QUANTITATIVE X-RAY TOMOGRAPHY FOR THE
DEVELOPMENT OF A PISTON CASTING PROCESS

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INTRODUCTION

The development of castings for automotive components [1] can be accelerated by "statistical experimental design" or Taguchi-like methods [2] which use quantitative measures of the component quality to isolate and optimize the casting control parameters. In the present work the internal quality of aluminum pistons is determined using x-ray tomography. This technique allows internal voids such as shrink porosity to be detected. Both these defects occur when the gates or risers supplying molten aluminum freeze before the casting is completely solidified. These voids can be eliminated by carefully selected mold designs and casting conditions which lead to directional solidification. A casting development cycle is illustrated in Fig. 1 and shows how the casting parameters can be optimized during mold-tryout using statistical experimental design methods.

For the optimum use of the casting quality information, the tomography must be quantitative and the analysis of the data should be simple and comprehensive. A minimal goal would be to use the entire 3-D tomographic dataset to give the size or missing mass occupied by the voids.

In this work we describe how raw tomographic data can be corrected for the polychromatic x-ray source (beam hardening) and how a commercial visualization package can be programmed (using "visual" programming) to quantify the casting voids in preproduction pistons. Due to the small size of the voids, simple threshold detection of voids cannot be used. For these pistons, the voids correspond to less than 0.5 g missing out of a total piston mass of 500 g.

Fig. 1 Casting development cycle using statistical experimental design methods.
X-RAY TOMOGRAPHY

The x-ray tomography is performed using a commercial tomographic scanner [3]. Individual slices of the piston density are formed first by measuring the x-ray attenuation along many different ray-paths in a fanbeam geometry, reducing the attenuation data to ray-sums, and applying a tomographic reconstruction to the ray-sums. Sequential slices are then stacked to give a 3-D reconstruction of the piston density.

While the quality and resolution of the reconstruction depends on how many ray-sums are measured in each slice and the details of the reconstruction, the basic requirement of tomography is that each ray-sum is a line integral of some quantity. If the x-rays along ray \( \ell \) are monochromatic (single energy \( E \)), have initial intensity \( I_0(E) \), and reach the detector with intensity \( I(E) \), the total attenuation is the line integral of the local attenuation coefficients \( \mu(E,x,y) \):

\[
- \ln \left[ \frac{I(E)}{I_0(E)} \right] = \int_\ell \mu(E,x,y) d\ell
\]  

(1)

However, for scanners using x-ray tube sources which are inherently polychromatic, the intensity reaching the detector is an integral over the transmission at each energy:

\[
I(E) = \int_{E_0}^{E_\ell} S(E) R(E) \exp \left[ - \int_\ell \mu(E,x,y) d\ell \right] dE
\]  

(2)

where the intensity of the source is expressed as an intensity density \( S(E) = \frac{\partial I_0(E)}{\partial E} \) and the energy dependent response of the detector \( R(E) \) is included. Because low energy (soft) x-rays are absorbed preferentially, the x-ray spectrum shifts to higher energy (harder x-

![Extinction In (lo/l)](image)

Fig. 2 Total attenuation of x-rays from a Philips MCN 166 tube operating at 140 kV as a function of material thickness for two wrought aluminum alloys 2024 (solid line, circles) and 6061 (dashed line, triangles). Symbols indicate experimental measurements, lines indicate calculations.

Table I. Densities and mass fractions for the piston alloy and two reference aluminum alloys.

<table>
<thead>
<tr>
<th>Material</th>
<th>339</th>
<th>2024(^a)</th>
<th>6061(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>density, g/cm(^3)</td>
<td>2.72</td>
<td>2.77</td>
<td>2.70</td>
</tr>
<tr>
<td>aluminum</td>
<td>0.851</td>
<td>0.935</td>
<td>0.979</td>
</tr>
<tr>
<td>chromium</td>
<td>0.002</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>copper</td>
<td>0.012</td>
<td>0.015</td>
<td>0.010</td>
</tr>
<tr>
<td>magnesium</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>manganese</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nickel</td>
<td>0.008</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>silicon</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

rays) as it passes through a sample, hence the term "beam-hardening". The attenuation of polychromatic x-rays is no-longer linear but instead has the curvature shown in Fig. 2. The presence of beam-hardening can be readily seen in uncorrected tomograms as high attenuations at the surface of the part (see Fig. 3).

The beam hardening correction is performed by constructing a table which relates a given total attenuation to a length of material in the ray-path [4]. This relationship can be expressed by replacing the linear attenuation coefficient as the product of an attenuation coefficient per unit mass $\mu(E)$ and the local density $\rho(x,y)$:

$$\mu(E,x,y) = \mu(E) \rho(x,y)$$  \hspace{1cm} (3)

A given level of attenuation can then be related to a material thickness $\tau$ via

$$I_t = \int_0^E S(E)R(E)\exp[-\mu(E)\tau]dE$$  \hspace{1cm} (4)

where $\tau = \int \rho(x,y)d\ell$. The material thickness $\tau$, which is a line integral, is then used for the tomographic reconstruction.

The beam hardening correction is both measured experimentally and calculated theoretically given the elemental composition of the material. The theoretical calculation is based on the NBS emission and x-ray attenuation data. The theoretical calculation is important for evaluating the strong dependence on alloy composition. The experimental and theoretical attenuations for two different wrought aluminum alloys with differing amounts of copper are shown in Fig. 2. These alloys are radiographically similar to the aluminum piston casting alloy as seen in Table I. Samples of these alloys are cut into a staircase shape with a series of millimeter and centimeter steps. The scanner is run as a digital radiometer to measure the transmission of each step.

The quality of the reconstructions can be seen in Fig. 3 which shows the variation of the density in a 105 mm diameter piston casting with and without the beam hardening correction. The original reconstruction had a density variation of roughly 30% from the outside to the inside. The reconstruction with beam hardening shows less than 2% systematic variation across the part. The local noise in the density (±4% rms) is much higher than the systematic variation and is due to the almost complete attenuation of the beam through 105 mm of aluminum. This noise is determined by the x-ray counting statistics and can be improved by increasing the photon counting time for each ray-sum by increasing the x-ray flux, or by increasing the x-ray
energy to give higher penetration.

3-D VISUALIZATION AND QUANTITATION

Although each tomographic slice can be analyzed using image processing techniques, the full power of the tomographic data can only be realized by 3-D visualization and processing techniques. This allows the 3-D topology of voids to be extracted, visualized, and quantified. Using the 3-D dataset avoids problems associated with image analyzing individual slices and then trying to weight the results of each slice. A particularly powerful program which can perform the needed visualization and numerical functions and which runs on many UNIX workstations is AVS from Advanced Visual Systems [5]. This uses a "visual" programming interface to diagram/program the data-flow between analysis modules.

A series of tomographic slices are combined into a single AVS field file which can be directly imaged by constructing contours (lines of constant density in each plane) or isosurfaces (surfaces of constant density) and then using the computer to rotate the piston representation in three dimensions. In Fig. 4 an
isosurface construction of the pin boss/center core part of a piston is shown. The shrink volume can be extracted and magnified as shown in Fig. 5.

It has been found in AVS that better numerical analysis of the pistons and cropping can be performed by transforming the rectilinear field data into AVS's finite element format known as "unstructured cell data". These finite elements allow linear interpolation between the nodes and hence "sub-pixel" analysis. A parallelepiped crop volume can be manually centered over a void in the piston. Then, using a finite element integration tool, various properties inside the volume-of-interest can be calculated. Two different measures of the shrink voids have been performed.

In one method, the missing mass in the void is calculated. First the volume $V_0$ of the volume-of-interest is calculated. Then the integral of the tomographic density $\delta$ in the volume-of-interest is calculated and normalized by the full density tomographic density $\bar{\delta}$ (determined from part of the piston where there is no void). Since the tomographic density is proportional to the mass density $\rho$, this normalized volume is proportional to the actual mass contained in $V_0$. The missing mass is the difference of these two quantities:

$$ \text{missing mass} = \rho \left( V_0 - \int_{V_0} \bar{\delta} dV \right) $$

The distribution of missing mass for 16 pistons cast under one set of conditions is given in Fig. 6. The average missing mass is 0.33 g with a standard deviation of 0.07 g. The weakness of this method is that it depends on the small difference (2%) of two large numbers. The noise can be reduced by cropping closer to the void, but this would be done at the expense of having to manually resize or rotate the crop volume repeatedly. The crop volume selected ($30 \text{ mm} \times 18 \text{ mm} \times 9 \text{ mm}$) is large enough to include all the shrink voids encountered. This method is felt to give a reliable measure of the mean mass missing, but the variability is of the order of that expected for the uncertainty with which the integrals are calculated (0.1%).

The second method for quantifying the size of voids is based on a threshold density and is the 3-D analogue of threshold detection in image processing. This method is found to be less noisy than the missing mass method, but overestimates the size of the voids. The continuous density variations in the piston are replaced with a binary density $\delta'$:

$$ \delta' = 0, \text{ if } \delta > \text{threshold} $$

$$ \delta' = 1, \text{ if } \delta < \text{threshold} $$

Integrating over this binary image $\delta'$ within the volumes-of-interest gives the volume of the voids which is below the threshold. The volumes measured depend entirely upon the threshold selected, which is arbitrary. In pixel units, the average density inside the piston is $\bar{\delta} \approx 134$ with a standard deviation $\sigma$ of 5 (see Fig. 7). Inside the voids, the density does not
necessarily go to zero, so that a threshold of $\delta/2$ would miss void volume. By contrast, well-defined and isolated voids appear at a threshold value of 110 which is $5\sigma$ below the mean. This is consistent with the maximum of the data at 159 which is $5\sigma$ above the mean. Using a threshold of 110, the average missing void volume is 225±38 mm$^3$. As seen in Fig. 8, these missing volumes correlate very well with the missing mass but predict a missing mass (225 mm$^3 \times 2.7$ g/cm$^3 = 0.61$ g) roughly twice as large as that measured above (0.33 g).

DISCUSSION AND CONCLUSIONS

It has been shown how 3-D tomographic data can be obtained and analyzed to give a quantitative measure of casting porosity. First the "beam hardening correction" eliminates the major systematic distortions of tomographic reconstructions using uncorrected projection data with wide band x-ray sources. Second, using the finite element mapping of the density with the AVS programs allows ready visualization and quantification of the 3-D images. The quantitative measures have been used to optimize a piston casting process using statistically designed experiments. Despite these successes, both the analysis and the tomographic data need further enhancements.

The major analysis problem is that the present procedure requires that the volume-of-interest around the voids be adjusted manually. This is because the pistons are not precisely positioned in the tomographic scanner. The present positioning arrangement is similar to a lathe chuck so that the pistons vary in rotational position and also in x,y position (perpendicular to the piston axis). A potential solution is to use a filling algorithm (similar to a paint operation in a paint/drawing program) which could be used to fill the core and the area outside the piston with a value equal to the full density of the piston. This would make the core and outside edges disappear, leaving only the voids as discernable objects. The details of the painting operation may be important. If the paint spreads to all nodes which are less than the paint value, the paint will tend to diffuse into the piston. How far the paint diffuses

Fig 7. Distribution of tomographic densities measured in the fully dense part of the pin boss of one piston.

Fig 8. Correlation of thresholded missing volume with missing mass for 16 pistons. See discussion for selection of threshold value.
into the piston will depend on whether the paint spreads only in the x or y or z directions or whether it is also allowed to spread diagonally. The shrink voids occasionally come very near the core surface, and it may be possible the paint would diffuse into those voids.

An additional problem in pistons is measuring micro-porosity on some of the critical surfaces such as the pin boss and ring-groove areas. Measuring this micro-porosity would require the noise in the density (presently ±4%) to be significantly reduced.

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REFERENCES

5. Advanced Visual Systems, Inc., 300 Fifth Avenue, Waltham, MA 02154.