Filtration of aluminium – a Weibull statistical approach to the analysis of mechanical properties

Introduction

Filtration has been used in the industry for many years and the benefits in terms of casting quality are well documented. As quality is one of the main market driving forces it is no surprise that the technology has continued to evolve. Competitive pressures are fierce and these quality improvements must be economically justifiable. The development of the direct pouring approach – KALPUR – now offers the potential of increased quality, together with yield and often productivity improvements, leading to lower process costs.
However, there is no doubt that advances in filtration and evolution of the technology require a parallel understanding of the mechanisms of the process, so that technology and knowledge move forward together.

Recent research at the University of Birmingham, UK, on the effects of mould filling and the subsequent impact on casting integrity, has been both innovative and exciting[1,2]. Direct observation of mould filling by the latest in line X-ray equipment together with more sophisticated analysis of fracture strengths using Weibull[3] statistics, has enhanced our understanding of the link between process parameters and the end result.

This brief paper describes the results of a study commissioned by Foseco International Ltd, UK, at the University of Birmingham, UK on the effects of filtration on the mechanical properties of cast Al-7Si-Mg Alloy LM25 using these latest statistical techniques. It adds to the existing database of filtration knowledge gained in-house and from field experiences.

Experimental method

Test bars of 12.5mm nominal diameter were cast in LM25 alloy in resin bonded moulds, see figure 1. For top filling the mould was inverted and the riser and pouring basin blocked off. The metal was initially melted and held at 640-650°C and held for 30 minutes to allow the hydrogen content to equilibrate with the atmosphere, rapidly heated to 750°C and cast. Four filling methods were employed:

- Bottom filled with filtration – 10ppi SIVEX filter.
- Bottom filled no filtration.
- Top filled with KALPUR direct pour unit.
- Top filled without filtration.

120–130 test bars were cast for each of the four filling methods. All bars were heat treated at 540°C for six hours, water quenched and then aged at 160°C for four hours. This produces maximum strength and minimum ductility. Testing then measured Young's modulus, 0.2% proof stress, tensile strength and elongation.

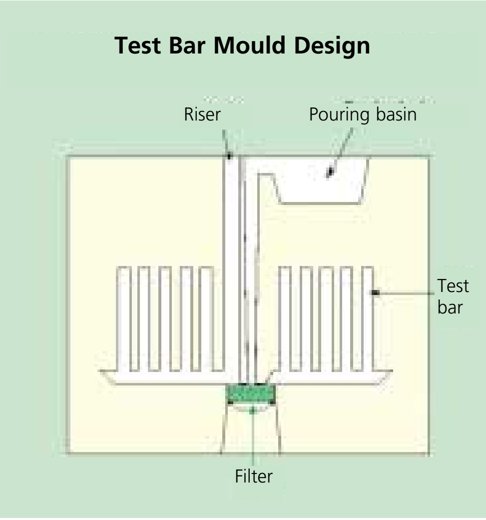

Figure 1.

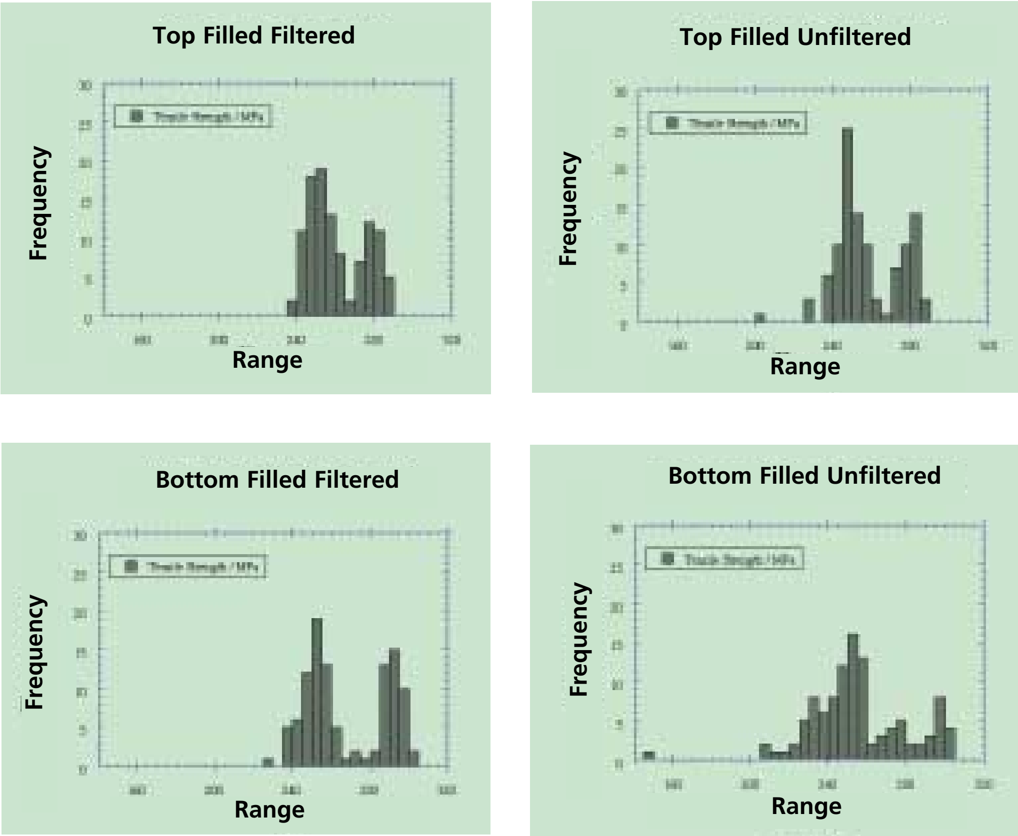

Figure 2.

Results

Histograms of each set of the tensile tests are shown in figure 2. Here the tensile strengths of each of the filling mode categories are plotted against the frequency of occurrence.

A number of facts are immediately apparent:

- Unfiltered castings show few but very significant low strength test pieces, known as outliers.
- For each filling category the plots show two distinct bands of tensile strength.

A typical fracture surface is shown in figure 3.

Examination of the fracture surface of the low strength outliers by both optical and SEM reveals the cause quite clearly, see figure 4. Massive oxide fragments are resolved quite clearly and higher magnification examination shows the folded nature of the oxide film and associated crystals of trigonal magnesium aluminate. This indicates that the oxide is an 'old' fragment that has been carried over from the holding furnace. No low strength outliers were observed from the filtered test bars thus showing that filtration has removed these large exogenous fragments.

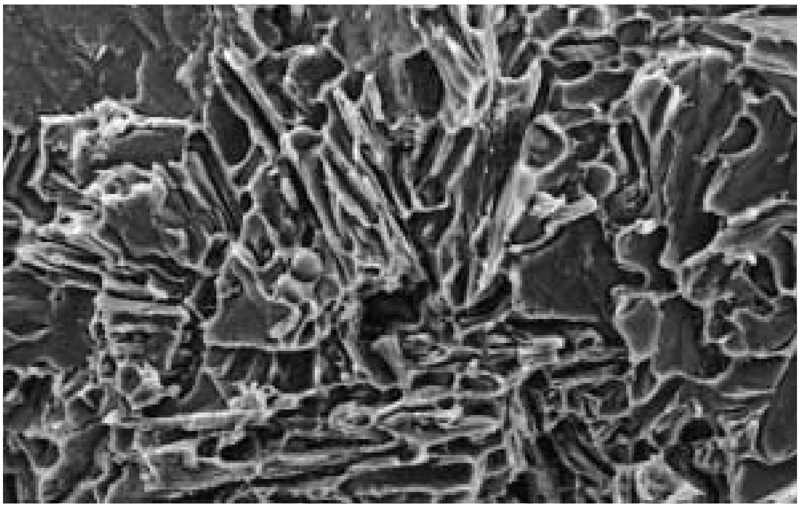

Figure 3 Scanning electron micrograph of a typical fracture surface.

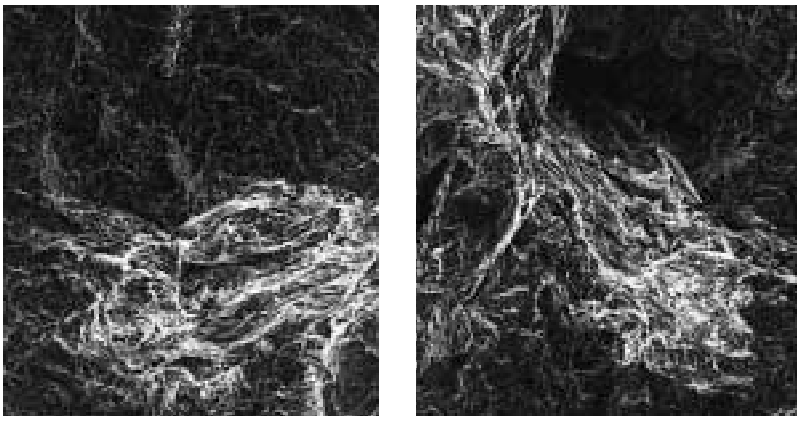

Figure 4 SEM fractographs of specimen 27A (bottom filled unfiltered low strength data set) showing massive oxide fragment observed in each half of the fracture surface.

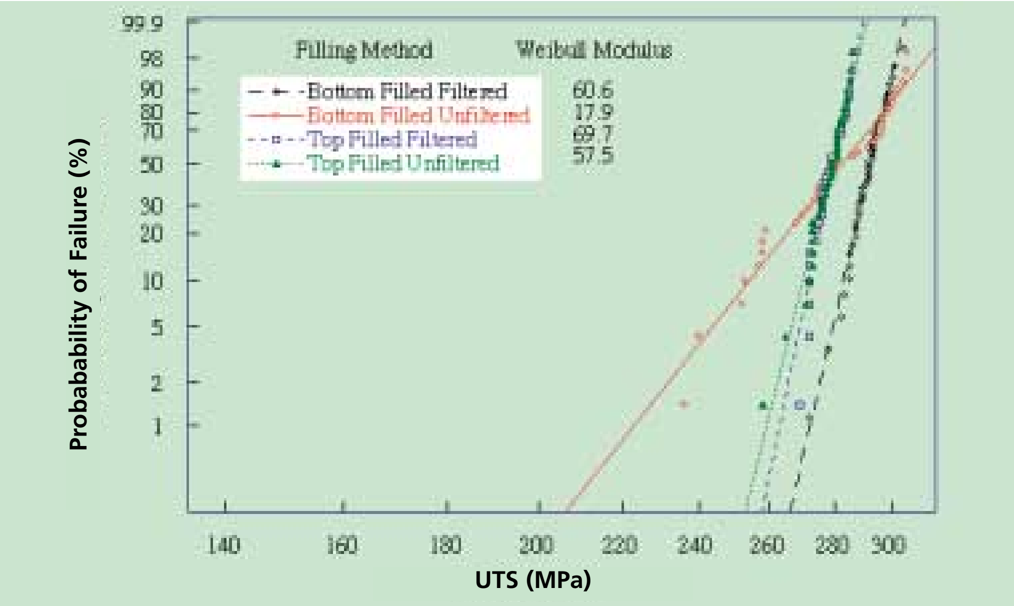

Figure 5 Weibull plot, High Strength data set.

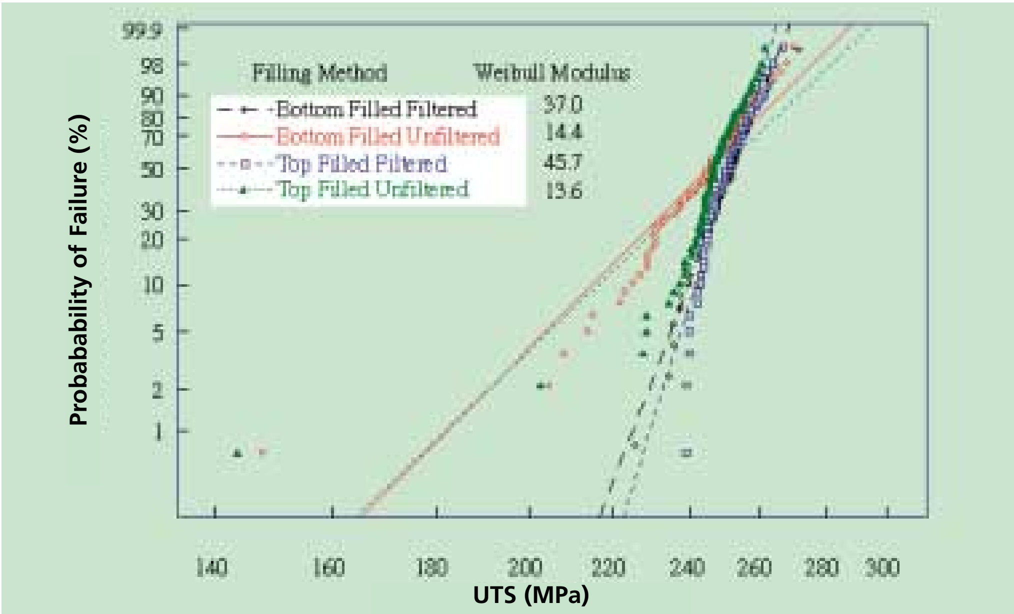

Figure 6 Weibull plot, Low Strength data set.

Data analysis

The distribution of strengths in brittle materials was first modelled by Weibull who defined a probability of survival which is skewed. The technique is used very commonly in glass and ceramic materials and essentially, in these materials, the strengths are determined by the distribution of defects which initiate fracture. Recent work has demonstrated that this technique is applicable and gives a useful insight into this type of heat treated aluminium alloy and effects of casting conditions. The Weibull distribution enables a single figure quantification of the scatter of the measured property – tensile strength – and this is referred to as the Weibull modulus. The higher the modulus the less the scatter.

The double band appearance of the histograms results is normally interpreted as indicating that more than one defect is acting to control the behaviour at fracture. Metallographic examination of the specimens showed that a variety of defects were present including entrained oxide films with associated microshrinkage porosity and a limited number of hydrogen pores. This evidence of multiple defects supports this view. However, in this study the tensile property data falls into two distinct strength bands namely, 240 - 270 Mpa – for castings 2 - 33 – and 270 - 300 Mpa – for castings 34 - 51. The reason for this is unclear, one possible reason was the batch nature of the heat treatment. These results were therefore considered separately and analysed in isolation as high and low data sets.

The results are shown in table 1 for each filling method, the Weibull moduli are given for both the high and low strength bands observed in the histograms. The benefit of filtration is obvious for both top and bottom filling modes.

The Weibull plots of the high and low strength data sets are shown in figures 5 and 6.

Confidence levels of statistical significance of these results also have been calculated by the Monte Carlo simulation method and are given in table 2.

Real time x-ray

Further insight into the reasons for the difference in casting reliability that occur in the different filling methods was obtained from real-time x-ray observations. Observations of the metal during bottom filling of the test bars without a filter showed a short lived, severely damaging turbulent mode during priming of the running system. This 'affected' metal was then flushed into the test bars so giving a high population of folded oxide defects. Incorporating a filter into the system eliminated this turbulent mode and, as has been seen, also filtered out the large exogenous inclusion.

Observations made during pouring of the top filled castings showed that the opportunity for entrained oxide generation through turbulence did not exist for this particular geometry. Turbulence was generally low and the KALPUR unit provided benefit in control of the initial fall of the metal stream.

Conclusions

- Tensile tests have been performed on a total of 430 test bars filled through top or bottom gated systems, with and without filters.

- The data sets were analysed by Weibull statistics and showed a significant difference between the filtered and unfiltered test bars. The higher Weibull modulus in the filtered castings showed much less scatter in the results. The degree of confidence that the filtered castings were better than unfiltered castings was extremely high.

- Some unfiltered test bars contained exogenous inclusions that were not present when a filter was used. Examination of the fracture surfaces of the low strength outliers showed that unlike the typical fracture surfaces, the outliers contained massive exogenous fragments of oxide.

- SEM and real time x-ray observations gave valuable insight into the causes of defects including oxide film formation caused by turbulence and large exogenous inclusions.

The study clearly supports the activity seen in the field where the adoption of filtration, and more recently direct pouring devices – KALPUR - has led to quality and often economic benefit for foundries. Control of the quality of the metal entering the mould cavity by removal of exogenous conclusions is one facet. Equally important is the control of how the cavity fills, and non-turbulent flow is important in reducing the presence of folded oxide films in the casting.

References

1. N.R. Green and J. Campbell 1993, "Statistical distributions of fracture strengths of cast Al-7Si-Mg alloy", Materials Science and Engineering, A173, 261-266.

2 N. R. Green and J. Campbell 1994, "The influence of oxide film filling defects on the strength of Al-7Si-Mg alloy castings", Transactions of the American Foundrymen's Society, 102, in press.

3. W. Weibull 1951, "A statistical distribution function of wide applicability", Journal of Applied Mechanics, 18, 293-297.

Acknowledgement

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Table 1 Summary of Weibull Moduli

Casting Method	Low Strength Band	High Strength Band
Top filled filtered	45.7	69.7
Top filled unfiltered	13.6	57.5
Bottom filled filtered	37.0	60.8
Bottom filled unfiltered	14.4	17.9

Table 2 Monte Carlo Simulation Confidence Levels

Casting Method Comparison	Low Strength Band	High Strength Band
Bottom filled filtered is better than unfiltered	>99.99%	>99.99%
Top filled filtered is better than unfiltered	>99.99%	92%