How Properties Vary Throughout a Casting

A study set out to show how properties can vary throughout a casting and why that's OK.

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The bulk of A356 castings are poured in permanent molds with solidification times generally less than 10 minutes. This process normally provides the best metallurgical properties when compared to the other common casting processes such as high pressure die casting (traditional or vacuum), sand casting, plaster molding and investment casting. Because of these properties, the tilt poured permanent mold process is used often for high integrity parts (Fig. 1).

Fig 1. This aluminum A356 wheel rim and steering knuckle are produced by the permanent mold process.

Tensile strength and ductility are closely tied to metallurgical properties such as secondary dendrite spacing, the level of microporosity, and the metal cleanliness which impacts the level of inclusions.

Permanent molds are often gravity poured down a sprue, which results in a fair amount of turbulence. In this process, the hotter metal will often end up at the bottom of the mold, while the feeding devices (risers) are located on top. This disserves directional solidification, which requires the hotter metal be near the risers. In the tilt pour process, the mold cavity, starting in a horizontal position, is slowly brought to an upright position, reducing turbulence and providing the hotter metal at the top of the mold.

To examine this phenomenon, an "autopsy" was performed on a swivel guide plate submitted to extreme tensile and bending loads, the failure of which would have serious consequences (Fig. 2).

Unlike wrought components, castings cannot always provide handbook tensile properties evenly throughout the part for any foundry alloy. This leads to confusion among casting users, as they are given a range of properties for the supposedly same alloy depending on the suppliers, academics or handbooks

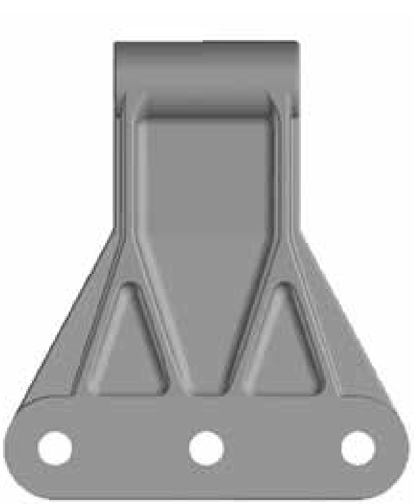


Fig 2. The tilt poured aluminium A356 casting studied measures 14.2 x 16.1 x 2.8 in. and weighs 11.9 lbs. Its solidification time is about 3.5 minutes.

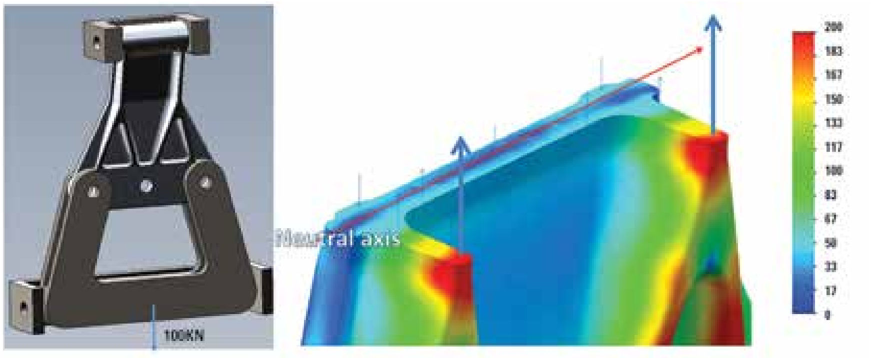


Fig 3. Stress distribution in the critical section of the casting during the proof test (Von Mises criterion in MPa) is shown.

they may consult. They will often conclude that a design value one can trust does not exist.

The truth is, mechanical properties in castings not only change with the process but may vary within the same casting. For instance, in the swivel guide plate, elongation varied from 2.1-0.8% depending on the solidification conditions at a particular location (solidification time and temperature gradient). Metalcasters can reliably predict properties at various locations to ensure the appropriate properties are present at critical areas.

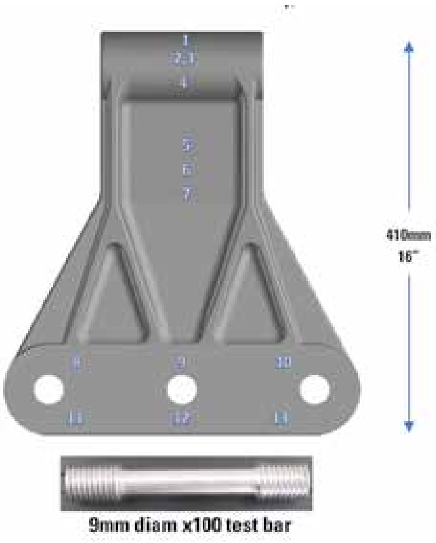


Fig 4. Location of the 13 tensile samples excised from the casting – Photograph of a subsize specimen.

Presenting the potential user with an analysis such as the one developed in this study may go a long way to convince non-metallurgists that the mechanical properties of structural castings can be reliably evaluated.

The Casting Under Study

The swivel guide plate sketched in Figure 2, has a typical thickness of 0.5 in. (12mm). In the study it was submitted to combined tensile and bending stresses, as shown in Figure 3. Its composition, measured on a coupon excised at the bottom left corner of the part was: 6.65 Si, 0.11 Fe, 0.01 Cu, 0.006 Mn, 0.30 Mg, 0.002 Sr (i.e. the alloy was not modified) which corresponds to the composition of a top quality A356 primary alloy.

Before being put into service, this casting is proof tested at the extreme level of stress shown in Figure 3. The sketch on the left shows the condition of the test, while the distribution of the Von Mises stresses is plotted in color on the right. It clearly shows the extremity of the ribs is subjected to tensile stress close to the yield strength of alloy A356 T61. The values of the Von Mises criterion indicate where the material is expected to yield, i.e when the value of the tensile yield strength of the material is reached (~ 180 MPa/26ksi for heat-treated aluminum A356 aged four hours at 311F (155C) after solutionizing eight hours at 1,004F (540C) and quenched in 140F (60C) water.

The Study

ASTM E8 subsize tensile specimens were excised at the locations numbered 1-13 shown in Figure 4.

Since only one specimen was tested per location, the tensile results (yield strength, ultimate tensile strength, and elongation) must be interpreted with caution.

The typical relative standard deviation on UTS and elongation are 5% and 25%. It should consequently be born in mind that, assuming a normal distribution of the individual results, the average value based on a large number of tests would stand within ±10% and ±50% of one individual value measured (with a probability of 95%). The results of the tensile tests,

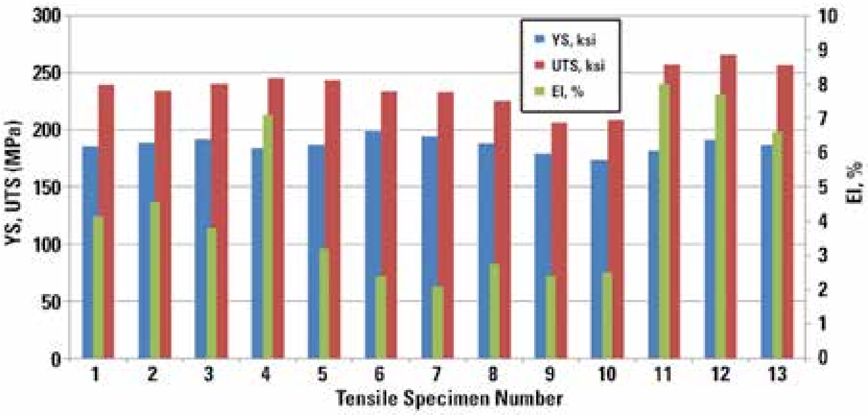


Fig 5. Tensile results at the 13 locations in the casting shown in Figure 4.

Metalcasters can reliably predict properties at various locations to ensure the appropriate properties are present at critical areas.

shown in Figure 5, indicate:

- The yield strength is similar throughout the casting ~ 180MPa/(26ksi).
- The elongation varies within a wide range, from 2.1-0.8%.
- The ultimate tensile strength is strongly correlated to the elongation.

When the process conditions are known (i.e. pouring temperature, tilting time, ejection time and mold open time), it is possible to predict the solidification conditions everywhere inside the casting once a dynamic steady state has been reached. For instance, the solidification time predicted after 10 cycles is plotted in Figure 6a.

The primary information obtained from solidification modeling is the location of hot spots, where late solidification has cut the zone off from the feeding liquid path. Depending on its severity, this situation would result in a shrinkage cavity.

As shown in Figures 6a and 6b, hots spots due to the casting geometry were detected at two low stress locations. The resulting shrinkage is shown in Figure 7. In order to reduce this defect and meet the requirement of Grade C, the melt could be slightly gassed so as to reduce the overall liquid to solid contraction.

The gassing of the melt is controlled by measuring the density of the reduced pressure test sample to a density close to 2.50. The normally degassed melt corresponds to a sample density of 2.60, compared to a compact density of 2.68 for alloy A356. An alternative solution would have been to use artificial cooling: modeling had shown that air cooling would have been insufficient, so gassing of the melt was found to be more practical than providing water cooling channels in the mold.

However, more can be extracted from the simulation than the solidification sequence and the locations of hot spots. Tensile properties also can be predicted.

A quality index Q has been defined for heat treated Al-Si-Mg alloys which, in a first approximation, depends only on the metal-

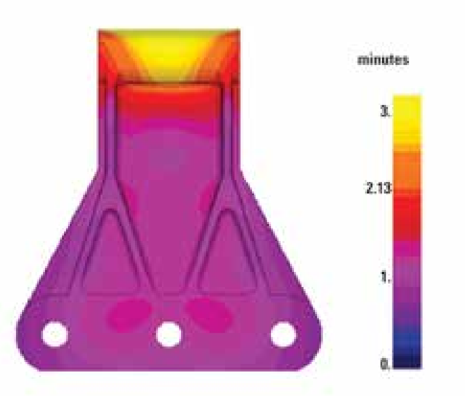


Fig 6a. Solidification time predicted by the thermal modeling of the casting solidification is shown.

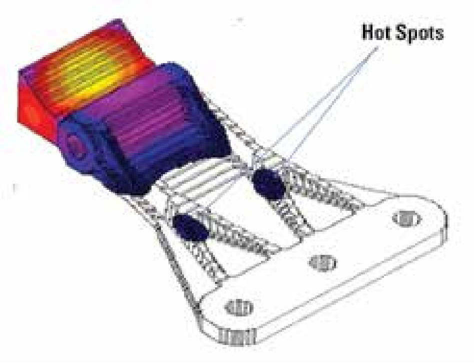


Fig 6b. A hot spot is detected due to part geometry.

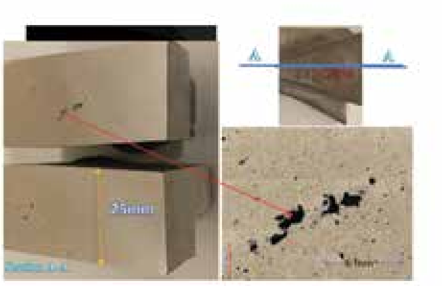


Fig 7. Shrinkage at the hot spot shown in Figure 6b is shown.

lurgical quality of the alloy and not on the temper applied following solutionizing and quenching.

The metallurgical quality depends on the fineness of the microstructure measured by the secondary dendrite arm spacing (DAS) expressed in micrometers and the level of microporosity, expressed in percent volume. The presence of inclusions will also reduce the value of Q. Q is defined by the relationship:

Q = UTS + 150 Log El

In a clean alloy, Q depends only on the dendrite fineness and level of microporosity. Since DAS is related to the solidification time, and microporosity can be expressed in terms of solidification time and the solidus velocity, Q may be calculated from the results of the thermal modeling which provides a value for solidification time and solidus velocity everywhere in the casting. Note that local solidification time is the time elapsed between the beginning and end of solidification, hence it is shorter than the solidification time in Figure 6. Expressions for Q have been proposed for a moderately gassed melt with a reduced pressure test sample density of 2.48, corresponding to a dissolved hydrogen gas content of about 0.20 ppm. Accordingly, the Q distribution color map shown at the top of Figure 8 could be obtained. It can be seen that the zone of lower Q corresponds to slower solidification times and high values of the solidus velocity (i.e. zones of low thermal gradient).

In AlSiMg alloys, the tensile properties YS, UTS (MPa) and El are not independent. The following empirical relationship has been proposed:

YS = UTS - 60 Log El -13

Since by definition, Q = UTS + 150 Log El, YS may be written as:

YS = Q - 210 Log El -13

Consequently:

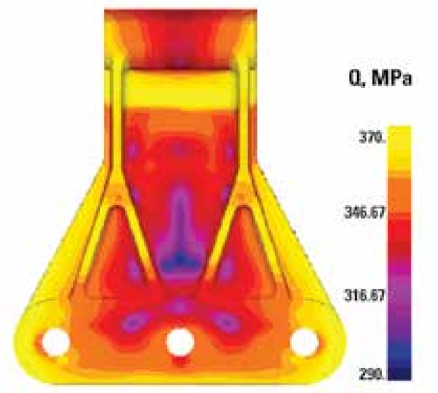
El = 10^(Q-YS+13)/210 [Equation 1]

The yield strength depends mainly on the magnesium content and temper conditions, which are identical throughout the casting. Yield strength can be calculated, based on the magnesium content (0.30%) and the aging conditions (4h at 311F). Yield strength was determined equal to 180 MPa, in good agreement with the tensile results of Figure 5, which are based on only one tensile test.

Under the assumption of constant YS=180MPa, elongation can be computed from Q using equation 1.

In Figure 8, the predicted Q varies from 308 to 363 MPa, which, from the table in the same figure, corresponds to predicted elongations varying from 2.4-4.6%, a narrower range than what was measured since experimental elongations vary from 2.1-0.8%. However, this apparent discrepancy might not be significant because the experimental results were obtained on a unique test per location. The typical standard deviation for elongation being 25% means that for these two extreme numbers, the "true value" of elongation would lie in the ranges 2.1±1.0% and 8.0±4.0% with a probability of 95%. The "true value" would be obtained by averaging the results of an infinite number of tests. It is thus impossible in the present circumstances to state that the predictions are in accordance or in contradiction with reality. A much higher number of tests would be necessary. It can, however, be stated both experiment and theory show a wide range of mechanical properties exist within the same casting. The measured tensile properties (Figure 5) seem generally superior to the predicted ones, attesting to the higher than average metallurgical quality of the casting.

The microporosity level was measured at each of the 13 locations by image analysis. The mosaics, 0.4 in. (9 mm) in diameter, are shown in Figure 9 at locations 1, 2, 4, 9, 11 and 13, as numbered in Figure 4. The void maximum length is also indicated. This maximum length is relevant to the fatigue strength of the part, more so than the porosity expressed in volume percent. Despite the partial gassing of the melt, intended to reduce the shrinkage cavity to an acceptable level, the rapidly solidified, high temperature gradients at locations 11 and 13 result in very low levels of microporosity. The predicted values of the microporosity are usually higher than the experimental values, except at location 9 where



YS = 180 MPa		
Q, MPa	UTS, MPa	El, %
290	234	2.4
310	243	2.8
330	251	3.4
350	259	4.0
370	268	4.8
390	276	5.7

Fig 8. Shown is the predicted distribution of the quality index. The table shows elongation (El%) and ultimate tensile strength (UTS) from Q for YS=180MPa.

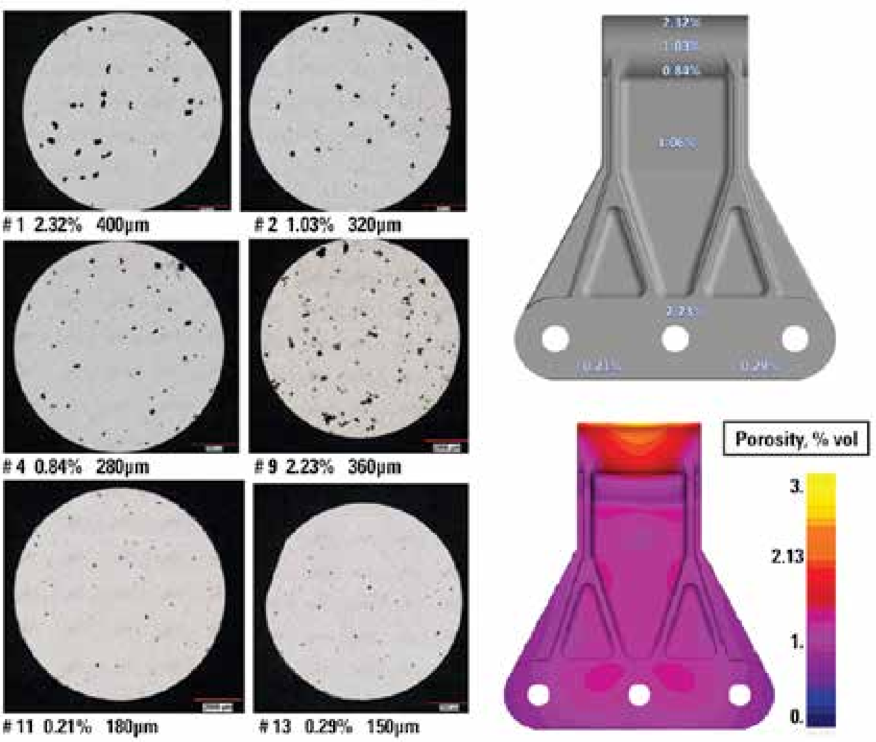


Fig 9. Mosaics at locations shown in Fig.4 indicate the level of microporosity measured (top right) and predicted (bottom).

the measured level is unexpectedly very high (2.23%). At this location, the void morphology is also very peculiar (see mosaic #9 in Figure 9), indicating a particular phenomenon has possibly taken place at this location. It could be the presence of trapped inclusions which could have acted as nuclei for the molecular hydrogen gas to form.

The generally higher value of the predicted microporosity compared to the measured one might be due to natural degassing or because the actual level of atomic hydrogen dissolved in the melt was less than the 0.20 ppm corresponding to the formula used to predict the microporosity distribution.

The microstructures shown in Figure 10 are typical of an unmodified heat treated Al-Si alloy. As expected, the dendritic structure coarsens as the solidification time increases; the measured values of DAS are indicated under the micrographs. The distribution of the predicted DAS (Figure 11) resulting from the solidification modeling is based on a previously proposed relationship which depends only on the local solidification time, i.e. the time elapsed between the beginning and the end of solidification.

What We Now Know

The metallurgical study of 13 excisions in a tilt poured permanent mold aluminum A356 casting, with local solidification times comprised between 0.5 and 2.5 minutes lead to the following conclusions:

- Local tensile properties vary widely with solidification conditions, the quality index Q spanning from 308 to 363MPa. These values are expectedly lower than the minimum Q required for the standard ASTM B108 separately cast test bars (Q > 367MPa), the local solidification time of which is less than 20 seconds.
- The variations in the microporosity and tensile elongation can be reasonably predicted when the local value of the solidification time and solidus velocity are known via solidification modeling. The measured values of the elongation (2.1-8%) vary in a much wider range than the predicted ones (2.4-4.6%). This discrepancy is due to the fact only one tensile test was performed per location, the confidence interval on the elongation of cast aluminum being typically 25% of the average value obtained on a very large number of tests.
- The secondary dendrite arm spacing (DAS) can be accurately predicted when the time between the beginning and end of solidification is determined by solidification modeling.
- In addition to its conventional use to predict macroshrinkage in castings (i.e. "hot spots"), it was shown solidification modeling could be used to evaluate the variations in microporosity and tensile elongation inside a cast part. This tool should however be used with some caution and plenty of discernment.

In the realm of solidification, a prediction should be considered as a "relatively" faithful caricature of reality. For a given alloy, the trust it may inspire should be built after a long process of experimenting on a wide range of geometrical configurations and process conditions. MC

This article is based on the paper "Metallurgical Properties inside a Tilt Poured Permanent Mold Structural Aluminum AlSi7Mg03 (A356) Casting" (Paper 18-011) originally presented at the 122nd Metalcasting Congress.

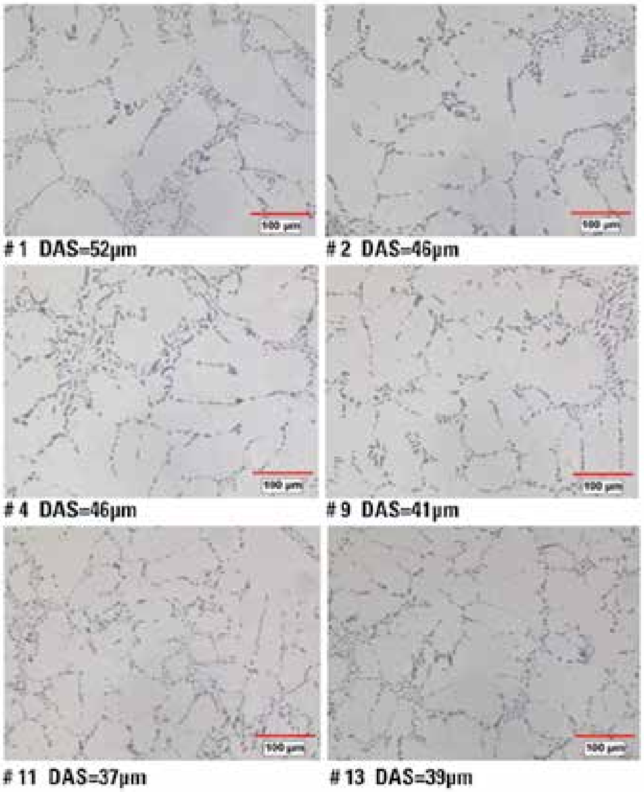


Fig 10 – Metallographic structures at locations 1, 2, 4, 9, 11 and 13 indicated in Figure 4 are shown here.

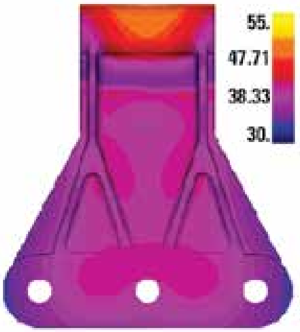


Fig 11. Shown is the dendrite arm spacing distribution predicted (micrometers).