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Effect of Casting Form Variability on Machining Fixturing Error

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ABSTRACT

Many castings are eventually machined to create additional features or tighter tolerances that are beyond the capabilities of the casting process. To accomplish this machining, the castings must be located in a fixture. Surface errors on the casting will cause the position and orientation of the casting to be offset from the nominal. This could result in problems, since the cutting tool is often programmed with respect to the fixture.

A method is developed to calculate the deviation of the workpiece position and orientation, based on the position of the fixture locating pins and the expected casting surface errors. The model can be used to develop the optimal fixture design and determine the appropriate machining allowances. The machining allowance is the sum of the positional error for the particular surface to be machined, half of the flatness tolerance specified for the surface and the minimum depth of cut dictated by the machining operation. This machining allowance determination differs from the current practice of specifying the machining allowance, based on the casting process.

INTRODUCTION

Although the metalcasting process can create complex components, the castings often require subsequent machining to create additional features or achieve tighter tolerances. To conduct the machining, the casting will need to be held in a fixture. The purpose of the fixture is to locate the part, restrain the part from moving and support the part if it is large. The fixture is the critical element between the casting and machining operations.

The casting rests on fixture locating pins, which determine the position of the casting within the fixture. If the casting surface at the locators is different from the nominal value, the casting will not be located in the nominal position. This could lead to the casting not being machined properly. Machined features may not be in the proper location or orientation with respect to other features. Another problem is that the casting may not 'clean up,' meaning that there was not enough stock on the surface for the particular machining operation. In particular with computer numeric control (CNC) machining, the tool is often programmed to move to a position with respect to the fixture. Problems may occur if the casting is not located properly with respect to the fixture. This can occur, even though the casting is in tolerance.

To allow for the machining operation, the casting is designed with a machining allowance. The machining allowance ensures that enough stock will be on a casting surface to allow for proper machining. If there is not a sufficient amount of metal on the surface to be machined, the cutting tool may plow over the surface instead of cutting.

Many controversies have ensued between the casting producer and the machining company about who is responsible for the casting “not cleaning up” or other problems. The casting producer is usually primarily responsible for the casting design and application of the machining allowance. The party conducting the machining will typically specify the fixture design. Proper communication between the companies that produce and machine the castings during the design stages would eliminate many problems. This would allow all parties to jointly reduce the cost of the final machined component.

This paper will present a model that can be used to choose the optimal design of the fixture and the appropriate machining allowance. The model calculates the position and orientation error of a casting in a machining fixture, based on the position of the fixture locators, and the surface errors on the locating surfaces of the castings. While the dimensional capabilities of the metalcasting process are improving, casting surface errors are inevitable. This method will help design fixtures such that the impact of the surface errors is minimized.

PREVIOUS WORK

The previous work related to this paper can be divided into those guidelines that suggest machining allowances, and the research in fixture design. The machining allowance guidelines that are currently used will be reviewed, because the technique to calculate the machining allowance presented in this paper is significantly different.

There has been little research published on the effect of workpiece surface errors on the locational accuracy of fixtures. In their work on machining accuracy, Bai and Rong only assumed that the workpiece could be offset from the nominal by a constant amount in each of three orthogonal directions.1 Rotations due to locator positions with different surface errors were not considered. Prilutskii developed a method to predict the locating accuracy for blanks on arbors, based on periodic surface irregularities.2

Other researchers have considered errors due to the deflection of the workpiece during the machining operation. Menassa and De Vries developed models to determine support locations to reduce workpiece deflection under static loading conditions.3 Hockenberger and De Meter developed a model to predict the deflection of the workpiece/fixture system resulting from the machining forces.4 These models do not consider the original locational error of the workpiece in the fixture.

The ISO standard for casting dimensional issues defines the machining allowance on raw castings as "a material allowance to permit the removal of the effects of casting on the surface by subsequent machining, and to allow the achievement of the desired surface texture and the necessary accuracy of dimension."5 In addition to ISO, the Aluminum Association,6 Steel Founders' Society of America (SFSA)7 and DIN of Germany8 have published tables of recommended machining allowances to be applied to metal castings. Figure 1 clearly shows that all of the recommended machining allowances are a function of the largest dimension of the casting. The ISO tolerance specifications are also plotted to provide a comparison.
It is interesting to note that the purpose of the machining allowance is to allow enough stock for the machining operation; however, the magnitude is dependent on the casting process. Each source of the machining allowance tables also provided dimensional tolerance guidelines for castings. These guidelines offer suggested tolerances for the casting process, based on a variety of casting related issues. Since the dimensional variability of the casting process is already accounted for in the tolerance, there is little need to also have a machining allowance that is dependent on the casting process.

SFSA states that the magnitude of the machining allowance is dependent on the following: size and shape of the casting, surface to be machined, the pouring position, the tendency to warp and the setup method for machining. The tendency to warp and casting size should be reflected in the tolerance guidelines. The surface and its position in the casting could be critical, if, for instance, the cope surface required a greater allowance to clean up any defects on that surface. The object of this paper is to determine the magnitude of the last factor: the machining setup error.

The ISO guideline provides ten different machining allowance grades, which are chosen based on the casting alloy and molding method. A footnote in the document suggested that the two smallest machining allowance grades should “only be applied in special cases, for example, with series production in which the pattern equipment, the casting procedure and the machining procedure, with regard to clamping surfaces and datum surfaces or targets, have been agreed between the customer and the foundry.”

Once again, the tolerance guidelines and not the machining allowance should account for the improved dimensional performance, which is the result of having a long production series. Communication between the foundry and customer regarding the location of the casting in the fixture during the design state should be standard practice, not a special case, as suggested in the standard. The method presented in this paper should aid in this communication, by providing analysis of the fixturing method based on expected casting surface variability. The analysis could be a basis for decisions regarding casting process options.

The use of geometric dimensioning and tolerancing, to communicate the functional requirements of metal castings, is increasing.

ISO has released a draft standard of geometric tolerances for metal castings.9

The flatness and perpendicularity tolerances applied to the datum planes control the acceptable amount of surface error that can exist. For this paper, the surface error is defined as a positive or negative deviation from nominal surface location, and is perpendicular to the datum plane. The direction of a negative error is assumed to be into the workpiece.

The most common fixturing method for prismatic workpieces is the 3-2-1 method illustrated in Fig. 2. In this method, the workpiece is located on the primary plane by three points restricting one linear and four rotational degrees of freedom. The secondary plane is established by two additional points restricting one linear and two rotational degrees of freedom. Finally, the tertiary plane is located by one locator, which restricts an additional linear degree of freedom. The six locators are effective at eliminating nine of the 12 degrees of freedom. The remaining degrees of freedom can be eliminated by clamps.

**FIXTURING ERROR MODEL**

The existence of errors on the fixtured workpiece surfaces will result in the cumulative location and orientation error, as shown in Fig. 3. To calculate the cumulative error, the error due to each plane must be determined. The magnitude of the error at each locator position must fall within the flatness or perpendicularity specification for the respective datum. The model described herein predicts the final workpiece position and orientation, based on the surface error at each of the locators.

The deviation of the workpiece from the nominal position and orientation is calculated in a stepwise approach. The deviations that are a result of surface errors on the primary datum are initially calculated. The effects of these initial deviations will be used to calculate the deviations from the secondary datums. Finally, the cumulative deviation caused by all the surface is determined. Even though the calculations are conducted in the same order as the part placement in the fixture, only the deviation of the final part position and orientation from the nominal is determined. The deviations do not correspond to actual physical movements of the part.

The coordinate system of the casting and fixture will be aligned when the casting is in the nominal position. The calculations determine the deviations of the casting position and location from the nominal position and orientation.

The methodology of the prediction model is described herein. The reader is referred to Salisbury and Peters for the specific details.
of the calculations. As the part is initially lowered onto the three primary locating pins, the casting locator area with the highest surface will be the first to make contact. The location of the casting will be translated from the nominal by the difference between the nominal and actual height of the casting surface at this contact location.

Because the first pin restricts further translational deviation, the casting rotates about a primary axis until it contacts another primary plane locator. Then, the casting will rotate about an axis formed by the first two locators, to make contact until it contacts with the third pin. To summarize, the surface errors at the primary locating pins cause a translational and a rotational deviation of the casting from the nominal position and orientation.

The casting, which has already been deviated from its nominal position, then makes contact with one of the secondary locators. The distance between each of the two fixture locating pins and their respective casting surface is calculated. Note that the casting position and orientation used for these calculations is that determined by the deviations caused by the primary plane. The casting will be translated by an amount equal to the minimum of the absolute value of the two distances. Next, the rotation that the casting must undergo, so that the casting will make contact with the other pin on the secondary datum, is determined. Note that this rotation will be about an axis perpendicular to the plane established by the primary datum. To summarize, locating on the secondary datum will result in another translational and another rotational deviation.

The distance between the single tertiary datum pin and the casting, in the position determined by the cumulative effect of the prior deviations, is calculated. This distance, which is the last deviation that needs to be calculated, is parallel to both the primary plane and the line formed by the secondary locators.

RESULTS OF THE MODEL

The casting shown in Fig. 4 will be used to demonstrate the effectiveness of the model to determine the fixturing error and the resultant machining allowances necessary to ensure cleanup of the specified surface. On the example part, the top surface is to be machined. In an automated machining process, the tool will be programmed to move to some location with respect to the fixture coordinate system. However, the surface errors on the locating surfaces cause the location of the surface to vary with respect to the fixture. Therefore, the machining allowance must account for this variability of the surface location.

A general rule, when designing fixtures, is to spread out the locators as much as possible. The first set of trials to be conducted is for the locators on the primary and secondary surfaces to be near the edges of the part, as shown in Fig. 4 and listed in Table 1.

The surface error input into the model was based on the draft ISO standard for geometric tolerances for castings. For each alloy poured and molding type, this draft standard indicates a range of grades. For this paper, values were selected from the ISO CTG6 grade. (Machine molded iron and light alloy castings are designated grades CTG5-7 and steel castings are designated grades CTG 6-8).

Based on the largest length of the primary datum 254 mm (10 in.), the total flatness tolerance was 2 mm (0.079 in.) and the perpendicularity tolerance was 3 mm (0.118 in.). The flatness tolerance would apply to the primary datum. The meaning of this tolerance is that the primary datum must be contained between two parallel planes spaced 2 mm (0.079 in.) apart. The perpendicularity tolerance would apply to the secondary and tertiary datums. The interpretation of this tolerance is that each of these surfaces must be wholly contained between two planes spaced 3 mm (0.118 in.) apart and perpendicular to the primary datum.

Table 1 shows the predicted deviation of the surface to be machined for a set of surface errors on the primary datum targets. The surface error at two of the locators was -1 mm (-0.040 in.) and the other was at +1 mm (+0.040 in.) The surface at the other three locators was at the nominal (0 mm). The vertical displacement from the nominal of the four corners of the machined surface was calculated. As seen in Table 1, because of the surface errors on the primary datum, one of the corners is 1.27 mm (0.050 in.) below the nominal position.

The machining allowance will now be calculated for this particular case. First of all, the process requires a minimum depth of cut so the tool does not merely plow over the surface. A typical minimum value is 0.75 mm (0.030 in.). The surface in question will have a flatness tolerance on it. Per the ISO draft standard, the flatness tolerance for a surface with a maximum length of 152 mm (6 in.) is 2 mm (0.079 in.) Therefore, the machining allowance must include half of this value to account for any deviations in the surface. Finally, the position of one of the corners is 1.27 mm (0.050 in.) below the nominal value. The machining allowance will be the sum of these three components, 3.02 mm (0.119 in.)

The machining allowance calculated previously is only good for that specific case. The machining allowance that should be specified must cover all potential cases allowed by the specified tolerances. The fixturing error model was used to calculate the largest negative deviation from the nominal for any of the four corners of the machined surface. This value was found to be 2.02 mm (0.080 in.) (Coincidentally, based on the geometry of the example part, this value is the same as the total flatness tolerance. This does not generally hold true.)

Due to symmetry, there are two combinations of surface errors that will result in this deviation; the last column of Table 1 contains one such combination. The machining allowance that should be included in this casting design is 3.77 mm (0.148 in.). This value is the sum of the maximum location error on the surface, half of the flatness tolerance for the surface, and the minimum depth of cut prescribed by the machining operation.

The casting and fixture should be designed so that any areas of the casting that are prone to large surface errors, such as near the parting line, gates or riser contacts, are not used to locate the casting. The use
Fig. 4. Example casting with first set of datum targets. Top surface is to be machined.

Table 1.
Data Target Locations for Fig. 4

<table>
<thead>
<tr>
<th>Datum Target Location (mm)</th>
<th>primary datum errors (mm)</th>
<th>worst case datum errors (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25,25,0)</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>(25,127,0)</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>(229, 76,0)</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>Secondary:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,25,76)</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>(0,127,76)</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Tertiary:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(127, 0,76)</td>
<td>0</td>
<td>-1.5</td>
</tr>
<tr>
<td>Deviation</td>
<td>-1.27</td>
<td>-2.02</td>
</tr>
</tbody>
</table>

The first set of datum target locations and the effect of various surface errors at those locations on the final position of the surface to be machined. The deviation reported is the largest negative deviation of any of the four corners of the surface to be machined.

Fig. 5. Example casting with second set of datum targets. Top surface is to be machined.

Table 2.
Data Target Locations for Fig. 5

<table>
<thead>
<tr>
<th>Datum Target Location (mm)</th>
<th>primary datum errors (mm)</th>
<th>worst case datum errors (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary:</td>
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<td>1</td>
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<tr>
<td>(25,127,0)</td>
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<tr>
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<tr>
<td>(0,25,76)</td>
<td>0</td>
<td>-1.5</td>
</tr>
<tr>
<td>(0,127,76)</td>
<td>0</td>
<td>-1.5</td>
</tr>
<tr>
<td>Tertiary:</td>
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<td></td>
</tr>
<tr>
<td>(127, 0,76)</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Deviation</td>
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<td>-2.24</td>
</tr>
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</table>

The second set of datum target locations and the effect of various surface errors at those locations on the final position of the surface to be machined. The deviation reported is the largest negative deviation of any of the four corners of the surface to be machined.

CONCLUSIONS

Using this model during the concurrent casting and fixture design process, designers can make informed decisions of the result that different casting designs will have on the subsequent machining. Often times, there is not enough communication between the casting designer and the fixture designer. This model will provide the data that would help each of these parties to quantify the result of their design ideas.

The machining allowances specified in casting standards and guidelines are currently a function of the size of the casting feature. The machining allowance should be dictated by the machining process, and not the casting process. The dimensional tolerances on the casting should account for any variability, eliminating the need to also account for this variability in the machining allowance.

The machining allowance, as calculated in this paper, was the sum of the following three terms. The first term is the minimum depth of cut dictated by the machining operation. The deviation of the
surface to be machined, as determined by the model, is the second term. The final term is half of the flatness tolerance specified for the particular feature.

The model presented is only applicable for the deviation of a surface of a prismatic part. Future work will develop similar models for other casting geometries and fixturing methods.

REFERENCES

8. Steel Raw Castings - General Tolerances, Machining Allowances, DIN 1683 (1980). 