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Invisible macrodefects in castings

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SYNOPSIS

There is a wide spectrum of controls which are required to be in place to ensure the maintenance of quality in castings. Most of these are well known, and are not therefore considered in this paper. The parameters which are often overlooked, and thus not controlled, are (i) the rate of flow of liquid metal in the mould to avoid surface turbulence and the generation of macroscopic crack-like defects as a result of folded-in surface films; and (ii) the rate of quench following solution heat treatment. As a result of failure to control these critical parameters castings traditionally exhibit random failure from leakage, and mechanical failure, especially fatigue. Mechanical failure is enhanced by internal stress which is superimposed on service stress to promote premature failure. It is considered that these are the main reasons why in the past castings have been found to be unreliable, compared to other production techniques such as forging. Techniques to control both surface turbulence and internal stresses include respectively (i) the limiting of flow velocities in moulds to less than 0.5 m/s, and (ii) eliminating the water quench from casting heat treatments. These actions are expected to revolutionise the concept of castings as totally reliable products.

INTRODUCTION

Foundries have advanced significantly over the last decade, introducing many control features, particularly metal temperature control, gas content control, and structural control by metallurgical additions and/or by control of cooling rate. Prediction of the rates of solidification and cooling is now beginning to be routinely carried out by computer simulation. The development of better mould and core production processes have allowed the achievement of more accurate castings, with fewer problems from metal/mould reactions. Overall control of the foundry operation is achieved by careful documentation, allowing traceability of finished products back to the source metal, and by sophisticated statistical methods such as Statistical Process Control (SPC). All of these developments are of course most welcome. There is no doubt that casting integrity has improved significantly as a result of their implementation.

However, there remain two areas which have so far eluded control, and which have a crucial effect on the reliability of the casting. If these last two obstacles can be overcome, then castings may, for the first time in their 5000 year history, become as reliable, or possibly more reliable, than forgings. This quest is the subject of this paper.

OXIDE FILMS CREATED DURING THE FILLING OF THE MOULD

Bulk turbulence, assessed by Reynolds Number, is the chaotic eddying flow of the bulk liquid. This is not our concern here.

Surface turbulence is the chaotic breaking up of the surface of the liquid, allowing the surface oxide film to become incorporated into the bulk melt. This is one of the really damaging effect which we need to control. The second damaging effect is bubble damage. We shall deal with this later.

SURFACE TURBULENCE

Clearly, it is possible to avoid surface turbulence in liquids during mould filling, whereas the avoidance of bulk turbulence is probably impossible. Nevertheless, as we shall see, there is no particular problem in allowing much bulk turbulence, whereas even a little surface turbulence can be fatally damaging to the casting.

We can gain an estimate of the velocity at which the surface of the liquid metal becomes unstable. The inertial pressure against the surface if metal of velocity V and density ρ impacts against it is ρV^2 . The pressure of restraint due to surface tension γ is $2\gamma/r$ where r is the radius of curvature of the spherical deformation which results (Figure 1). If V exceeds a critical value then the inertial pressure will cause the surface to form a droplet, of radius approximately r . To gain an idea of the size of this, if within the droplet the pressure due to depth within it ρgh will equal $2\gamma/r$, and, of course, $2r = h$. Thus finally the critical velocity to break the surface is given by

$$V = 2^{1/2} \{g\gamma/\rho\}^{1/4}$$

The fourth power relation ensures that practically all metals have the same critical velocity; for all practical purposes it works out close to 0.35 to 0.5 m/s for all liquid metals.

This is therefore a fundamental parameter which must be observed during the filling of moulds. If not, then the breaking of the surface by droplet formation, or by jetting, or by the breaking of a wave etc, will fold in the surface oxide film. when incorporated into the bulk in this way constitutes a crack in the liquid, which of course freezes into the casting as a crack (1).

The folding in of the film at this critical velocity has been observed by the author (2) by watching the emergence of a liquid metal stream from an ingate on video (Figure 2). At 0.5 m/s an emerging stream of liquid aluminium alloy flooded out into the mould without the breaking of the surface; whereas at 0.55 m/s a small wrinkle could be seen (Figure 3). At higher velocities the emerging stream develops a mushroom form, and finally a jet form. Clearly, on falling back under gravity, the stream chaotically folds in its surface oxide.

A series of simple shaped plate castings, made at various ingate velocities were a sobering demonstration of the correctness of these concepts. At entry velocities below 0.5 m/s the plates were free from cracks. Above this value, the plates were a disaster: all contained cracks, and many of these were found to extend through the complete thickness of the plate.

A further sobering finding was that plates could not be top gated under any circumstances without introducing surface turbulence, with consequent disastrous through-thickness cracks. This is an evident consequence of the simple fact that falling only 12 mm under gravity will produce the critical velocity of 0.5 m/s. Since in practice, all top pouring situations will exceed this many times, top pouring can be seen to be a completely unacceptable way of making castings.

(The only exceptions to this general conclusion are expected to be grey iron castings made in green sand moulds, where the oxide film is a liquid silicate, and thus harmlessly spheroidises and floats out (1), and possibly very heavy section castings where the folded-in films may experience sufficient time and pressure to cause them to heal by diffusion bonding or welding (1)).

If these conclusions were not already sufficiently dramatic, a further finding was that bottom gating of castings was also capable of producing castings full of crack defects. To produce a sound casting it was necessary simultaneously to (i) bottom gate, and (ii) introduce the metal into the mould at a velocity lower than the critical velocity.

It is clear therefore that many engineering products currently being made for the automotive industry are being produced in a way which guarantees the production of random cracks in the product. Methods which worked for cast iron, and on which our text books have therefore been based since the industrial revolution, are thus demonstrated by both theory and experiment to be unacceptable. It is of no use simply pouring metal into moulds and hoping for the best. Filling systems for moulds clearly have to be designed (1). If they are designed successfully, so as to avoid the critical velocity for the creation of folded films, then castings of guaranteed freedom from film defects will be attainable.

Figure 4 shows the strength of castings as a function of metal filling velocity. Above approximately 0.5 m/s occasional castings free from cracks may be possible, but clearly cannot be guaranteed. In any case, whether apparently free from cracks or not, the strengths were uniformly low. Below the critical velocity strong, reliable products are to be expected as the norm(2).

BUBBLE DAMAGE

Bubble damage occurs in castings because of the passage of bubbles through the liquid metal. This is a common feature of many filling systems. Air is entrained at a number of points, so that swarms of bubbles are caused to enter the mould cavity with the metal. Each bubble oxidises its surface, which then drags behind, collapsing as the bubbles moves on, to become a long, collapsed sack. The passage of numerous bubbles results in a tangle of bubble trails with fragments of bubbles trapped in the mass of oxide films.

Such damage is often seen at the point at which ingates are cut from castings, but is most often erroneously identified as shrinkage. The damage usually extends far into the casting, however, giving particularly porous metal in the upper regions of castings where the bubbles become entrapped.

However, the major problems with this common form of damage in light alloy castings is not the bubbles, which are clearly visible on radiography. The bubble trails are far more extensive, and constitute long cracks through the casting.

In higher melting point materials, such as carbon steels, the bubble trails are at a high enough temperature to be molten, or at least sticky. The consequence is that in such alloys the extensive oxides caused by bubbles tend to coalesce to form macroscopic inclusions, often called ceroxide defects as a result of the cerium oxide which they will contain as one of the more oxidisable of the minor elements in the steel which is commonly present.

QUENCH STRESSES

The stresses which reside in castings from the casting process may be high in those die casting processes in which the casting is cooled quickly. In sand castings, cooling is generally sufficiently slow that residual stress is expected to be low.

In any case, if these products are subsequently heat treated with a full solution treatment, quench and age, then the casting stresses are completely eliminated during the solution treatment.

The problem arises during the quench.

Parts of the casting are cooled and contract, becoming strong and resistant to deformation, whilst other parts, generally in the centre of the casting, are still hot and thus weak and deformable. The central parts thus are forced to plastically deform, becoming shorter, so that, at a later stage, when the central part cools into its elastic regime, it then starts to suffer a tensile stress.

The problem clearly arises therefore from the rate of cooling being too high for the rate of heat flow to equalise temperatures.

In practice of course, the equalisation of temperatures can never be perfect. However temperature can be equalised sufficiently to reduce residual stress to a negligible value.

A sensible negligible value might be acceptable as perhaps 10 per cent of the yield stress. This would correspond to a loss of strength of approximately 20 to 30 MPa for most Al alloys. However this would be considered by many in the industry to be not negligible and illustrates the quaint irrelevance of an inspector who fails products which fall 1 or 2 MPa below the specified minimum requirements when measured by test bar when the internal (hidden) losses usually greatly exceed this. At the present time we clearly do not have our priorities in logical perspective.

Many will argue that internal stress is not necessarily bad. This is undoubtedly true. However the number of instances where it has been used in the design of the quench so as to enhance the performance of the casting can be counted on one hand (1). In general few have stopped to consider how residual stresses may affect the performance of the casting. Indeed, although it is starting to be possible in principle, it is still difficult, and surrounded by uncertainty. We are forced to conclude therefore that on average, we would expect 50 per cent of castings to be enhanced by residual stress, and 50 per cent to be impaired. This is a lot of substandard castings!

A further argument which is sometimes quoted to deny the importance of residual stress in reducing a casting's ability to withstand stress goes as follows: the tensile and compressive stresses in the casting have to be balanced, so that the ability of the casting as a whole to withstand load is unimpaired. This argument effectively reminds us that parts of the casting are in compression and thus better enabled to withstand failure, and these of course support the regions in tension. The logic clearly applies if the whole casting is subjected to uniform loading.

However, in practice, (i) loads in the casting are not usually uniform, but are highly localised, and may add to the local residual stress. Thus locally, the casting may become overloaded, and may fail. Also, (ii) defects are of course localised. Thus a combination of local residual tensile stress plus either local loading or a local defect would normally be expected to result in local failure. This may grow to extensive and possibly total failure of a heavily stressed casting as the load redistributes during the progress of the failure.

Measured rates of quench for a 20 mm diameter bar of aluminium are shown in Figure 5. The modulus of this shape of material is assessed by its volume to surface area ratio (equivalent to its area to perimeter ratio) and thus works out at 5 mm. Clearly a plate of 10 mm thickness has a similar modulus and therefore a similar cooling rate, illustrating the usefulness of the concept of modulus. Thus the cooling rate Q of any shape having a modulus close to 5 mm, from approximately 500 to 250 C, is seen to be approximately 100, 17, 3.6 and 1.0 C/s for water quench, polymer quench, forced air, and still air cooling (1).

How can we obtain some estimate of Q , the rate of quench at which problems might arise?

The thermal diffusivity D is defined as $K/\rho C_p$ where the assumed values are given in Table 1 (ref 1) and relate approximately to Al at 250 C and steel at 500 C.

TABLE 1

	Thermal Conductivity K (W/m/K)	Density ρ (kg/m ³)	Specific Heat C_p (J/kg/K)	Thermal Diffusivity D (m ² /s)
Aluminium	200	2700	1000	10 ⁻⁴
Steel	50	7800	500	10 ⁻⁵

Using the order of magnitude relation

$$x = (Dt)^{-1/2}$$

which for Al becomes

$$x = 10^{-2}t^{1/2} \quad 1.$$

For the time t available during the critical stages of cooling from 500 to 250 C when the casting is still somewhat plastic, we can now estimate the average distance x to which heat can diffuse. From Equation 1 we have for $x = 10$ mm, $t = 1$ s, so that cooling rate $Q = 250/1 = 250$ K/s. In this way Figure 6 has been built up, showing the relation between average diffusion distance at various cooling rates.

If we use the relation that $t = \Delta T/Q$ where $\Delta T = 500 - 250 = 250$ C approximately for most Al alloys (and equals approximately $1000 - 750 = 250$ C for some steels) then we can define a critical parameter

$$(x^2Q)_{\text{crit}} = D\Delta T_{\text{crit}} \quad 2$$

where the critical value $D\Delta T$ is approximately 2.5×10^{-2} for Al alloys, and approximately 2.5×10^{-3} for steels. If a quench is made in which x or Q are sufficiently high so that equation 2 is met, then the temperature during the quench will be far from equable in the casting.

It is clear that, taking data on real cooling rates from Figure 5, test bars in aluminium are in no danger of any significant residual stresses even when quenched as fast as possible into water. This follows from their small value of x . For steels, the threshold for safe quenching is significantly moved towards the left (requiring slower quenches, or limiting part sizes) because of the lower thermal diffusivity. (The test bars data for steel is also likely to be displaced to the left, so that all steel test bars should remain in the low stress zone of Figure 6).

In contrast with test bars, many castings, such as cylinder heads and blocks, or suspension components for cars, have dimensions of the order of 100 mm or more over which heat need to flow to equalise temperatures. Since sections are of the order of 10 mm or less, then quench rates into water will be typically 100 K/s, limiting heat flow distances to around 15 mm during the time of a water quench, as indicated from Figure 6. Such castings cannot therefore be quenched into water without major internal stresses being developed because the external parts will cool within this short time, but internal parts of such products are often protected from the quench. If they are entirely protected, then the slow rate of transfer of heat from the central regions requires a time of the order of 100 s, as indicated by Equation 1. This would have made a forced air quench appropriate, as shown in Figure 5.

During quenching it is common for hollow castings to remain almost dry inside until late in the quench because, following the entry of the first drops of liquid, the rate of the consequent expanding and escaping vapour effectively prevents further entry of liquid. These internal parts may therefore experience a quench rate approximating to that of a forced air quench, although the evaporation of liquid may enhance this rate somewhat.

As a real example of these problems: In the case of a recent failure of a Al alloy compressor housing which exploded in service, it was found that the casting appeared to be quite sound. However, when cutting off a portion for examination it further exploded in the saw, fortunately injuring no-one for the second time! It had been subjected to a full solution, quench and age treatment (T6 condition). When examples of this product were tested to destruction on a hydraulic test, it was found that the T6 casting performed badly, failing at a low applied pressure. An otherwise identical casting which had been subjected to a stress relieving treatment (and whose material was therefore much less strong) performed well, finally failing at a stress almost 50 per cent higher.

In passing, it is worth noting the further problems that (i) casting may fail by cracking in the quench itself; (ii) castings subject to a quench and then subjected to a rapid reheating during a subsequent stress relieving treatment may crack during the rapid reheat (1) because the internal tensile stress from the quench will be additive to the tensile extension applied by the reheating of the external walls of the casting. It is to be noted that all of these problems can be understood in terms of the concepts discussed here, although we have no time to discuss them separately in the detail they deserve. A general review is given in reference 1.

DISCUSSION

It is a matter of extreme seriousness and regret that we are currently putting castings into service which are designed to fail, simply because of the treatment which was applied in an attempt to raise their strength. How is it that we have got ourselves into the position of carrying out such an inappropriate treatment for castings?

The reason is that heat treatments were designed by metallurgists working on test bars. These compact shapes are safe from the development of residual stresses as shown in Figure 6.

The mistake has been to assume that we can go ahead to apply such drastic methods to more complex parts, when the technique should not have been extended in this way.

I regret therefore that we need to stop quenching castings (and other complex structures) into water (whether cold or hot makes almost no difference (1)). Polymer quenching may be possible for some parts. Air quenching will be appropriate for most current castings. The reduction in strength on subsequent ageing will be more than offset in many castings by the reduction in internal stress. Thus the parts will be more resistant to failure.

The world's heat treatment specifications require to be changed. This is of course a major revision of our thinking. Nevertheless, without such a change, we will be guilty of continuing to supply parts which are designed to fail under low applied loads because of the high internal load which the part is already having to bear because of incorrect processing (but correct according to the specification however!).

The new thinking will emphasise that resistance to failure is the desired criterion in castings. This new concept concentrates attention to the reduction in major defects, and reduction in internal stress.

It focusses attention on the fact that resistance to failure is not necessarily served by high strength materials, the quest for which has resulted in some instances of castings which are close to failure at the point at which they are put into service.

Neither the presence of occasional oxide film defects resulting from surface turbulence, nor internal stresses can be assessed by test bars, nor reliably by any other NDT technique. The only way forward therefore is the application of Process Control to ensure that such defects are not introduced in the first place. To guarantee to our customers that these Process steps have been properly engineered into our processing of the casting, the industry now requires new Process Specifications. Only then will the customer be assured that the casting is as reliable as can be engineered. We shall have arrived, after 5000 years of wanderings, in the Promised Land of the respected Casting Engineer.

CONCLUSIONS

1. When produced by competent foundries, current castings are controlled in almost every way. Only two factors are overlooked. Unfortunately these two factors have a major unpredictable effect on the ability of the product to resist failure. The first is random film defects which act as cracks. The second is residual stress which may act to add to the applied stress.
2. New suggested goals are *high reliability*, and *resistance to failure*, rather than the usual quest for *high strength*.
3. The attainment of these goals is currently within our grasp by the application of process control during manufacture to ensure that such defects are never introduced,

rather than quality control (such as NDT etc) which attempts (not altogether reliably) to detect whether such defects are present at the end of the manufacturing process.

4. The incorporation of random folded oxide films can be prevented by ensuring that (i) the speed of flow of liquid metal in the mould never exceeds approximately 0.5 m/s and by (ii) providing a filling system which avoids the entrainment of air into the liquid metal.

5. The rate of quench (or reheat) should never exceed a critical value of the product $\alpha^2 Q$ to eliminate the possibility of significant residual stress.

6. It is suggested that A Process Specification would guide manufacturers and would enhance customer confidence in this new regime of reliable castings. A draft Procurement Specification designed to be used by buyers of casting is in preparation⁽³⁾.

REFERENCES

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3. J Campbell; Castings Procurement; Minimum Process Requirements. Draft May 1993

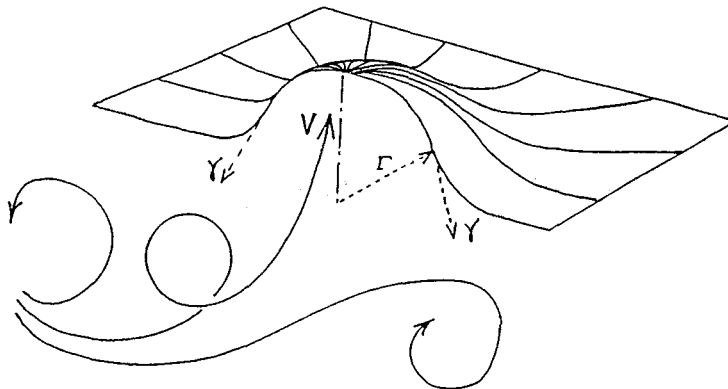


FIGURE 1

1. The balance of inertial and surface tension pressure at the surface of the liquid.

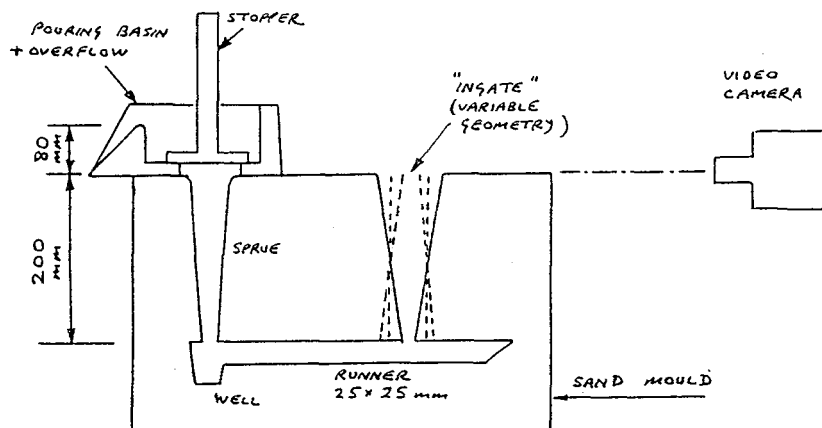


FIGURE 2.

2. The experimental arrangement to investigate the emergence of a metal stream from an ingate (the mould cavity is "open" to allow viewing by the video camera). The velocity of the emerging liquid was varied by altering the height of the sprue and the taper of the nozzle.

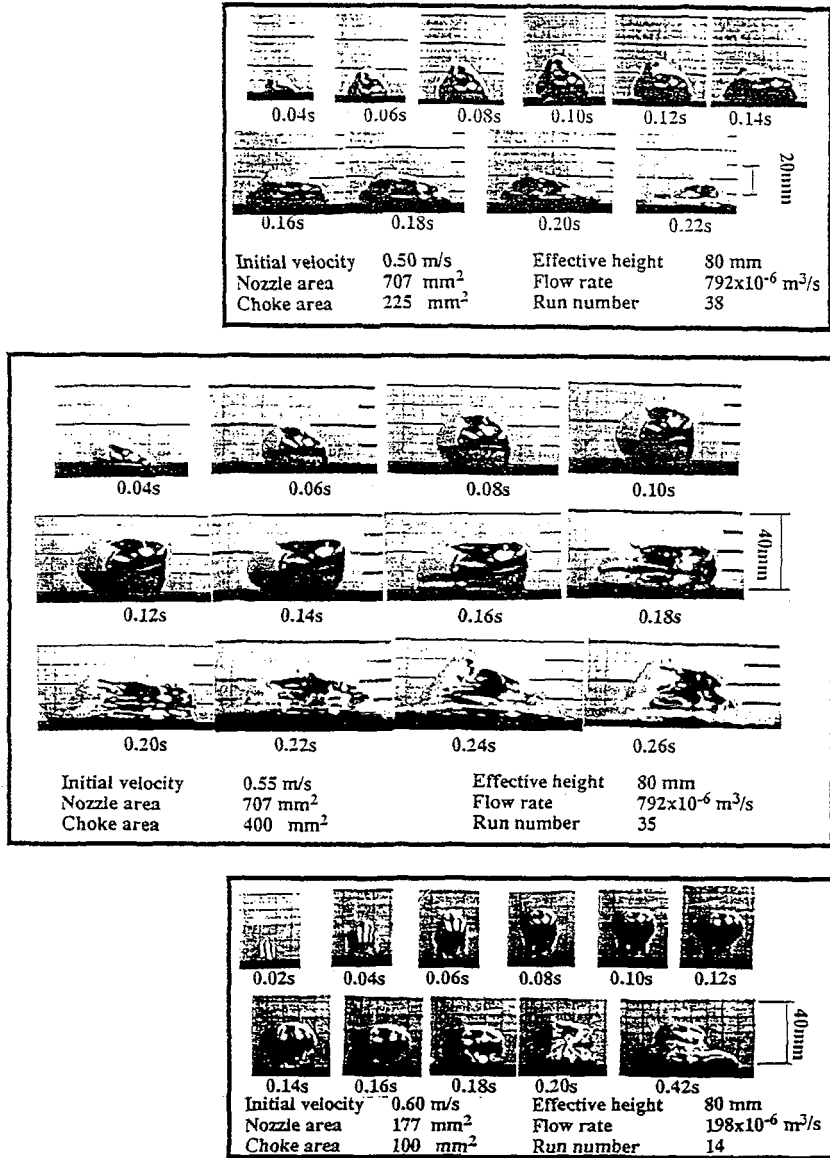


FIGURE 3

3. The emerging liquid aluminium alloy at 0.02 s intervals at velocities of 0.50, 0.55, and 0.6 m/s.

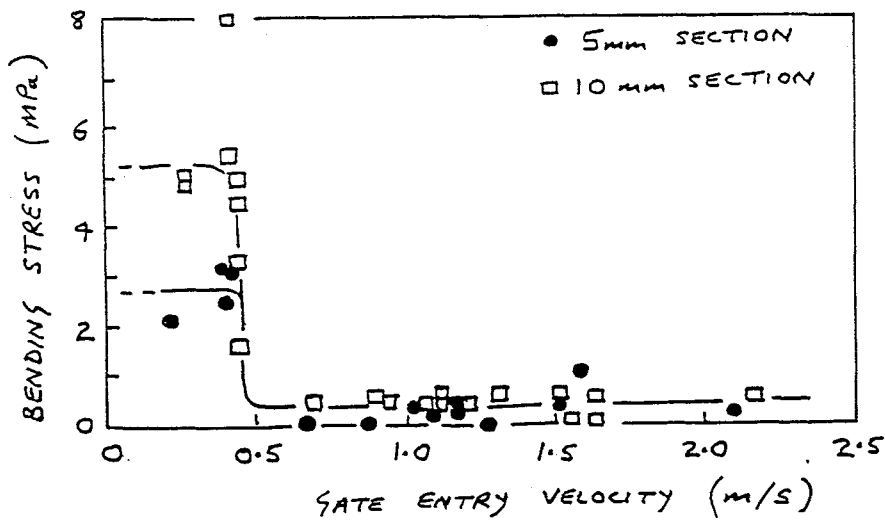
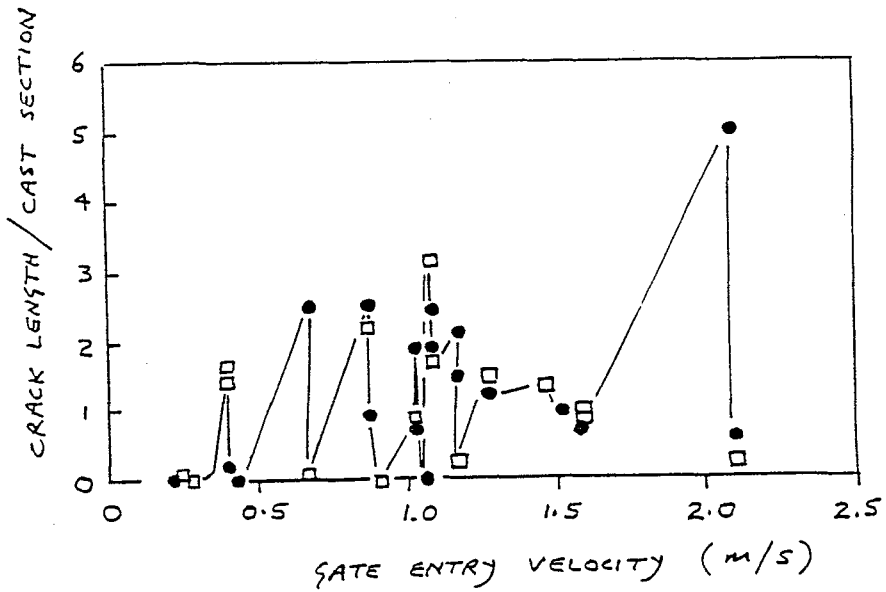


FIGURE 4.

4. Crack length and strength of 5 and 10 mm plate castings in aluminium as a function of metal entry velocity into the mould.

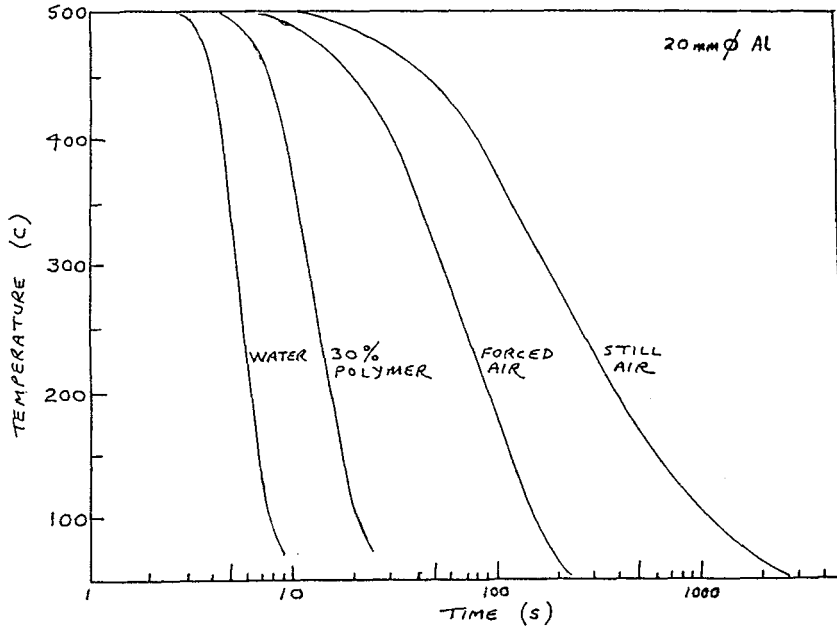


Fig. 5. The rate of cooling of a 5 mm modulus Al plate when subjected to various severities of quench (1).

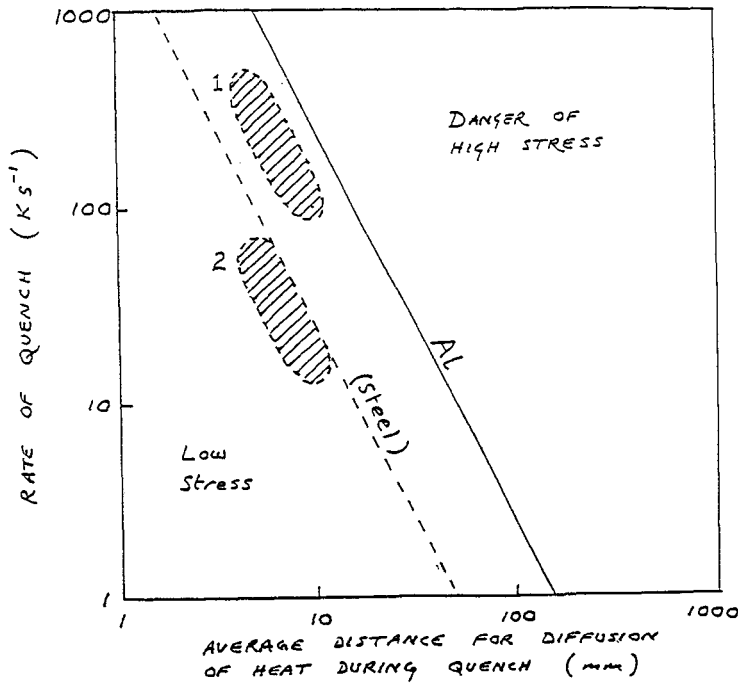


Fig. 6. Rate of quench versus the diffusion distance for heat during the critical time of the quench showing the extent of safe and dangerous regimes for Al castings and test bars (the threshold for steel castings is shown as a broken line). Area 1 indicates the regime for test bars quenched in water; area 2 in 35 % polymer.