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Simulation of Dimensional Changes in Steel Casting

Shouzhu (Hans) Ou and Christoph Beckermann

Department of Mechanical and Industrial Engineering

The University of Iowa, Iowa City, IA 52242

ABSTRACT

Pattern allowances in casting of steel are predicted using the casting simulation software MAGMASOFT. This software contains a module (MAGMAstress) that calculates the stresses, strains, and distortions during casting due to thermal effects (temperature differences) and volume changes (e.g., shrinkage, sand expansion, etc.). The purpose of the study is to assess the capabilities of this simulation software to predict dimensional changes occurring during solidification and cooling of a steel casting. For this purpose, the simulation results are compared to dimensional measurements performed by Voigt and coworkers at Penn State University on (1) cylindrical test castings with different mold and core materials and dimensions, and (2) a shovel adapter casting produced by McConway & Torley Group. The comparisons reveal that in many cases, the final dimensions of a casting can be predicted successfully both for free and hindered shrinkage cases. A key to accurate simulation is the use of accurate sand and metal properties, in particular the thermal expansion coefficients and density as a function of temperature. In those cases where a simulation result does not agree with a measurement, a detailed analysis is conducted to identify the underlying reasons. They include the following shortcomings in the simulations: (1) irreversible sand expansion is not taken into account, which is important when small cores or other portions of the mold are heated to temperatures above about 1,200 ^{o}C; and (2) the mold sand surrounding the casting is not taken into account in the stress simulations. The latter can cause problems in the predictions when (i) there is significant early sand expansion due to heating of the mold before a solid steel shell forms, (ii) the solidifying casting does not contract away from the mold (and an air gap forms) but, instead, pushes against it resulting in some stress buildup in and hindrance due to the mold, and (iii) the mold experiences some movement or yielding due to metallostatic and other forces acting on it before a solid steel shell forms (particularly for green sand). An attempt is made to estimate the magnitude of these effects and correct the pattern allowances predicted by the simulation code. After the corrections, good agreement with the measurements is obtained for the test cylinders in all cases. Recommendations are made for improving the simulations.

1. INTRODUCTION

Meeting dimensional requirements in sand casting of steel is more challenging than for most other metals and casting processes. Steel castings range in size from 1 to 100,000 pounds and have often complex geometries. There are many highly interdependent physical processes responsible for steel castings not having the same dimensions as the pattern from which they are made. Shrinkage of the steel upon solidification and contractions during cooling to room temperature are the primary reasons for dimensional changes during casting. In the case such shrinkage is free or unrestrained by the mold and an air gap forms between the casting and the mold, the needed pattern allowance is well known (see below). However, portions of a casting can contract onto a core or other parts of the mold. In that case, stresses develop and the resulting strains or deformations depend on the mechanical properties of the sand and the solidifying steel. Such hindered shrinkage of restrained casting features is usually less in magnitude than free shrinkage. Stresses also develop due to non-uniform cooling of the casting. They can be particularly severe during steel casting due to the high pouring temperature of steel (relative to ambient) and the presence of geometric complexity (different section thicknesses, risers, etc.). Such thermal stresses can result in distortion of a casting. The final dimensions of a steel casting are also strongly influenced by volumetric changes of the mold and core sand. The high pouring temperature of steel can cause significant early heating and thermal expansion of the mold sand and, especially, of small cores. Since such expansion can occur before a solid steel shell forms, liquid steel may be "pushed" into the riser or back into the gating system, and dimensional changes result. Upon cooling, the sand usually contracts again. However, early sand expansion can be irreversible if the local temperature exceeds the temperature for the quartz to crystobolite phase transformation (about 1,300 ^{o}C). The outcome is again much different final casting dimensions. Other factors include a lack of strength of the sand resulting in early mold wall movement due to the action of metallostatic and other (e.g., impact during filling) forces. Finally, mold assembly inaccuracies, the presence of a parting line, oxide scale removal, measurement difficulties, heat treatment, and other factors can all contribute to dimensional variability. Clearly, most of the expensive pattern rework occurring in steel foundries is due to dimensional accuracy issues.

There have been many previous efforts to understand dimensional changes and quantify pattern allowances in steel casting. The "pattern allowance" (PA) is defined as:

$$\text{PA [\%]} = \frac{\text{Pattern feature size} - \text{Casting feature size}}{\text{Casting feature size}} \times 100 \qquad (1)$$

In the 1930s, Briggs and Gezelius [1] measured the shrinkage of 0.35% C steel under various restraints. They found that the PA for free shrinkage is equal to 2.4%, and for hindered shrinkage the PA ranges from 0.39% to 2.4%. Henschel et al. [2] investigated the effect of mold dilation on the PA. They measured the linear expansion properties of silica, zircon, and olivine sands up to 1,093 ^{o}C during solidification of white iron, nodular iron, Al-Si alloys, and Ni-Al bronze. Their results show that mold/core expansion and lack of strength or density in parts of the mold play an essential role in determining the PA. Several studies have used statistical methods to formulate relationships between the PA and factors such as the casting method, degree of hindrance, parting line, etc. [3-6]. Wieser et al. [5] demonstrated the difficulty of determining the PA for steel castings, particularly for dimensions less than 10 in (254 mm). Andrews et al. [7] measured the linear thermal expansion of sand molding materials with different binders (resin, furan, and sodium-silicate), for various additions of iron oxide, and under a simulated mold atmosphere. The results for silica sand show a large expansion of up to 12% at temperatures above 1,200 ^{o}C to 1,300 ^{o}C. This expansion is attributed to the formation of cristobolite [8, 9]. Voigt and coworkers [10-15, and references therein] have performed extensive studies on PAs in steel castings during the 1990s and later. They performed careful measurements of the variability of PAs and developed statistical relations for the dependence of PAs on the degree of restraint for various steels and molding materials.

Increased competitiveness in the casting industry has mandated a reduced scrap rate and lower casting lead and cycle times. For this reason many foundries are using computer simulation to design the casting process and ensure quality castings before the first metal is poured. Computer simulation of mold filling and solidification has attained a high level of maturity, and gating and risering design can reliably be done using simulation. However, the prediction of pattern allowances by casting simulation has not yet been possible. Recently, casting simulation software has become available that allows for the calculation of stresses and strains during casting due to thermal effects and volume changes. This capability may allow for the prediction of the dimensional changes occurring during solidification and cooling and, thus, of pattern allowances.

The objective of the present study is to provide an assessment the capabilities of casting simulation software to predict pattern allowances in steel casting. The simulations are performed using the MAGMAstress module of the commonly used commercial software MAGMASOFT. The simulation results are compared to available benchmark dimensional measurements performed by Voigt and coworkers for two cases:
(1) cylindrical test castings with different mold and core materials and dimensions [13, 14], and
(2) a shovel adapter casting produced by McConway & Torley Group [15].
The comparisons reveal the instances where pattern allowances can be predicted successfully using the available software and the areas where additional software development may be needed.

In the next section, our work on assembling the expansion properties of various sands and other simulation conditions are described. In Section 3, the simulations for the cylindrical test castings are presented. The predictions are compared to the measurements and any disagreements are explained in detail. The simulation results for the shovel adaptor casting are provided in Section 4 and compared to the measurements. The findings of this study are summarized in Section 5.

2. THERMAL EXPANSION COEFFICIENTS AND OTHER SIMULATION CONDITIONS

The thermal expansion coefficients of the steel and sand as a function of temperature are important input data for the stress simulations. The necessary data for steel, in the form of densities were obtained from the interdendritic solidification software IDS developed by Miettinen et al. [16, 17]. This software calculates the solidification path for a given steel composition and cooling rate. It outputs, among other data, the density variation with temperature starting from liquid at the pouring temperature, across the solidification interval (solid-liquid mixture), down to solid at room temperature. The MAGMAstress module uses the linear thermal expansion coefficient, α, in units of 1/°C, instead of the density, ρ [18]. The two properties are related by:

$$\alpha = -\frac{1}{3\rho}\frac{\partial \rho}{\partial T} \tag{2}$$

The thermal expansion coefficients of the sand materials were obtained from the measurements of Henschel et al. [2] and Andrews et al. [7]. Their data for zircon sand, sodium-silicate bonded silica sand without iron oxide, pepset silica sand with black oxide addition, furan silica sand with 2% oxide addition, and green sand are shown in Figures 1 to 5, respectively. They measured the relative change of length, $\varepsilon = \Delta L / L$, rather than the linear thermal expansion coefficient, α. These two quantities are related by

$$\alpha = \frac{\varepsilon}{\Delta T} \tag{3}$$

where ΔT is the temperature interval over which the sand expands by a length ΔL. The conversion from the graphs of $\varepsilon(T)$ to $\alpha(T)$ is done numerically using the following formula:

$$\alpha(T_i) = \frac{\varepsilon_i - \varepsilon_{i-1}}{(T_i - T_{i-1})(1 + \varepsilon_{i-1})} \tag{4}$$

where ε_i (ε_{i-1}) is the relative change of length at temperature T_i (T_{i-1}) and the subscript i denotes a discrete point on the graph $\varepsilon(T)$. The interval between points i and $i-1$ is chosen sufficiently small so as to obtain an accurate conversion. The converted data for $\alpha(T)$ are also shown in Figures 1 to 5 using the scale on the right-hand-side of the graphs. Some extrapolations of the data above the measured temperature range were necessary because sand temperatures in the simulations reached as high as 1,500 °C. The accuracy of these extrapolations is not known, but they are believed to have a relatively minor effect on the results presented here. The data for silica sand in Figures 2 to 4 illustrate the phase transformations taking place upon heating. According to the phase diagram of silica sand [8, 9], the α-β quartz transformation takes place at 573 °C, the transformation to tridymite at 870 °C, to cristobolite at 1,470 °C, and finally to melted quartz at about 1,700 °C. The α-β quartz transformation at 573 °C is reversible upon cooling. However, the phase transformations of β quartz to tridymite at 870 °C and of tridymite to cristobolite at 1,470 °C are irreversible. The measurements indicate that β quartz transforms directly to β cristobolite and that this transformation is slow below 1,200 °C and relatively rapid above 1,300 °C [7, 8]. The irreversible nature of the sand expansion at high temperatures is not taken into account in the simulation software. In other words, the simulation software assumes that during cooling, the thermal expansion coefficient follows the lines in Figures 1 to 5. The effects of this assumption on the predictions are assessed below.

All other properties of the sands and the mechanical properties of the steels in the various simulation cases are taken from the MAGMASOFT database. The thermal properties of the steels, including the solid fraction-temperature relation, are generated using IDS and also input into the MAGMASOFT database.

A few other remarks are needed on the simulation setup. The outer mold sand surrounding the casting is excluded in the stress calculations (but not in the casting/solidification simulation). This is done because MAGMAstress cannot account for the separation of the casting from the mold due to shrinkage and the formation of an air gap. If the outer mold parts were included, an unrealistic tension would be transmitted into the mold when an air gap forms. As discussed further below, the exclusion of the outer mold in the stress simulations can cause problems in cases where the mold-metal interface is in compression (e.g., due to sand expansion). The cores are, however, taken into account in the stress simulations, because in most cases the core-metal interface is in compression. The risers and gates, as well as their removal, are also simulated. The simulations are stopped when the casting has cooled to room temperature. Filling simulations are not performed because the effect of filling on the temperature distributions is small for the castings simulated here.

3. CYLINDRICAL TEST CASTINGS

3.1 Description

Simulations were performed of four of the benchmark dimensional experiments of Peters and Voigt [14], a more complete description of which can be found in Peters [13]. As shown in Figure 6, the hollow cylindrical test castings, made of WCB steel, had an outside diameter of 4 in (101.6 mm) and length of 8 in (203.2 mm). Two different core diameters of 1 in (25.4 mm) and 3 in (76.2 mm) were used. All other dimensions and the coordinate system used in the simulations are also provided in Figure 6. The four combinations of sands and binders analyzed here are summarized in Table 1. The two sands are zircon and silica, the latter of which contained iron oxide in two of the four cases. The two binders used for the silica sand are an organic phenolic urethane (pepset) binder and an inorganic ester cured sodium silicate binder. The casting simulations were performed with exactly the setup shown in Figure 6. Two cylinders, fed by a single riser on one end, were cast horizontally in a single mold. For the stress simulations, the mold sand between the two cylinders was included by treating it as a core in the simulation setup. This was done because this sand can be expected to be in compression. The remainder of the mold sand around the cylinders was not included for the reason explained earlier.

The dimensions of the cylinders were measured after the removal of the riser and gating system, but without heat treatment. The exact measurement procedures are described in Refs. [13, 14]. The measured ranges of the pattern allowances (PAs) for the outer diameter (OD) and the inner diameter (ID) for the four cases simulated here are given in Table 1. It can be seen that the PAs for the IDs range from +3.7% to -16.7%, while the OD PAs are all in the range from 2.0% to 4.5%. Peters [13] obtained estimates of the PAs by performing relatively simple calculations of the temperature distributions, sand expansions, and steel contractions in the various cases. These estimates are also included in Table 1 and tend to agree with the measurements. The results of the present simulations are discussed in the next subsections. The discussion is divided into various sections according to the physical mechanisms involved.

Table 1: Measured and predicted pattern allowances (PAs) for the cylindrical test castings of Peters and Voigt [13, 14].

Category		Case 1	Case 2	Case 3	Case 4
Mold		Pepset silica sand with iron oxide addition	Pepset silica sand with iron oxide addition	Pepset silica sand with iron oxide addition	Sodium silicate-bonded silica sand without iron oxide addition
Core		Zircon sand	Sodium silicate-bonded silica sand without iron oxide addition	Sodium silicate-bonded silica sand without iron oxide addition	Zircon sand
ID [mm]		76.2	76.2	25.4	25.4
OD [mm]		101.6	101.6	101.6	101.6
PA-ID [%]	**Measured**	1.2 to 1.7	0.1 to 0.7	-12.4 to –16.7	0.9 to 3.7
	Peters' prediction	---	1.4	-15.9	---
	Simulated	1.44	0.83	-2.84	1.64
PA-OD [%]	**Measured**	2.2 - 3.9	2.2 – 3.9	3.1 – 4.5	2.0 - 3.5
	Peters' prediction	2.8	2.8	3.9	3.9
	Simulated	1.79	1.54	1.98	2.18

3.2 Free shrinkage: cylinder length

The first step in verifying the simulations is to examine the value of the PA predicted for the case of free or unrestrained shrinkage. An example of a feature that undergoes free shrinkage in the test castings is given by the length of the cylinder at the end opposite to the riser. Figure 7 shows the Y-direction (along the cylinder axis) displacements and stresses as a function of time at two points (S11 and S25) on the end of the cylinder for case 1 in Table 1. The exact location of the two points is provided in Figure 8. It can be seen from Figure 7 that the points S11 and S25 both move in the negative Y-direction, indicating shrinkage, and that the total displacement is equal to 2.44 mm and 2.71 mm in magnitude for S11 and S25, respectively. Furthermore, the Y-direction stresses remain very close to zero, indicating that the end of the cylinder indeed moves freely. The reason S11 and S25 are not displaced by the same amount is that the cylinder solidifies and cools asymmetrically due to the presence of the riser and of the other cylinder. Figure 8 shows the predicted "zero displacement plane" (ZDP) for the Y-direction displacements. The ZDP is somewhat skewed and shifted towards the riser end, instead of being exactly in the middle between the two ends.

These results can now be used to calculate the PA for free shrinkage predicted by the simulation code. The pattern lengths from the ZDP to points S11 and S25 are 104.2 mm and 115.88 mm, respectively (see Figure 8). Using Equation (1) and the displacement values noted above, the calculated PA is equal to 2.4% for both points on the end of the cylinder. Peters and Voigt [13, 14] did not measure the PA for the cylinder length, so no comparisons are possible. However, the agreement of the predicted PA with the 2.4% PA value measured by Briggs and Gezelius [1] for free shrinkage establishes some confidence in the simulations.

3.3 Hindered shrinkage in the presence of reversible core expansion: PA-ID in cases 1 and 4

The IDs in cases 1 and 4 with a zircon core are examples of features that undergo hindered shrinkage in the presence of reversible core expansion. As the cylinder solidifies and cools, it contracts on to the core. The core is under compression, and the strength of the core provides a hindrance to the shrinkage. The early expansion of the zircon sand is believed to be fully reversible upon cooling.

Before discussing the PAs, it is necessary to understand the different solidification and cooling behaviors in the cases with the large (1 and 2) and small (3 and 4) diameter cores. Figures 9 to 11 show cooling (temperature versus time) curves for various points of interest. For cases 1 and 2 with the 3 in (76.2 mm) core, Figure 9 indicates that the outer and inner walls of the cylinder solidify at 108 s and 122 s, respectively, after pouring; furthermore, the sand adjacent to the outer (and inner) cylinder diameter heats up to about 1,200 ^{o}C, and the sand at the center of the core to less than 100 ^{o}C. Hence, there are temperature differences of more than 1,000 ^{o}C inside the large diameter cores of cases 1 and 2. The temperatures are much different in cases 3 and 4 with the 1 in (25.4 mm) core, because significantly more steel is present and the thermal mass of the core is much less. Figure 10 shows that the outer and inner walls of the cylinder solidify at 12.1 min and 16.4 min, respectively, which is more than 10 min later than in cases 1 and 2. Sand temperatures for cases 3 and 4 are provided in Figure 11. The small diameter core is almost isothermal and reaches a maximum temperature of 1,500 ^{o}C; this should be contrasted to the maximum temperature of less than 100 ^{o}C at the center of the large diameter core (cases 1 and 2). The sand adjacent to the outer diameter reaches about 1,300 ^{o}C, which is 100 ^{o}C higher than in cases 1 and 2. The sand 0.5 in (12.7 mm) away from the cylinder still reaches a maximum temperature of almost 1,200 ^{o}C.

The predicted X-direction displacements for the casting and the cores after cooling to room temperature are shown in Figures 12 and 13, respectively, for case 1. The X-direction is the direction normal to the cylinder axis in the horizontal plane. Note that a relatively large magnification factor of 15 is applied in order to make the displacements more visible in the figures. Figure 13 illustrates the deformation of the cores in case 1. It can be seen that the cylinders make an impression on the cores. Figure 12 indicates that there is some distortion of the casting, with the non-riser ends of the two cylinders bending towards each other and the other ends held in place by the riser. Because of uneven solidification and cooling, the displacement pattern on the surface of each cylinder is non-uniform. This non-uniformity, particularly at the ends of each cylinder, would result in different predicted PAs at each point on the cylinder. For the purpose of comparing to the measurements, only averages are reported here. The predicted PAs are averaged using between 14 and 22 points evenly distributed over the inner or outer cylinder surface. Note that the measured PAs in Table 1 are reported as ranges that reflect the non-uniformities over the cast cylinder surface; a mean of the individual measurements is not available. Although not shown here, the ranges in the predicted PAs are of a similar magnitude as the ranges in the measured PAs.

Returning now to the IDs in cases 1 and 4 with zircon cores, Table 1 shows that the predicted PAs are equal to 1.44% and 1.64%, respectively. These predictions are in good agreements with the measurements, which range from 1.2% to 1.7% in case 1 and 0.9% to 3.7% in case 4. They are considerably lower than the value of 2.4% for free shrinkage, because the shrinkage is hindered or restrained by the cores. The good agreement between the predictions and measurements indicate that (i) the expansion of the zircon cores is indeed reversible and (ii) the mechanical behavior of the materials in compression is modeled reasonably well. It is also noteworthy that the predicted PAs for the ID in cases 1 and 4 are slightly different. This is caused by the different diameters of the cores, which result in different temperature distributions and expansion/contraction behaviors. Hence, the PAs for restrained features are functions of the feature size, with everything else being the same.

3.4 Hindered shrinkage in the presence of irreversible core expansion: PA-ID in cases 2 and 3

Examples of hindered shrinkage in the presence of irreversible core expansion are provided by the ID in cases 2 and 3. In these two cases the cores are made of sodium silicate bonded silica sand, as opposed to zircon sand in cases 1 and 4. The silica sand undergoes a much larger expansion (up to 12%) at high temperatures than the zircon sand (see Figures 1 and 2). In addition, the high temperature expansion in the case of silica sand is largely irreversible; however, this irreversibility is not taken into account in the simulations, as noted earlier.

The predicted PA for the ID in case 2 is 0.83% (see Table 1), which should be contrasted to the 1.44% PA predicted in case 1. The smaller PA for the ID in case 2 compared to case 1 can be expected because of the larger core expansion in case 2. This effect is predicted even though the sand expansion is assumed to be reversible in the simulation. In case 3 the predicted PA for the ID is -2.84%, which should be compared to 1.64% in case 4. The negative PA in case 3 indicates that the ID is predicted to expand, rather than contract, which again can be attributed to the large core expansion in case 3. The difference in the PAs between cases 3 and 4 is much larger than between cases 2 and 1 because of the difference in the core diameters (25.4 mm versus 76.2 mm). Since the smaller core in cases 3 and 4 is heated to a much higher temperature (up to 1,500 ^{o}C, see Figure 11), the core expansion will be much greater than in cases 1 and 2.

Table 1 shows that the quantitative agreement between the predicted and measured PAs for the ID in cases 2 and 3 is not good. The prediction that the PAs in cases 2 and 3 are lower than in cases 1 and 4, and that the PA in case 3 is negative, is in qualitative agreement with the measurements. In both cases 2 and 3, however, the measured PAs for the ID are lower than the predicted PAs. The difference is relatively small in case 2, but in case 3 it is large (<-12.4% measured versus -2.84% predicted).

In order to verify that this disagreement is due to the fact that the simulation does not take into account the irreversibility in the core expansion, the magnitude of the effect of the irreversibility on the PA is estimated for cases 2 and 3. Figure 14 shows the predicted displacements of points S3 and S4 on opposite sides of the inside diameter as a function of time for case 2. It can be seen that before a solid steel shell forms at a time of 122 s, the inside (core) diameter is predicted to expand by 0.7 mm at this location (or 0.52 mm on the average). Since in reality this expansion is irreversible, the core would not contract back upon cooling as rapidly as shown in Figure 14. Thus, a rough estimate of the irreversibility effect can be obtained by subtracting the early (average) expansion of 0.52 mm from the predicted contraction in case 2 (0.63 mm) when calculating the PA. This is demonstrated in Table 2. The same procedure was applied in case 3. The corrected PAs in Table 2 show much better agreement with the measured ones than the PAs directly taken from the simulations. This indicates that irreversible core expansion is indeed responsible for the disagreement. The corrected PA in case 3 still underestimates the measured expansion, which may be attributed to the fact that the present correction procedure does not include the irreversibility effect after solidification begins. In particular, the irreversible expansion of the core would provide additional hindrance after solidification, which is not accounted for presently.

Table 2: Effect of irreversible core expansion on the predicted pattern allowances (PAs) for the inner cylinder diameter (ID) in cases 2 and 3.

Case	Predicted by simulation		Estimated contribution due to irreversible core expansion		Corrected PA-ID [%]	Measured PA-ID [%]
	Shrinkage [mm]	PA-ID [%]	Shrinkage [mm]	PA-ID [%]		
Case 2	0.63	0.83	-0.52	-0.68	0.15	0.1- 0.7
Case 3	-0.74	-2.84	-1.67	-6.17	-8.67	-12.4 to –16.7

3.5 Partially hindered shrinkage in the presence of irreversible mold expansion: PA-OD in cases 1 to 4

The outer diameter (OD) of the cylinders is considered a partially restrained feature because of the presence of the core on the inside. Partially restrained features typically have a PA less than the one for unrestrained features that undergo free shrinkage (about 2.4%). However, Table 1 shows that the measured PA's for the OD are larger on the average, with the upper limits of the measurement ranges being as high as 3.5% to 4.5%. Peters [13] attributed this effect to expansion of the outer mold sand around the cylinders. The expanding mold would tend to push the outer cylinder diameter inwards, causing a reduction in the OD, in addition to the one due to shrinkage of the steel. By estimating the magnitude of this mold expansion effect, Peters [13] was able to predict the PAs for the ODs and obtain good agreement with the measurements in all four cases of Table 1.

The simulations predict PAs for the OD ranging from 1.54% to 2.18% in the four cases of Table 1. As expected, these PAs are lower than the one predicted for free shrinkage (2.4%) because the simulations account for core hindrance. The PAs for the OD in cases 1 and 2 are predicted to be about 0.4% lower than in cases 3 and 4, because the larger core in cases 1 and 2 provides more hindrance. Furthermore, the predicted PAs for the OD in cases 2 and 3 with the silica sand core are about 0.2% lower than in the corresponding cases 1 and 4, respectively, with the zircon sand core.

Compared to the measurements, which give PAs for the OD that are all above 2.4% as noted above, the predictions are too low by at least 1% on the average. This disagreement can be attributed to the expansion of and hindrance by the outer mold. Recall that the outer mold sand is not taken into account in the simulations, other than for the sand between the two cylinders. The situation is further complicated by the fact that some of the sand expansion is irreversible, because the mold adjacent to the cylinders reaches temperatures as high as 1,200 ^{o}C to 1,300 ^{o}C (see Figures 9 and 11).

In order to estimate the magnitude of the mold expansion and hindrance effects, the following procedure was adopted. Figure 15 shows the predicted displacements of two points (S22 and S7) on the outside diameter in case 1. Point S22 is located on the side facing the second cylinder, whereas point S7 is located on the opposite side of the cylinder. Because the sand between the two cylinders is included in the simulations, the displacements predicted for point S22 include the effects of (reversible) mold expansion and hindrance, while the ones for S7 do not. Before solidification, point S22 shows a maximum inward displacement of 0.04 mm (at about 60 s) due to early mold expansion. Since in reality this expansion is irreversible, the 0.04 mm is added to the predicted contraction at this point. The same amount is added to the predicted contraction at point S7. In addition, Figure 15 shows that point S7 undergoes a large outward displacement (expansion) of 0.29 mm before solidification. This can be attributed to the fact that point S7 moves freely (no mold hindrance) in the simulations, and the 0.29 mm outward displacement simply reflects the early expansion of the core. Hence, 0.29 mm is added to the predicted contraction at point S7, since in reality the mold would provide sufficient hindrance to prevent the outward movement of the outer cylinder surface before solidification. No such correction is needed for point S22. A summary of all corrections made for the OD PA in all four cases is provided in Table 3. The corrected PAs for the OD are in better agreement with the measurements than the PAs predicted directly by the simulations, although they are still somewhat lower. Nonetheless, the rough estimates indicate that the disagreement between the measurements and predictions is indeed due to the neglect of the outer mold in the simulations. More exact corrections are not possible due to the complex interplay of the various phenomena present.

Table 3: Effects of outer mold expansion and hindrance on the predicted pattern allowances (PAs) for the outer cylinder diameter (OD).

Case	Predicted by simulation		Estimated contributions due to outer mold		Corrected PA-OD [%]	Measured PA-OD [%]
	Shrinkage [mm]	PA-OD [%]	Shrinkage [mm]	PA-OD [%]		
Case 1	1.787	1.79	0.37	0.366	2.17	2.2-3.5
Case 2	1.541	1.54	0.43	0.425	1.98	2.2-3.5
Case 3	1.973	1.98	0.48	0.475	2.47	3.1-4.5
Case 4	2.168	2.18	0.2	0.197	2.39	2.0-3.5

4. SHOVEL ADAPTER CASTING

4.1 Description

The shovel adapter was cast by McConway & Torley Group and the dimensional measurements were performed by Deo and Voigt [15]. Figure 16 shows a photograph of the casting before heat treatment. The casting was made of AISI 4130 steel in a green sand mold inside a bounding box of dimensions 41 in (1041.4 mm) by 17 in (431.8 mm) by 15 in (381 mm). The pouring temperature was at 1,600 ^{o}C and shakeout was performed at room temperature. A tie rod connection was cast between each of the two legs of the U-shape to avoid excessive distortion of the legs. A solid model of the casting, including the rigging and mold, was obtained directly from McConway & Torley Group. The casting rigging and arrangement of the cores is shown in Figure 17.

The measurements used in the present study for the comparisons with the simulations were performed with the tie rods before heat treatment. A Faro arm was used for scanning two-dimensional profiles of the casting [15]. The scans of interest here were taken 0.25 in (6.35 mm) below the upper edge of the casting as shown in Figure 17. The figure also indicates the location of the "stress points" used in the simulation to compare the predicted displacements to the measurements. Five castings were scanned, and each casting thrice, to provide an average value; three scans of the core boxes and patterns were taken [15]. The scans were dimensionally analyzed using CAD software and the shrinkage and PAs were calculated [15]. Measurements performed by Deo and Voigt [15] across the parting line and after heat treatment are not used in the present study.

All three no-bake silica sand cores (Figure 17) were included in the stress simulation. The green sand in part of the U shape cavity (Figure 17) was also modeled as a core for the purpose of the stress simulation. For the reasons explained in Section 2, the surrounding green sand mold was not included in the stress simulation (it is, of course, accounted for in the casting/solidification simulation). The data for the thermal expansion coefficients of no-bake silica sand and green sand, shown in Figures 4 and 5, respectively, were used. As an example of simulation results, the predicted Y-direction displacements are displayed in Figure 18. It can be seen that the casting undergoes the expected shrinkage, but considerable non-uniformities in the shrinkage pattern and distortions due to uneven cooling are present. A detailed comparison of the predicted and measured PAs is presented in the next subsection.

4.2 Comparison of measured and predicted PAs

Comparisons between measured and predicted PAs as a function of distance along various features are shown in Figures 19 to 21. The measured and predicted PAs are indicated as solid (filled) and open symbols, respectively. A total of six different features are examined. Features B and D in Figure 19 are the fully restrained inside dimensions of the U shape. Feature B is restrained by the green sand, while feature D is restrained by the no-bake silica sand core. Features A, E, and G in Figure 20 correspond to the thickness dimension of the legs of the U shape and are unrestrained. Features C and F in Figure 21 are the outside dimensions of the U shape. Feature C is partially restrained, whereas feature F is unrestrained.

In Figure 19, the measured PAs for the restrained feature B start at about 0% from the far end of the casting (where the tie bars are located) and increase to between 0.8% and 1.8% towards the end of the green sand core. The predicted PAs for feature B show a similar increase, but are consistently below the measurements by about 0.5% to 1%. As expected, the PAs are below the value of 2.4% for free shrinkage, since feature B is restrained by the green sand core. Both the measured and predicted PAs near the far end are negative, indicating some expansion. This expansion can be attributed to distortion of the legs of the U shape that occurs despite the presence of the tie bars. The sensitivity of the PAs to the distance from the edge is illustrated by the shaded point which represents the predicted PA exactly at the tie bar location, whereas all other PAs correspond to locations 0.25 in (6.35 mm) from the edge (see Figure 17). It can be seen that the PA at the tie bar is near 0% which agrees better with the measurements at the same distance from the far end. The measured PAs for feature D (restrained by the no-bake silica sand core) are all around 3.5%, whereas as the predicted PAs for that feature remain around 0.5%. This prediction is in the same range as the predicted PAs for the (fully restrained) IDs of the cylindrical test castings of Section 3. The reason for the large measured PAs for feature D, which are even above the values for free shrinkage, is not known.

Features A, E, and G are all unrestrained features, and Figure 20 shows that the predicted PAs are all around 2.4%, as expected, except for a small increase with distance for feature E. The measured PAs, on the other hand, show considerable deviation from this value: the PAs for features A and G change sharply, starting at values higher than 3% at the far end and decreasing to around 1% near the end of the green sand core; the PAs for feature E adjacent to the no-bake silica sand mold are all around 1.5% to 2%. It is possible that mold movement is responsible for these discrepancies, particularly in view of the fact that green sand molds are known to be dimensionally less reliable. Recall that the outer mold is not taken into account in the simulation.

The PAs as a function of distance from the far end for the outside dimensions of the U shape, features C and F, are shown in Figure 21. The PAs for feature C are a direct consequence of the PAs for features A, B, and G. This is case because the PA for feature C can be calculated by adding up the shrinkages for features A, B, and G (see Figure 21). The validity of this “addition rule” was verified for both the measurements and predictions. Due this relation, any disagreement between the measured and predicted PAs for feature C can be directly contributed to the disagreements already discussed in connection with features A, B, and G. It can be seen that the PA for feature C is strongly under predicted at the far end of the casting, but the agreement becomes better towards the end of the green sand core. The measured and predicted PAs for feature F show the same general trend, but the measurements are about 0.5% below the predictions. It is interesting to note that both the measured and predicted PAs for the unrestrained feature F are below the 2.4% value for free shrinkage. This may be attributed to expansion of the cores on the sides of this feature, which is accounted for in the simulation. As before, the disagreement is most likely due to the fact that the outer green sand mold is not included in the stress simulation. Furthermore, wall movement of the green sand mold during casting may contribute to the measured PAs being somewhat different from what would be expected for silica sand molds (especially for features D and E). Such mold wall movement would be difficult to account for in a simulation, partially because the mechanical properties of green sand molds are not well known.

5. CONCLUSIONS

The capabilities of combined casting and stress simulation to predict pattern allowances (PAs) in steel castings are assessed. The simulation results are compared to careful dimensional measurements by Voigt and coworkers for (i) cylindrical test castings and (ii) a large shovel adaptor casting produced by McConway & Torley Group. The comparisons show that in many cases the PAs are predicted well if accurate thermal expansion properties for the steel, mold, and core materials are used in the simulations. There are basically two shortcomings in the stress simulations that cause persistent disagreements with the measurements. One is that irreversible expansion of silica sand is not taken into account in the model. This is particularly important for small cores or other mold portions that reach temperatures higher than about 1,200 ^{o}C. The second shortcoming is that the stress model cannot account for the formation of an air gap between the casting and the mold. For that reason, the outer mold typically needs to be excluded from the stress simulations altogether. This can cause problems in the predictions when there is significant mold expansion, mold hindrance, or mold movement. Work is underway at MAGMA GmbH to improve the stress simulation model and a new version should be available soon.

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