mould was then immersed in an alcohol bath for 3.5 hr followed by burning-out (igniting using a torch). The mould was further fired at 950 °C for 4 hr and cooled in the furnace to room temperature before dimensional assessments.

The minimum wall thickness of the ceramic mould was 38 mm.

2.3 Casting conditions

Using the ceramic moulds, nine castings were produced with P20 tool steel. Casting was carried out in a vacuum casting furnace evacuated to 13 Pa and back-filled with argon to 26 kPa. The ceramic mould was pre-heated to 800 °C for 16 hr in the furnace. The steel charge was melted and overheated to 1580 °C before pouring at 1540 °C. The casting and the mould were left to cool in the furnace till the casting temperature was below 200 °C. After breaking the mould, the casting was cleaned by sand blasting at a low air pressure (276 kPa).

2.4 Assessment of dimensional changes and dimensional variability

When discussing dimensional errors or non-conformity in castings, it is important to distinguish between dimensional accuracy and dimensional variability. Dimensional accuracy is an indication of how close a casting dimension is to the actual target value. It consists of two components: (a) the deviation of the mean casting dimension from the target value, which is often referred to as a systematic error, and (b) the variation of individual casting dimensions about the mean casting dimension, i.e., the dimensional variability, which is often referred to as random error. The dimensional systematic errors occur as a result of, among other factors, incorrect estimate of shrinkage factors for the slurry/mould and for the metal. Such errors can usually be corrected before production runs begin, although this reverse engineering is costly and tedious. Dimensional variability of castings, or the random error, on the other hand, is affected by many metal casting process variables. It is important that significant sources of dimensional variability be identified, and that appropriate process controls be established to minimise them.

In this study, a coordinate measuring machine (CMM) was used to measure the linear dimensional changes (shrinkage or expansion) of the ceramic moulds and the castings. The variability of these dimensions about the mean values was assessed based on the CMM data. Flatness and straightness on some of the planes of the part (Figure 1) were also measured to reflect the tendency of mould/casting distortions (shape variations) under different conditions. Data obtained on the dimensional changes (shrinkage or expansion) of moulds and castings helps to reduce the systematic error and improve casting accuracy.

The linear shrinkage or expansion of each feature on the ceramic mould or the casting was calculated relative to the corresponding feature dimension measured on the pattern. Two directions were distinguished for the measurement of the linear dimensions: the horizontal direction (X & Y in Figure 1) and the vertical direction (Z in Figure 1). The vertical dimensions were measured against the plane on the pyramid base as shown in Figure 1. Results for the horizontal direction were obtained by averaging the measurement results from the X and Y directions.

The linear dimensional variability was expressed in terms of three standard deviations ($\pm 3\sigma$) of measurement results on a feature about the mean. The standard deviation of measurements is a measure of data dispersion. In normally distributed data, 99.73% of the data lie within plus or minus three standard deviations ($\pm 3\sigma$) of the mean. Thus for a feature with the mean centred on the specified drawing dimension, the scrap rate of castings due to dimensional errors would be less than 1% if the total specified tolerance is greater than six times of the standard deviation or if three standard deviations is less than one half of the total tolerance for a feature.

3. Results and discussion

The variation of dimensional changes (shrinkage or expansion) of the castings as a function of pattern dimension is compared with that of the ceramic moulds in Figure 2. The data for castings and for ceramic moulds are roughly in parallel for the corresponding vertical and horizontal features, respectively. The distance between the two sets of data for castings and for moulds represents the shrinkage of the casting relative to the mould.

Analysis on the original data gives a shrinkage value of 2.06% (standard deviation 0.09%) for the metal casting in relation to the ceramic mould; there is no statistically significant difference in shrinkages between the horizontal and the vertical directions. This is consistent with typical shrinkage values for steel castings under free shrinking conditions.

Figure 3 shows the linear dimensional variability (3σ) as a function of pattern dimension for castings and the ceramic moulds used to produce the castings. The dimensional variability of castings varied in a similar manner as that for the ceramic moulds; they are closely related. This is more clearly demonstrated in Fig. 4(a) which shows a linear relationship between the dimensional variability of castings and that of the ceramic moulds with a fairly high value for the coefficient of determination ($R^2 = 0.9404$). For most of the features, the dimensional variability of the mould exceeded 50% of the variability of the castings, as shown in Fig. 4(b). The above data suggests that the dimensional variability of ceramic moulds must be carefully controlled in order to produce high precision castings.

Straightness and flatness analysis of the castings and the ceramic moulds on some of the selected features (cf. Figure 1) showed that shape distortions of the castings were dominantly affected by distortions of the ceramic moulds, as shown in Figure 5. This again emphasises the importance of controlling the dimensional quality of the ceramic mould in order to obtain high precision castings.

3.1 Effect of feature dimension and orientation on dimensional changes

In Figure 2, the dimensional changes (shrinkage or expansion) for features oriented in the vertical and in the horizontal directions followed apparently different trends for both the castings and the ceramic moulds. By referring to Figure 1, data in Figure 2 shows that in the vertical (Z) direction, the features near the large pyramid base on the pattern ($Z \rightarrow 0$, Fig. 1) expanded but those towards the apex of the pyramid shrank; however, in the horizontal (X & Y) direction, the variation was the opposite, i.e., shrinking occurred at the large dimensions corresponding to the pyramid base while expansion was observed at the small dimensions corresponding to the pyramid apex. The extent of expansion or shrinking in the horizontal direction was significantly smaller as compared to that in the vertical direction. On the castings, parallel trends to those for the ceramic moulds were observed except that the castings shrank for all the dimensions.

From the close relationship between the dimensional variations of the castings and those of the ceramic moulds as shown in Figs. 2 - 5, it is reasonable to suggest that the dependence of dimensional changes of the castings on feature orientations results primarily from the non-uniform dimensional variations occurred during the fabrication of the ceramic moulds. Therefore, the following discussions are focused on the dimensional variations in the ceramic moulds.

Previous studies [10-12] using thin bar-shaped specimens on dimensional changes of ceramic mould under various processing conditions showed that when a specimen is immersed in an alcohol bath, no measurable dimensional changes occur in 30 to 40 minutes after adding gelling agent to the slurry. After this initial stage, the specimen

shrinks slowly and continuously over time. The main effect of immersing the specimen in alcohol is to prevent evaporation of alcohol released from the binder in the ceramic mould to promote uniform dimensional changes in the mould/specimen. In the current study, before the pattern is stripped, alcohol in the ceramic mould is prevented from escaping, a condition similar to immersing the mould in an alcohol bath. It is thus expected that little dimensional changes would occur in the ceramic mould before stripping the pattern (30 min from adding gelling agent to the slurry). Following pattern stripping, the green ceramic mould was immersed in an alcohol bath and continuous shrinking would occur. During the immersion period, conditions are uniform (saturated with alcohol) within the whole body of the ceramic mould and hence shrinking in the mould should be uniform. Thus, the non-uniform dimensional variation behaviour of the ceramic mould along the different feature orientations is primarily related to the burning-out process, because firing following burning-out would also lead to uniform shrinkage of the mould in all the directions.

3.1.1 The burning-out process of ceramic moulds

During the burning-out process, complicated dimensional changes occur. Figure 6 shows some typical curves for the variation of length changes (expansion or shrinking) as a function of time during burning-out obtained using bar-shaped ceramic mould specimens (12 x 25 x 218 mm) under different treatment conditions: immersing specimens in alcohol or drying in air for different times followed by burning-out. Although these results were obtained from thin specimens and cannot be quantitatively applied directly to the moulds used in the current study, the basic phenomena observed during the burning-out process as

revealed by these curves should be similar and could be applied here to understand the dimensional changes of the ceramic moulds.

There are two major processes that occur during burning-out and contribute to dimensional changes of the ceramic mould [12]. One is microcracking in the mould due to the rapid escape and volume expansion of alcohol from the mould; this leads to the expansion of the mould. On the other hand, if escaping of alcohol (e.g., by diffusion) from inside of the specimen is relatively less violent and/or the mould strength is high such that microcracking cannot be initiated, the removal of alcohol will lead to the agglomeration of solid particles in the binder to form a more compacted solid binding structure, causing shrinking in the mould. These two processes may occur consecutively or simultaneously at different stages of burning-out and result in the complicated shapes of the burning-out curves (Fig. 6).

Several factors affect the extent of expansion due to the formation of microcracking and the shrinking due to the relatively less violent removal of alcohol. These include the strength of the mould and the concentration of alcohol in the mould upon burning-out. If the mould/specimen has been substantially strengthened, it becomes difficult for microcracking to occur and consequently the expansion during the initial stages of burning is considerably reduced. One such case is to immerse the mould in alcohol for an extended period of time, as shown by the curve for 28.5 hr immersion in Figure 6. Similarly, if the concentration of alcohol in the mould is low, then the driving force for the formation of microcracking due to rapid alcohol escaping and volume expansion is considerably

reduced, and much less expansion of the mould/specimen during burning-out is expected. This is the case when the mould is left drying in air for a certain period of time before burning-out. As shown in Figure 6, the air-dried samples showed reduced expansion in the burning curves as compared with the alcohol treated samples, and the sample dried in air longer showed smaller expansion. It should be pointed out that plotted in Figure 6 are only the length changes of the bar specimens during the burning-out process. The removal of alcohol during drying in air before burning-out leads to a significant amount of shrinking, much higher than length changes during the burning-out process, as was previously reported [10, 12].

Thus, for specimens immersed in alcohol before the burning-out, alcohol concentration is high in the early stages of burning-out. At the same time, the mould strength is relatively low. When burning is started at the mould surface, microcracking dominates the process and rapid expansion is observed (Fig. 6). As the concentration of alcohol in the mould/specimen decreases, burning and removal of alcohol become less violent and the mould strength increases. As a result, the rate of microcrack formation decreases while the effect of shrinking due to slow removal of alcohol from the mould/specimen increases, leading to the observation of a peak on the burning-out curves following the initial rapid expansion (Fig. 6). After alcohol in the mould is completely removed, a plateau is observed on the burning-out curves where the length of the specimen remains relatively unchanged (Fig. 6). As the temperature of the specimen is reduced below the boiling temperature of water (100°C), an expansion stage follows the plateau on the burning-out

curves (Fig. 6); this expansion has been attributed to the absorption of water vapour by the silica gel structure in the binding phase [12].

3.1.2 Dimensional changes of different mould features during the burning-out process

Based on the above information, the dimensional changes of ceramic moulds investigated in the current study during the burning-out process can be discussed as follows.

Figure 7a shows a schematic diagram of a sectioned ceramic mould at its burning-out position. Major events and their corresponding effects on dimensional changes of the mould in the various feature locations and orientations are briefly summarised in Table 1 for different stages of burning with respect to the location of burning front. For the convenience of discussion, a unit strain cell as shown in Figure 7b will be used to indicate the directions of tensional strains, ϵ_1 , ϵ_2 , and ϵ_3 , at a certain point in the mould that cause dimensional changes. A positive (+) sign for the strains indicates expansion while a negative (-) sign means shrinking/contraction at the given point.

3.1.2.1 Start of burning

At the beginning of the burning-out process, the burning of alcohol does not follow the exact contour of the mould surface. Instead, on the mould cavity side, the flame forms a curtain covering the cavity opening. At locations deep into the cavity (e.g., points 2 and 3, Figure 7), no burning occurs due to the lack of air supply. However, alcohol will evaporate from the surface of the mould cavity; this evaporation is accelerated by the burning heat

and the flow of burning products near the opening of the mould cavity. These events lead to the following dimensional changes in the mould (Table 1) at the various locations:

- (a) On the outer surfaces of the mould where burning takes place (e.g., points 1 and 5 in Figure 7), rapid and significant expansion occurs in all the three prime directions as a result of microcracking ($\epsilon_1 \gg 0$, $\epsilon_2 \gg 0$, $\epsilon_3 \gg 0$). The expansion corresponds to the initial rapid expansion stage on the burning-out curves shown in Figure 6.
- (b) At locations down in the mould cavity where burning does not occur (e.g., points 2 and 3 in Figure 7), two competitive processes contribute to the dimensional changes of the mould at the corresponding locations. On the one hand, alcohol evaporation from the mould leads to shrinking in all three directions ($\Delta\epsilon_1 < 0$, $\Delta\epsilon_2 < 0$, $\Delta\epsilon_3 < 0$). On the other hand, as the strength of the mould at these locations are still relatively low, the expansion at regions around the outer faces of the mould (points 1 and 5), where burning takes place, can lead to tensile strains (expansions) at these locations (points 2 and 3); but this tension will mainly cause expansion in the ϵ_2 direction because no forces are transferred to the free step surfaces in the ϵ_1 and ϵ_3 directions. Thus, the overall dimensional changes at points 2 and 3 at this stage of burning are expansion along the ϵ_2 direction and shrinking in the ϵ_1 and ϵ_3 directions.
- (c) At locations inside the ceramic mould body, e.g. point 5 (Figure 7), alcohol out-diffusion may cause shrinking along all the three directions. However, at the early stages of burning, much of the burning alcohol comes from near the surface region of

the mould and this shrinking effect due to alcohol out-diffusion is minimal. On the other hand, as at points 2 and 3 mentioned above, large tensions and volume (three-direction) expansions at the inner part of the mould can result from the expansion at the outer portions of the mould where burning takes place. It is thus expected that the overall dimensional changes at the inner mould locations are expansions, i.e., $\epsilon_1 > 0$, $\epsilon_2 > 0$, $\epsilon_3 > 0$.

3.1.2.2 Burning front at the middle of the mould cavity

As burning-out continues, the concentration of alcohol near the outer mould surfaces (such as points 1 and 5 in Figure 7) decreases. As a result, the violent burning front at the cavity side moves away from the opening towards the bottom of the cavity, e.g., to the vicinity of point 2 in Figure 7. The major events occurring at the different locations in the mould now can be described as follows.

- (a) At areas near the opening of the mould cavity, shrinking due to alcohol evaporation starts to dominate, which corresponds to the stage on the burning-out curves shown in Figure 6 following the initial expansion peak. With time increasing, less and less alcohol remains in these areas of the mould and removal of residual alcohol leads to negligible dimensional changes. The mould temperature decreases. And eventually, when the mould temperature is below the boiling temperature of water (100°C), an expansion period ensues due to the absorption of water vapour from the environment [12]. For the convenience of discussion, these above-mentioned events (following the initial expansion peak on the burning-out curves) are collectively referred to as

“cooling down events” in Table 1 and hereafter. Referring to Figure 6, the overall effect of these events on the dimensional changes of the mould at these locations is expected to be expansion in all the three directions, although the extent of the expansion will be relatively low because the expansion at the last stage is partially compensated by shrinking following the peak expansion and there are more restraints on deformation in the moulds used in this study than those in the simple bar-shaped specimens used to obtain the burning curves in Figure 6.

- (b) At locations down in the mould cavity where burning starts to take place (e.g., point 2 in Figure 7), volume expansion as observed during the initial stages of burning-out (Figure 6) is expected. However, as compared with expansion at the outer regions and near the cavity opening of the mould at the beginning of the burning-out, the extent of expansion will be considerably smaller. This is because, before burning starts at these locations, a considerable amount of alcohol has been evaporated and, as a result, the strength of the mould is increased while the amount of available alcohol to support violent burning is decreased. Thus, it becomes more difficult to form microcracks in the mould.
- (c) Further down towards the bottom of the mould cavity where burning-front has not reached yet, alcohol evaporation continues, leading to mould shrinking. At the same time, the expansion at the neighbouring burning regions (point 2) may lead to expansion at these areas in the ϵ_2 direction. Compared with the previous stages of burning, this stretching expansion effect is considerably reduced because the mould has

become much stiffer in all the regions. Depending on the relative contributions of the stretching (expansion) and the alcohol evaporation (shrinking) effects, the net dimensional changes at these locations at this stage will be either shrinking in all the directions with less shrinking along the ε_2 direction than in the other directions or expansion in the ε_2 direction and shrinking in the other two directions.

- (d) At the inner part of the mould (such as point 4, Figure 7), similar events to those in the previous stage of burning will occur, i.e., alcohol out-diffusion and being stretched due to expansion at the outer regions of the mould. However, as the mould strength has increased and expansion caused by burning in the cavity is decreased, the expansion component due to stretching is expected to reduce considerably. The overall dimensional changes in the inner part of the mould will depend on the relative contributions of the expansion and the shrinking. It is apparent that the shrinking effect will increase with time. This may either cause shrinking of the whole mould body or may cause the formation of cracks at these locations if the deformation (compression) of the mould in the outer regions is difficult.

3.1.2.3 Burning front near the bottom of the mould cavity

When the burning front gradually moves towards the bottom of the mould cavity (e.g. point 3, Figure 7), most part of the mould will have been considerably strengthened and there is much less alcohol left to support violent burning than in the previous stages. Therefore, very limited amount of expansion, if any, will result due to the burning. It is likely that the burning mainly accelerates the removal of alcohol from beneath the cavity

surface and causes shrinking in these regions. In the outer portions of the cavity (e.g., points 1 and 2, Figure 7), the “cooling down events”, i.e., alcohol evaporation, mould cooling down, and followed by an expansion due to the absorption of water vapour from the environment, will take place. This may lead to some expansion in all the three directions, although the extent will be very limited as the mould strength is fairly high. Inside the mould, alcohol will continue to escape by diffusion, leading to further development of tensile stresses in these regions. As in the previous stages, the actual dimensional changes will be dependent on the magnitude of stresses, stress status and strength in the surrounding regions, and the structure of the mould.

After a sufficient period of time, alcohol is completely removed from the mould; the temperature is dropped to room temperature; and stresses built up within the mould are relaxed by either dimensional changes, deformations/distortions, or the formation of micro- or macro-cracks.

3.1.2.4 Overall dimensional changes after burning-out

In Table 1, plus (+) or minus (-) signs are used to indicate whether the strains, ϵ_1 , ϵ_2 , and ϵ_3 , at a given location in the mould are tensile or compressive at the various burning-out stages; and different numbers of plus (+) or minus (-) signs have been used to qualitatively reflect the magnitude of the strains. These numbers are to some extent arbitrary. However, considering the discussions in the previous paragraphs, they are not completely baseless and should provide some reasonable value in illustrating the general trend of mould

dimensional changes as a function of feature location and orientation during the burning-out process.

Referring to Figures 1 and 7, strain ϵ_1 corresponds to dimensional changes in the vertical (Z) direction while strains ϵ_2 and ϵ_3 contribute to dimensional changes in the Y and X directions respectively. However, it should be noticed that the contributions of strains ϵ_2 and ϵ_3 to the horizontal dimensional changes of the mould are in the opposite directions: Positive ϵ_2 (at locations on the mould cross-section shown in Figure 7) leads to increased dimensions (expansion) in the Y direction, but a positive ϵ_3 reduces the opening distance in the mould cavity measured in the X direction between the parallel faces of the same feature on the opposite sides. Thus, considering the symmetrical shape of the mould cavity, positive ϵ_2 and/or negative ϵ_3 will result in expansion but negative ϵ_2 and/or positive ϵ_3 lead to overall shrinking/contraction of the mould cavity in the horizontal direction. In mathematical forms, the relationship between dimensional changes of the mould in the horizontal, ϵ_H , and the vertical, ϵ_V , directions and strains, ϵ_1 , ϵ_2 and ϵ_3 , occurring in the various stages of burning-out can be expressed by

$$\epsilon_H \propto (\sum \epsilon_2 - \sum \epsilon_3) \quad (1)$$

$$\epsilon_V \propto \sum \epsilon_1 \quad (2)$$

Based on the number of plus (+) or minus (-) signs assigned to the strains, ϵ_1 , ϵ_2 and ϵ_3 , in the various stages of burning-out (Table 1), the expected overall dimensional changes of

the ceramic mould in the vertical and horizontal directions, ϵ_V and ϵ_H , are predicted in the last two lines of Table 1. According to these results, as height increases in the vertical (Z) direction (from point 1 to point 3), the dimensions measured in the mould cavity change from expansion at the cavity opening (point 1) to shrinking at the cavity bottom (point 3). This trend agrees well with the experimental results shown in Figure 2. In the horizontal direction, agreement between the prediction (Table 1) and experimental results (Figure 2) is also obtained in the general trend of the dimensional changes as a function of feature dimensions/locations, with the expansion decreasing with increase in the feature dimensions (from cavity bottom at point 3 to cavity opening at point 1, Figure 7), although the predicted range of overall dimensional change (7 plus (+) signs) in Table 1 is relatively large compared with those predicted for the vertical direction (also 7 units). In the above discussions, several factors have not been included. The uniform shrinking before burning-out during immersion in alcohol may reduce the overall expansion and shift the curve towards more shrinking. In addition, the inner portions (e.g. point 5, Figure 7) of the ceramic mould will restrict the dimensional changes in the outer portions of the mould. Similarly, the dimensional changes among the different parts of the mould will interfere and restrict with each other. These effects will obviously reduce the extent of dimensional changes; dimensions in the ϵ_2 (horizontal) direction will be affected more than in the vertical direction. Considering the highly qualitative and arbitrary nature in assigning the numbers of plus (+) or minus (-) signs to strains in Table 1, the above explanations for the dependence of dimensional changes on feature location and orientation should be reasonably acceptable.

3.2 Effect of feature dimension, location and orientation on the dimensional variability

In Figure 3, the dimensional variability of ceramic moulds and castings also followed apparently different trends as a function of pattern dimension for features in the vertical direction and for those in the horizontal direction. At similar linear dimensions, features in the vertical direction showed considerably higher dimensional inconsistency than in the horizontal direction. The reasons for this are not immediately clear but might have some connections with the mechanisms for dimensional changes during the burning-out process. Dimensional changes in the vertical direction are related to the strain ϵ_1 (eq. (1)) which is normal to the free surface of steps in the mould cavity (Figure 7). Very little restrictions are exerted by the surrounding mould on deformations in this direction as are in the horizontal direction (particularly in the ϵ_2 direction). Fluctuations in burning conditions such as burning intensity, airflow conditions, and temperature, are easily reflected in dimensional changes in this freely deforming direction. However, in the horizontal direction, deformations in the ϵ_2 direction are restricted by the surrounding mould structures, which reduces the sensitivity of mould dimensional changes to burning condition fluctuations. In addition, the horizontal dimensional changes are affected by strains in both the ϵ_2 and the ϵ_3 directions (eq. (1)). Some of the effects of burning condition fluctuations on ϵ_2 and ϵ_3 may cancel out. As a result, variability in the horizontal dimensions is less than that in the vertical direction.

4. Conclusions

A stepped pyramid-shaped part was used to investigate the dimensional changes and dimensional variability of ceramic moulds and steel castings in the ceramic mould casting process. The following conclusions can be drawn:

- (1) The accuracy of castings is dominantly influenced by that of the ceramic moulds: The linear dimensional variability of the ceramic moulds was more than 50% that of the castings; the linear dimensional changes of castings as a function of feature dimensions followed the same trends as those for ceramic moulds except for an approximately 2.06% shrinkage from the mould; the straightness and flatness, measured on selected surfaces, for castings increased only slightly from those for the ceramic moulds.
- (2) The overall linear dimensional changes and the variability (inconsistency) of the ceramic mould and the casting depend on both orientations and dimensions of a feature on the part: The variations in dimensional changes (expansion or shrinkage) as a function of feature dimensions were more significant and more rapid for dimensions measured in the direction normal to the pyramid base, the vertical direction, than those in the direction parallel to the pyramid base, the horizontal direction. The dimensional variability of moulds and castings was significantly higher in the vertical direction than in the horizontal direction with similar feature dimensions.
- (3) The complex dependence of dimensional variations on feature orientation and location on the part has been discussed on the basis of asynchronous burning on the

mould cavity surface at different locations during the burning-out process.

Reasonably good agreement with experimental observations is obtained.

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Captions for Tables and Figures

- Figure 1 Schematic diagram for the pattern used for the assessment of mould and casting dimensional changes.
- Figure 2 Shrinkage or expansion of castings and the ceramic moulds relative to the pattern as a function of pattern dimension.
- Figure 3 Linear dimensional variability of castings and the ceramic moulds used to produce the castings as a function of pattern dimension.
- Figure 4 (a) The relationship between linear dimensional variability of castings and that of the ceramic moulds. (b) Ratio of dimensional variability of the ceramic moulds to the dimensional variability of the castings.
- Figure 5 Variation of (a) straightness and (b) flatness of castings and the ceramic moulds as a function of pattern dimensions.
- Figure 6 Some typical burning-out curves for the variation of length changes of ceramic mould specimens as a function of time during burning-out. The specimens had a bar shape (12 x 25 x 218 mm) and were either immersed in alcohol or dried in air for different times before the burning-out.
- Figure 7 Diagrams showing (a) the sectioned half mould at its burning-out position and (b) a unit cell defining the positive directions of strain/deformation at a specific point within the mould.
- Table 1 Summary of major events and their effects on the dimensional changes at different feature locations in the ceramic mould during the burning-out process. Refer to Figure 7 for locations/points 1 to 4 in the mould and for the directions of strains, ϵ_1 , ϵ_2 and ϵ_3 .

Table 1 Summary of major events and their effects on the dimensional changes of different features in the ceramic mould during the burning-out process. Refer to Figure 7 for locations/points 1 to 4 in the mould and for the directions of strains, ϵ_1 , ϵ_2 and ϵ_3 .

Location in the mould			1	2	3	4
Burning starts	Mould strength		Low	Low	Low	Low
	Major events		▪ Alcohol burning	▪ Alcohol evaporation ▪ Stretched	▪ Alcohol evaporation ▪ Stretched	▪ Alcohol out-diffusion ▪ Stretched
	Strains	ε ₁	++++	--	--	++
		ε ₂	++++	+++	+++	++
		ε ₃	++++	--	--	++
Burning near point 2 starts	Mould strength		High	Low – medium	Low -medium	Low
	Major events		▪ Cooling down events (see below)	▪ Alcohol burning	▪ Alcohol evaporation ▪ Stretched	▪ Alcohol out-diffusion ▪ Stretched, restricted deformation
	Strains	ε ₁		+++	-	+/-
		ε ₂		+++	+	+/-
		ε ₃		+++	-	+/-
Burning near point 3 starts	Mould strength		High	High	Medium	Low – medium
	Major events		▪ Cooling down events (see below)	▪ Cooling down events (see below)	▪ Alcohol burning (little expansion)	▪ Alcohol out-diffusion ▪ Stretched, restricted deformation
	Strains	ε ₁			+/-	+/-
		ε ₂			+/-	+/-
		ε ₃			+/-	+/-
Cooling down events	Mould strength		High	High	High	Medium – high
	Major events		▪ Water absorption ▪ Residual alcohol evaporation ▪ Under tension			▪ Residual alcohol out-diffusion ▪ Water absorption ▪ Restricted deformation
	Strains	ε ₁	+	+	+	+/-
		ε ₂	+	+	+	+/-
		ε ₃	+	+	+	+/-
Overall dimension changes		Σε ₁	+++++	++	--	?
		Σε ₂	+++++	+++++	+++++	?
		Σε ₃	+++++	++	--	?
		ε _v	5 (+)	2 (+)	2 (-)	
		ε _H	0 (+)	5 (+)	7 (+)

Figure 1 Schematic diagram for the pattern used for the assessment of mould and casting dimensional changes.

Figure 2 Shrinkage or expansion of castings and the ceramic moulds relative to the pattern as a function of pattern dimension.

Figure 3 Linear dimensional variability of castings and the ceramic moulds used to produce the castings as a function of pattern dimension.

(a)

(b)

Figure 4 (a) The relationship between linear dimensional variability of castings and that of the ceramic moulds. (b) Ratio of dimensional variability of the ceramic moulds to the dimensional variability of the castings.

(a)

(b)

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