In the name of god

Residual stresses

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Action to reduce internal stress can be awesomely important. Unfortunately, it seems that in general, the engineering community has not been made aware of the central importance of this factor in the manufacturing of engineering components. All manufactured components contain internal stress, often high. The problem is that this very real danger is invisible. The problem is widespread, and not confined to metal products. A common example we have all seen is the high stress revealed by the maze of cracks around the plug hole in some plastic wash basins. In this case the stress has been relieved by cracking, probably aided and abetted by the soaps and detergents that encourage crack growth perhaps to be known as liquid surfactant embrittlement, analogous to liquid metal embrittlement or stress corrosion cracking in metals.

There are those metallurgists within the industry, some eminent, and whose opinions on other matters I respect, that have taken issue with me. They have argued that the presence of residual stresses, particularly those from quenching, are actually irrelevant since the whole component is in balance with its own stresses.

The question of balance is certainly true. However, this argument overlooks the fact that the distribution of stress is usually far from uniform, and parts of the component may be near to their failure stress even prior to the application of any service stress. Usually, as we shall see, the major tensile stress is in the centre, and it is this part of the component that fails first under tensile load.

Admittedly, not all components are necessarily endangered by internal stress. Indeed, the stress can be beneficial in some cases; However, the major risk is that the stress may not be beneficial. It may add to the service stress and so promote premature failure at only low service stress, to the bewilderment of the designer who imagines his component material to be inert. Because of the complexity of some castings, and the complexity of the state of stress, it is usually not easy to estimate the magnitude of either the internal residual stress or its precise action. Often, however, it is at least equal to or exceeds the yield
stress. Thus it is not trivial. In fact at this level it will dominate all other designed loads in a fatigue condition, and certainly lead to early failure. It is ignored at our peril. [1]

BMG

Bulk metallic glasses (BMGs) have many attractive properties for structural applications, including high specific and near theoretical strength combined with reasonably high fracture toughness, good corrosion resistance, low damping, large elastic strain limits, and the ability to precisely net-shape into complex geometries.[2]
A major drawback of BMGs is that they fail catastrophically by forming localized shear bands.To avoid this and to obtain more damage tolerant BMGs, they are reinforced with fibers or particulates .
These studies demonstrated that the composite approach could be quite beneficial. The reinforcements interact with the shear bands and act as obstacles against their propagation. Even in high rate dynamic deformation, the addition of

reinforcements causes the development of multiple shear bands, thus increasing the amount of strain accommodated by the material . Despite these significant improvements, there are a number of unresolved fundamental issues about how exactly the reinforcements interact with the shear bands. In addition, the ‘best’ reinforcement and its morphology are yet to be identified. A critical issue in the BMG-matrix composites is the presence of thermal residual stresses due to the coefficient of thermal expansion (CTE) mismatch between the matrix and the reinforcements. Since these stresses are predicted to reach several hundred MPa , they are expected to significantly influence the mechanical behavior of the composite. For instance, tensile residual stresses in the reinforcement will be beneficial in tension as cracks (or shear bands) will be attracted towards regions in tension increasing the probability of being blunted or stopped by the reinforcement. The goal of this work is to assess the thermal residual stresses/strains in BMGs and their composites using neutron powder diffraction (NPD). It is part of a systematic study of the interactions between the matrix and reinforcements in BMG composites.[3]

Modeling

When a component is casted it is obvious that residual stresses are developed during the solidification. It would be most interesting to include these stresses in the design of casted components.

This can be done by first applying a thermo-mechanical stress analysis of the solidification and then export this result into an established design procedure. It is crucial that the thermal stresses are predicted accurately when adopting such a design

Measurement

The assessment of residual stress is therefore of great interest to materials engineers and reliability researchers. Residual stress has been assessed using a number of methods: hole drilling, the curvature method, X-ray diffraction, Raman spectrophotometer and neutron diffraction, magnetic Barkhausen noise (MBN) and electronic speckle pattern interferometry (ESPI) [4–10]. Residual stress has been reported to be related to mechanical properties such as fatigue life, distortion, dimensional stability, and brittle fracture

Fig. 1 shows the many different methods and whether they are destructive or not. It also shows the associated depth of penetration. Furthermore, the stresses themselves may be viewed as first, second or third order in nature and affects choice of method.[11]

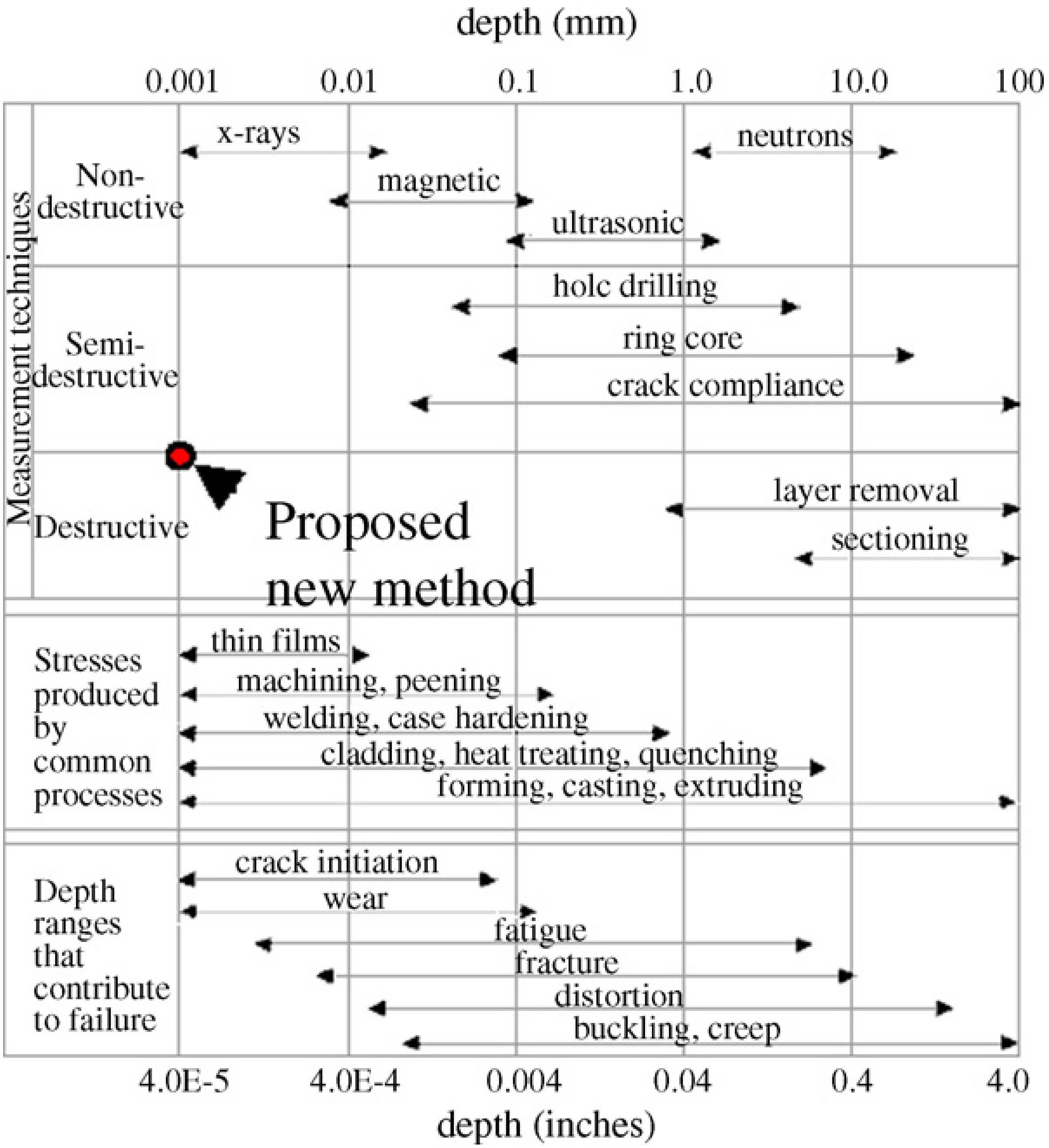


Fig. 1. Residual stress techniques illustrating micro and macro techniques and if the methodology is destructive or non-destructive.

Residual Stresses In Castings

In an aggregate mould, castings are cooled relatively slowly, so that the final internal stress in the product will normally be relatively low, and can often be neglected. It is true that the dimensions of the casting will often be changed by stress during cooling, but on shaking out from the mould the final, residual, stress will not normally be high. the distortions that have arisen during cooling in the mould are usually extremely reproducible. This is a consequence of the reproducible conditions of production, in which the mould is the same temperature each time, and the metal is the same temperature each time, so that the final shape is closely similar each time. This reproducibility is probably greater than for any other casting process.

This repeatable regime is not quite so well enjoyed by the various kinds of die-casting, particularly gravity die (permanent mould) casting, as a result of many factors, but in particular the variability of mould size and shape as a result of variation of mould temperature. The somewhat faster cooling, particularly because of the earlier extraction of the casting from the mould, is an additional factor that does not favour low final stress.

In general, internal stress remaining from the casting process is rarely high enough to be troublesome but we cannot always be complacent about this. The ability to predict stresses using computer simulation will be invaluable to maintain a cautious watch for such dangers. Ultimately, however, particularly for aluminum alloys, the stresses from casting are usually eliminated by any subsequent high temperature solution heat treatment.

There have been a number of test pieces that have been used over the years to help assess the parameters affecting the residual stress in castings.
Most of these take the form of the three-bar frame casting shown in Figure 2.

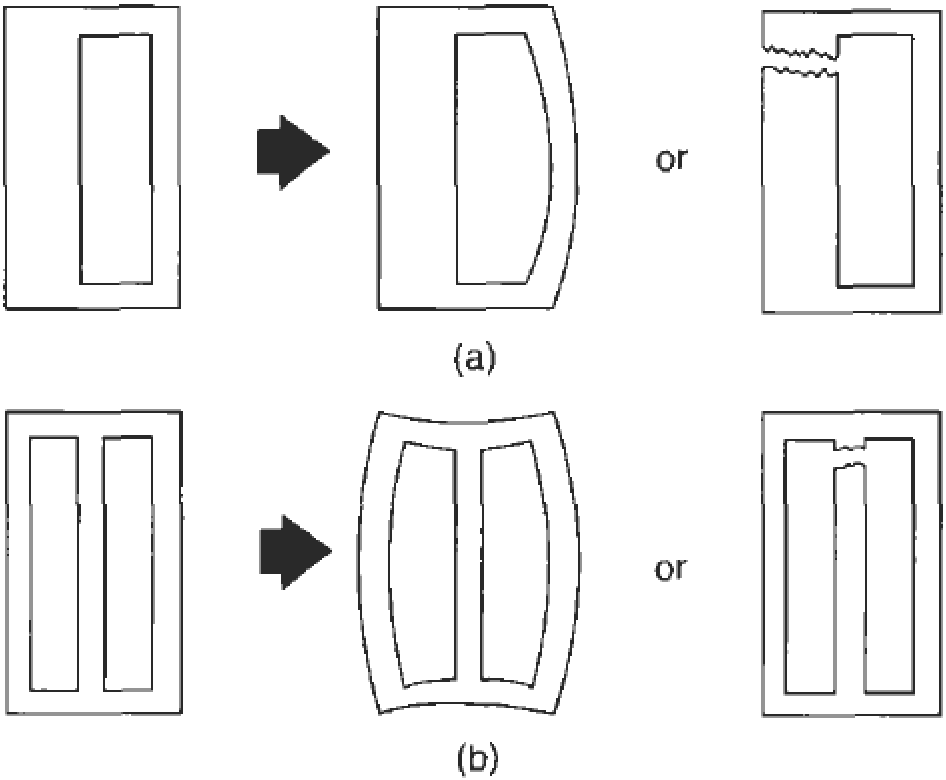


Figure 2

In practice the stress remaining in the casting is usually assessed by scribing two lines on the central bar and accurately measuring their spacing. The bar, of length ***L,*** is then cut between the lines, and, usually, the cut ends spring apart as the cut is completed. The distance between the lines is then measured again and the difference ***AL*** is found.

The strain **E** is therefore ***AL/L*** and the stress ***CT*** is simply found, assuming the elastic (Young's) modulus ***E,*** by the definition:

$$E = \sigma/\varepsilon$$

Such studies have revealed that the residual stress in castings is a function of the cooling rate in the mould, as shown for aluminium alloy castings from the effect of water content of the mould in Figure 3 . Dodd (1950) cleverly illustrated that this effect is not the result of the change of mould strength by preparing greensand moulds with various water contents, then drying each carefully so that they all had the same water content.

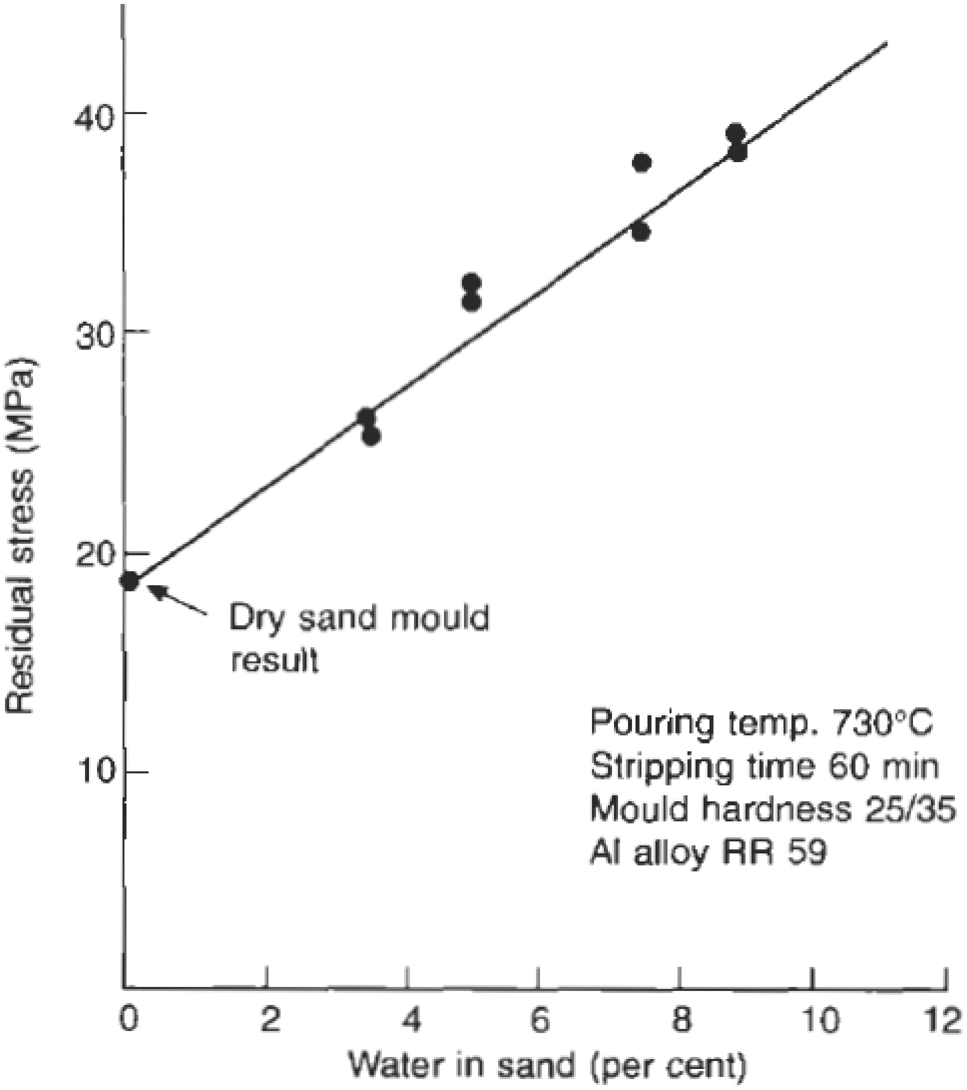


Figure 3 Residual stress in the centre member of a three-bar frame as a function of water content of the greensand mould (Dodd 1950).

This gave a series of moulds with greatly differing strengths. When these were cast and tested there was found to be no difference in the residual stress in the castings. This result was further confirmed by testing castings Water in sand (per cent) made in moulds rammed to various levels of hardness. Again, no significant difference in residual stress was found.

Dodd (1 950) also checked the effect of casting temperature, and noted a small increase in residual stress as casting temperature was increased.

As with cases of the constraint of the casting by the mould, removing the casting from the mould at an early stage would be expected to be normally beneficial in reducing residual stress. Figure 4 shows the result for iron and a high-strength aluminium alloy. The higher residual stress for cast iron reflects its greater rigidity and strength. The effects of percentage water in the sand binder, and of stripping time and casting temperature, have been confirmed in other work on high-strength aluminium alloys and grey iron using a rather different threebar frame (IBF Technical Subcommittee 1949, 1952).

All these observations appear to be explainable assuming that the main cause of the development of residual stress is the interaction of different members of the casting cooling at different rates. Beeley (1972) presents a neat solution to the problem. The strain *AL/L* due to differential contraction is determined by the temperature difference ***AT*** and the coefficient of thermal expansion of the alloy *a*.

We have :

$$\varepsilon = \Delta L/L = \alpha\Delta T$$

$$\sigma = \alpha E\Delta T$$

The stress therefore depends on the temperature difference between members. It is also worth noting that the stress is independent of casting length ***L.***

Further influence of the geometry of the threebar frame casting was found by Steiger (1913). He measured the increase of stress in the centre bar of grey iron castings by increasing the rigidity of the end cross members. Also he found that a centre bar of more than twice the diameter of the outer bars would suffer a residual stress of over 200 MPa, sufficient to fracture the bar during cooling. Working

Equation 8.10 backwards, it is quickly shown that the temperature difference was only about 100°C to produce this failure stress. Clearly, such temperature differences will be common in castings and often exceeded. Thus high stresses are to be expected.

In ferrous castings that experience a *y/a* phase change during cooling, any stresses that are built up prior to this event are probably reduced, their memory diluted by the plastic zone that the transformation causes. It seems probable therefore that the temperature differences and cooling rates applying below the gamma-alpha-transformation temperature that are the most important for the final remaining levels of stress. This fact prompts Kotsyubinskii (1961-62) to recommend that heavy sections of ferrous castings be cooled by forced air or chills to equalize their cooling rates with those of the thinner sections, up to the point at which the pearlite reaction occurs. Below this temperature, little can be done to avoid the build up of stress. This is because the metal is largely elastic, and plastic relaxation, occurring only slowly by creep, becomes ineffective; thus cooling should at that stage be slow and even, so as to take advantage of as much natural stress relief as possible

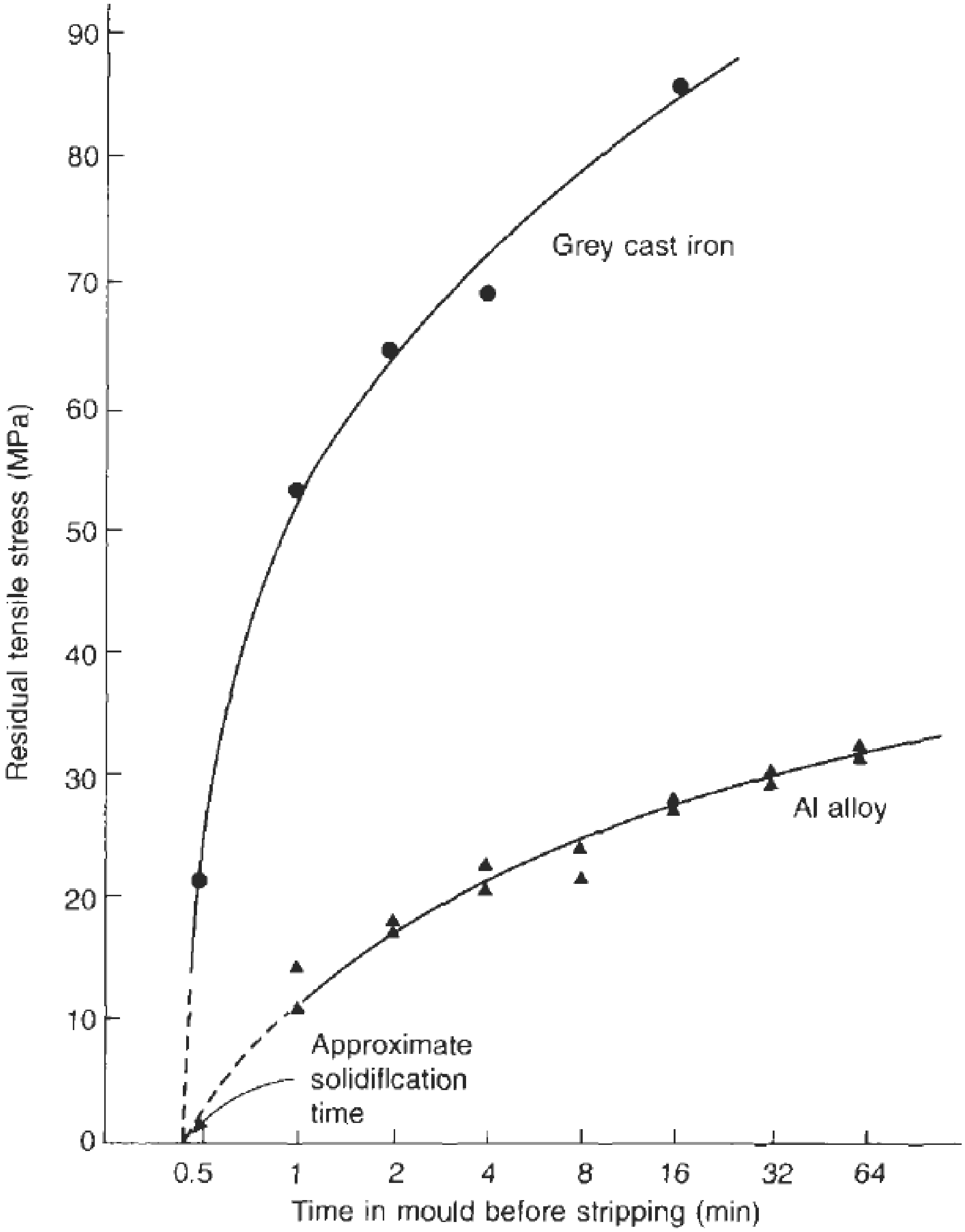


Figure 4 ***Residual*** *.stress* ***in*** *aluminum alloy and* ***grey*** *iron castings as stripping time. Dura,* ***from*** *Dodd (1950) and* ***IBF*** *Technical Suhcomniittre (I 949).*

Quenching stress

Most of the reasons why stresses remain after the casting has cooled from its casting temperature apply also to the situation where the component has cooled from a high heat-treatment temperature. If the cooling was rapid, especially by quenching in water, then the stresses are likely to be even higher. Following the same logic as in the previous section, the stress distribution in the casting after quenching is in general compressive in the outer features, which have the full benefit of the quench, and tensile in the central members of the casting, which are somewhat shielded from the quenching and so cool slowly. Stresses high enough to distort the casting are usual, and stresses even high enough to cause immediate fracture in the quench are not uncommon.

We can easily find how slowly we need to quench to avoid large temperature differences between the inside and the outside of the casting. From our familiar order of magnitude relations, we have the average distance x that heat will flow in time *t* in a material of thermal diffusivity *D:*

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

where $D = K/\rho C_p$ and ***K*** is the thermal conductivity, about 208 Wm-' K-' for aluminium, the density p is 2700 kgm-'. and the specific heat C, is approximately 1000 Jkg-' **K-'.** This gives the thermal diffusivity *D* as about IO4 m' **s-'.** For an aluminium bar of only 20 mm diameter, Figure 5 shows that quenching in water will cool the bar from 500 to 250°C within about *5* seconds. Below 250°C, stresses will start to accumulate because relaxation processes become slow. Substituting *5* s in Equation shows that heat will on average have travelled 20 mm during

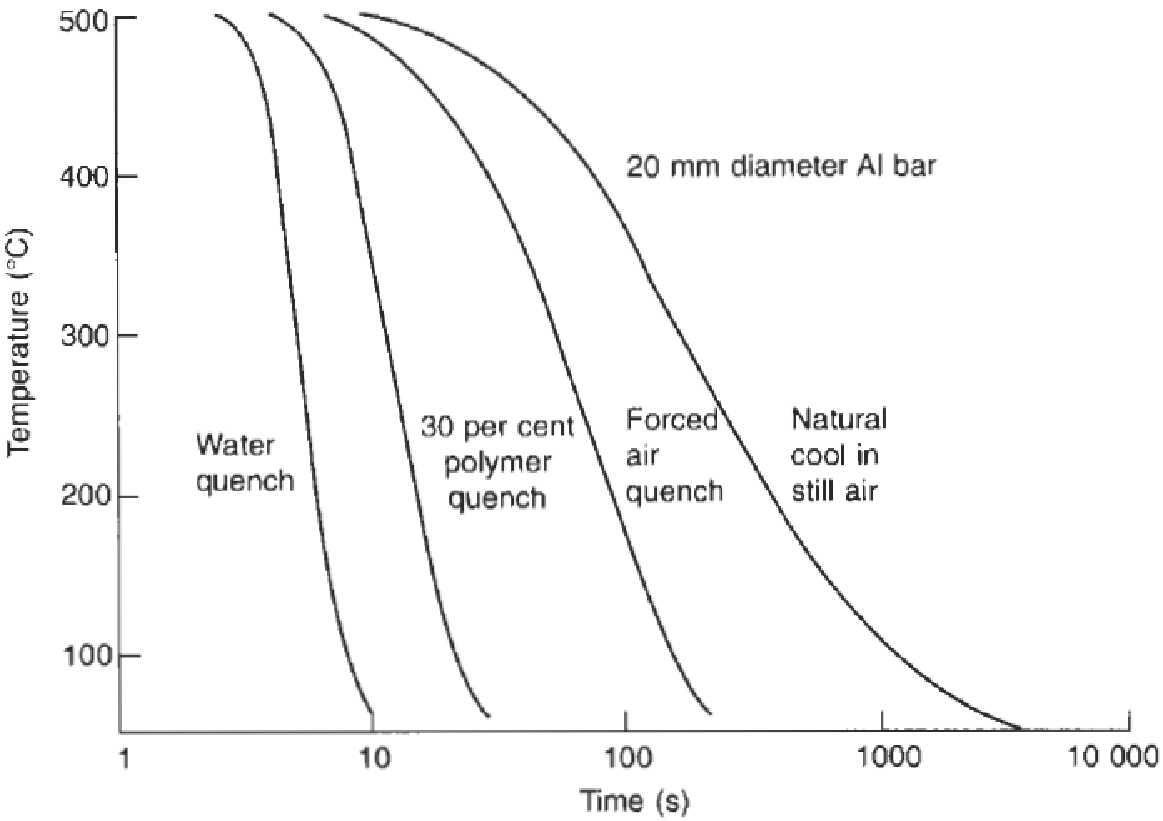


figure 5

this time. The bar will therefore be reasonably uniform in temperature, and large stresses will not be expected.

For a larger casting such as a cylinder block or head, however, the distance that heat would have to diffuse from the centre to the outside is now of the order of 100 mm. If it has walls of thickness 10 mm or less, then its outer walls will still cool at a similar rate to the 20 mm cylindrical bar (since they have similar modulus, defined as volume divided by the cooling area). Thus the time available is still only 5 s, so the heat will have travelled only 20 mm. The 100 mm distance in the cylinder block will therefore suffer extreme non-uniformity, and consequent high quenching stress.

To avoid high residual stress in the cylinder block the casting needs to be cooled at the rate at which it can equalize its temperature within tolerable limits. By using forced-air cooling, Figure 8.25 indicates that approximately 100 s is now available, sufficient time for the heat to diffuse the 100 mm distance, as Equation 8.1 1 confirms. Forced-air quenching would therefore be suitable for such a large component.

For steels the thermal diffusivity *D* is much lower, close to lo-' m2 s-'. This results in average diffusion distances for heat of only 7 mm in *5* s, and 30 mm in 100 s. These limited distances highlight the problem of quenching steels without the generation of internal stress. They explain the reason for long cooling times from annealing temperatures, especially for large castings. Even so, steel castings are not at the same risk of failure from a quenching stress as aluminium alloy castings. This is because steels in general enjoy an elongation to failure usually in the range 20 to 40 per cent. Thus 1 or ***2*** per cent quenching . strain can easily be accommodated with a modest amount of plastic strain. In contrast, many aluminium castings are often found to have only 0.5 to 2.0 per cent elongation, so that the application of a 1 per cent quenching strain may result in failure.

These differences in ductility are probably mainly the result of differences in the usual content of bifilms, the steel being relatively clean, compared to the aluminium that is expected to be full of bifilm defects.

Figure 5 shows that there are other intermediate quenching rate options available. The use of water, while being cheap and environmentally pleasant, causes problems for the quenching of most alloys, whether light alloys or ferrous. The rapidity of the quench is not suitable for larger parts, as we have seen above. In addition to this problem, water gives an uneven and non-reproducible quench because of its boiling action. When the parts are immersed in the water they are at a temperature hundreds of degrees above the boiling point. Thus the water in contact with the hot surface boils, coating it with a layer of vapour that conducts heat poorly. Thus that part of the casting is temporarily insulated while surrounding areas that happen to remain in contact with the water continue to cool rapidly. The pattern of contact varies rapidly and irregularly as the vapour film forms and collapses in the turbulent water. Thus the stress pattern in the casting is complex, and different from casting to casting.

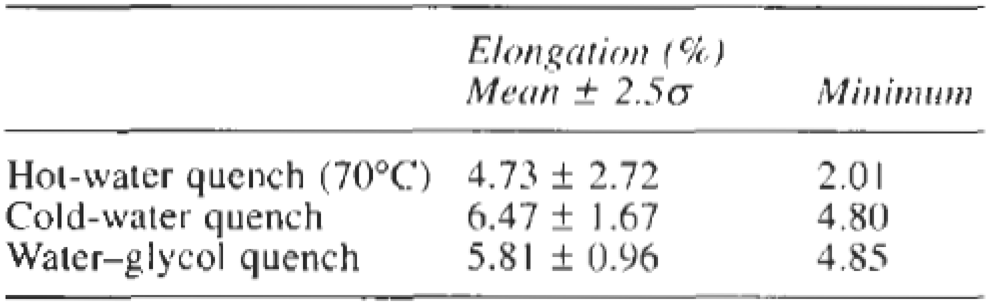
To overcome the blanketing action of the vapour, liquids with higher boiling point such as oils have been used. However, the flammability hazard and the smoke and fumes have caused such quenchants to become increasingly unacceptable.

Cleaning of the casting after the quench is also an environmental problem. Water-based solutions of polymers have therefore become widespread over the last decade or so. They are safer and somewhat less unpleasant in use. Fletcher (1989) reviews their action in detail. We shall simply consider a few general points. Some polymers are used in solution in water and appear to act simply by the large molecular weight and length of their molecules increasing the viscosity and the boiling point of the water. Such viscous liquids are resistant to boiling and so provide a more even quench, with the quenchant remaining in better contact with the surface of the casting.

Sodium polyacrylate solution in water produces cooling rates similar to those of oils. However, its action is quite different. It seems to stabilize the vapour blanket stage by enclosing the casting in a gel-like casing. The fracture of this casing towards the later stages of the quench is said to be almost explosive. Other polymers have a so-called reverse temperature coefficient of solubility. This long phrase means that the polymer becomes less soluble as the temperature of the water/polymer solution is raised. Many, but by no means all, of the polymers are based on glycol. One widely used polymer is polyalkylene glycol. This material becomes insoluble in water above about 70°C. The commercial mixtures are usually sold already diluted with water because the product in its pure form would be intractably sticky, like solid grease, and would therefore present practical difficulties on getting it into solution. It is usually available containing other chemicals such as antifoaming agents and corrosion inhibitors.

Such polymers have an active role during the quench. When the quenchant contacts the hot casting, the pure polymer becomes insoluble. It separates from the solution, and precipitates both on the surface of the casting and in the hot surrounding liquid, as clouds of immiscible droplets.

The sticky, viscous layer on the casting, and the surrounding viscous mixture, inhibit boiling and aid the uniform cooling condition that is required. When the casting has cooled to below 70"C, the polymer becomes soluble once again in the bulk liquid, and can be taken back into solution. Resolution is unfortunately rather slow, but the agitation of the quench tank with, for instance, bubbles of air rising from a submerged manifold, reduces the time required.



	Elongation (%) *Mean ± 2.5σ*	*Minimum*
Hot-water quench (70°C)	4.73 ± 2.72	2.01
Cold-water quench	6.47 ± 1.67	4.80
Water–glycol quench	5.81 ± 0.96	4.85

Table 1

Polymer quenchants have been highly successful in reducing stresses in those castings that are required to be quenched as part of their heat treatment. The properties developed by the heat treatment are also found to be, in general, more reproducible. Capello and Carosso (1989) have shown that the elongation to failure of sand-cast AI-751-0.5Si alloy, using 2.5 times the standard deviation to include 99 per cent of expected results, exhibits greater reliability as shown in Table 1. Thus the average properties that are achieved may be somewhat less than those that would have been achieved by a cold water quench, but the products have the following advantages:1. The minimum values of the random distribution of results are raised.

2. With castings nearly free from stress the user has the confidence of knowing that all of the strength is available, and that an unknown level of stress is not detracting from the strength as indicated by a test bar.

3. The castings will have significantly reduced distortion.

Capello and Carosso (1989) carried out quenching tests on an aluminium plate 150 x 100 x **1 .*S*** mm.

and found that, taking the distortion in cold water as 100 per cent, a quench with water temperature raised to 80°C reduced the distortion to 86 per cent of its previous value. Quenching in a water/20 per cent glycol mixture gave a distortion of only 3.5 per cent.

Other quenching routes to achieve a low stress casting have been developed involving the use of an intermediate quench into a molten salt at some intermediate temperature of approximately 300°C for approximately 20 s prior to the final quench into water (Maidment *et al.* 1984). Despite the advantages claimed by the authors, the expense and complexity of this double quench are likely to keep the technique reserved for aerospace components.

Not all residual stress need be bad. Bean and Marsh (1969) describe a rare example. in which the stress remaining after quenching was used to enhance the service capability of a component. They were developing the air intake casing for the front of a turbojet engine. The casting has the general form of a wheel, with a centre hub.

spokes and an outer shroud. In service the spokes reached 150°C and the shroud cooled to -40°C. With additional high loads from accelerations up to 7g and other forces, some casings were deformed out of round, and some even cracked. In order to counter this problem the casting was produced with tensile stress in the spokes and compressive loading in the shroud. This was achieved by wrapping the spokes in glass fibre insulation, while allowing the shroud to cool at the full quenching rate. By this means approximately 40 MPa tensile stress was introduced into the spokes. This was tested by cutting a spoke on each fifteenth casting, and measuring the gap opening of approximately 2 mm.

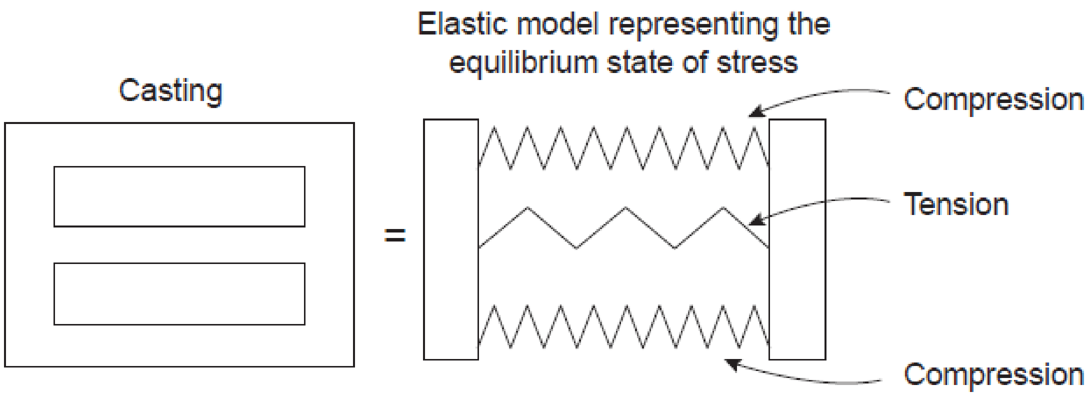
Another method of equalizing quenching rates in castings is by the clamping of shielding plates around thinner sections to effectively increase their section. The method is described by Avey *et al.* (1 989) for a large circular clutch housing in a highstrength aluminium alloy. The technique improved the fatigue life of the part by over 400 per cent. It may be significant that both of these descriptions of the positive use of residual stress relate to rather simple circular-shaped castings. The proper development of quenching techniques to give maximum properties with minimum residual stress is a technique known as quench factor analysis. It is also much used to optimize the corrosion behaviour of aluminium alloys. The method is based on the integration of the effects of precipitation of solute during the time of the quench. In this way any loss of properties caused by slow quenching or stepped quenching can be predicted accurately. The interested reader is recommended to the introduction by Staley (1981) and his later more advanced treatment (Staley 1986).

Distortion

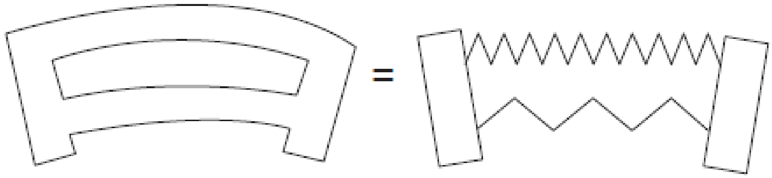
Residual stresses in castings are not only serious for parts that require to withstand stress in service. They are also of considerable inconvenience for parts that are required to retain a high degree of dimensional stability. This problem was understood many years ago, being first described as early as 1914 in a model capable of quantitative development by Heyn. The model of a three-bar casting is shown in Figure 6. The internal stresses are represented by two outer springs in compression, each carrying half of the total load of internal compressive stress, and an inner spring in tension carrying all of the internal tensile stress. If one of the surfaces of the casting is machined away, one of the external stresses is removed. It is predictable therefore that the casting will deform to give a concave curvature on the machined side as illustrated in the figure. The distortion of castings both before and after machining is a common fault, and typical of castings that have suffered a water quench. Once again, it is a problem so frequently encountered that I have, I regret, wearied of answering the telephone to these enquiries too.

After all, it is difficult to understand how a casting could avoid distortion if parts of it are stressed up to or above its yield point. For light alloy castings in particular a more gentle quench, avoiding water (either hot or cold), and choosing polymer or air will usually solve the problem instantly. As mentioned briefly above, such polymer performs well for aerospace castings but is expensive and messy, whereas air is recommended as being clean, economical and practical for high volume automotive work. Otherwise, stress relieving castings by heat treatment prior to machining is strongly recommended (Castings 2003). In either case, of course, some fraction of the apparent strength of the product has to be sacrificed.

(a) Casting



(b) After machining away one part of cast surface



(c) Relief of internal tension by internal fracture

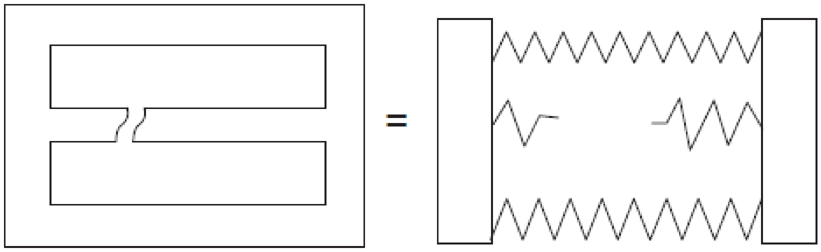


figure 6

Measurement

First order residual stresses are nearly homogeneous in value and direction, along a large material range, i.e. many grains. Second order residual stresses are nearly homogeneous along a small material range, i.e. a few grains . Third order residual stresses are those that are within the crystal lattice that cover distances that are less than the size of the grain (Fig.7). Third order residual stress measurement techniques are essentially non-destructive and to a limited extent, the actual distribution of stresses normal to the surface concerned can be determined . Measurement of such stress distributions at an atomic level is a complex process.

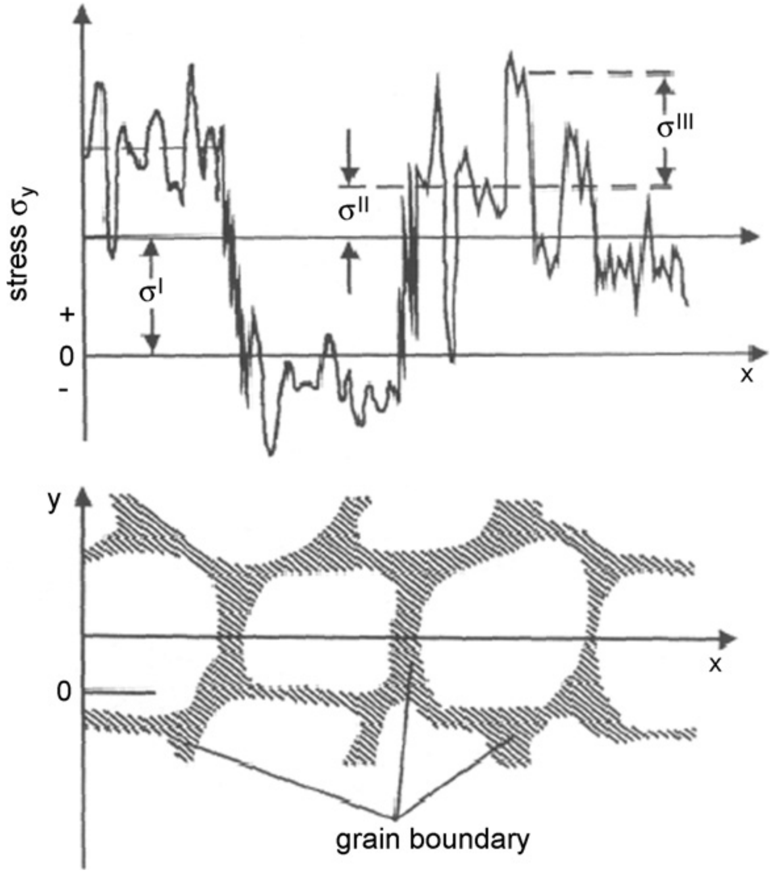


Fig. 7. Depiction of first, second and third order residual stresses

X-ray diffraction (XRD) is one of the most widely employed second and third order surface residual stress measurement methods, and has been used in the automotive and aerospace industries for over 40 years . It assumes the presence of linear elasticity as it directly measures the strain due to the distortion of the crystalline lattice structure and converts this to stress. This is basically a non-destructive method for measuring residual stresses but it is however limited, as it is restricted to materials that have a crystalline structure . Such results are also affected by surface roughness and grain size . This would clearly be a concern when the measurement of residual stress levels in sand castings, for example, are involved where both coarse as-cast grain size and variable surface roughness can occur.

The most common, least expensive and simple to use first and second order residual stress measurement involves hole drilling.

The system works on the principle that residual stresses will relax when material is removed by the drilling of a hole . Local strains around the hole are thus relieved and are measured with specialized strain gages. Hole drilling does suffer from potential errors and uncertainty of the strain measurements due to the hole geometry. Removing material and the uncertainty connected with associated stress fields clearly detract from its broad utility.

Development of the new method

Clearly it would be desirable to have in place a simple, inexpensive technique to estimate first and second order residual stresses that could be utilized by organizations responsible for the actual manufacturing operations .To this end the authors were attracted to a previously mentioned study which demonstrated that the indentation produced by a micro-hardness test changed once a previously applied tension was released . It was felt that micro-hardness testing could readily be used to determine if a residual stress was either tensile or compressive.

This led to the authors undertaking experiments employing pairs of micro-hardness indents as gage marks that would show changes in dimension upon stress relief. This method was patented [11], and has been described in depth in another article.

Experimental methodology and results

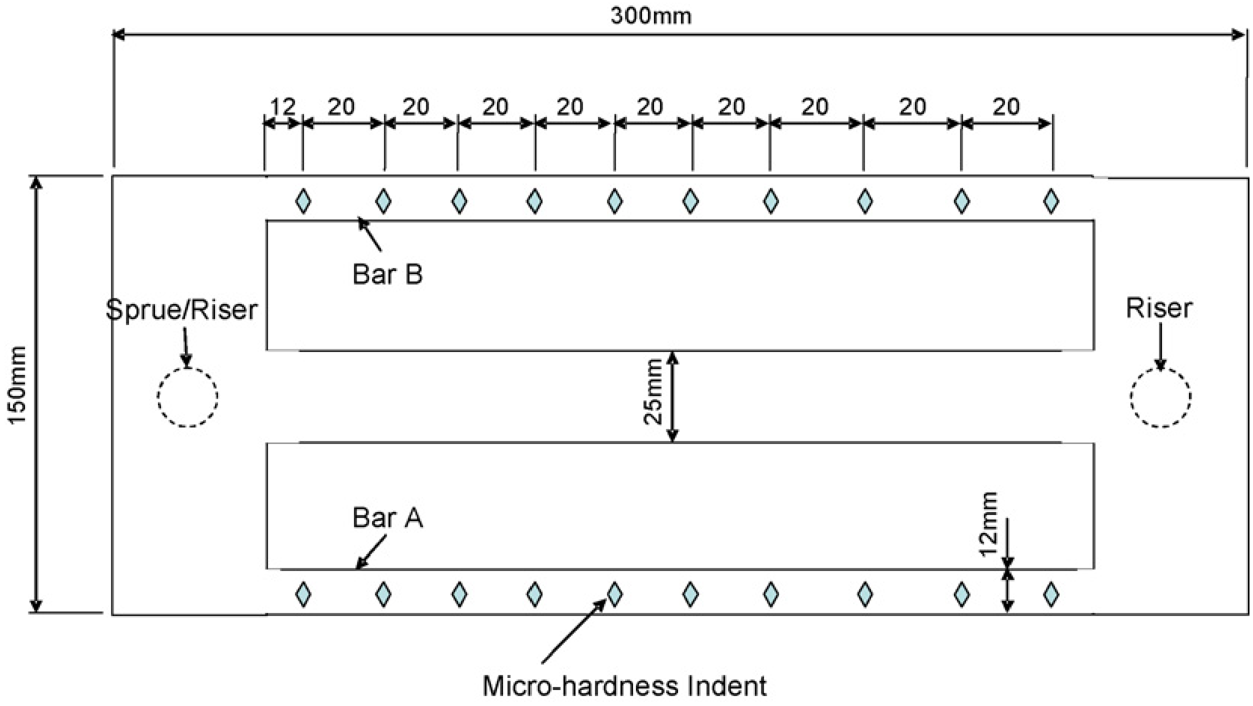


Figure 8 - An illustration of the test frame and the spacing of the micro-hardness indents.

The current work was concerned with the residual stresses in castings. These are involved in components that have differing cross-sectional areas, and therefore cooling rates. A 3 bar test frame was constructed to the dimensions shown in Fig.8. The outer members are assumed to contain only a uniaxial state of stress. The material to be cast was aluminum alloy A356, which was poured at a temperature range of 714–732 ◦C. There was no modifier, grain refiner or degassing prior to pouring. The castings were cooled in their sand molds. The castings were then gage marked at 20mm intervals (Fig. 8). Castings were refrigerated to prevent aging and any subsequent stress relief. Frames were cut and the spacing between pairs of micro-hardness indents measured. The castings were then stress relieved thermally and re-measured. The thermal stress relief involved a treatment of 250 ◦C for 200 min. It should be noted that for materials where stress relief will be associated with overaging (for example, 200 and 300 cast aluminum alloys) any change in Fig8. An illustration of the test frame and the spacing of the micro-hardness indents.

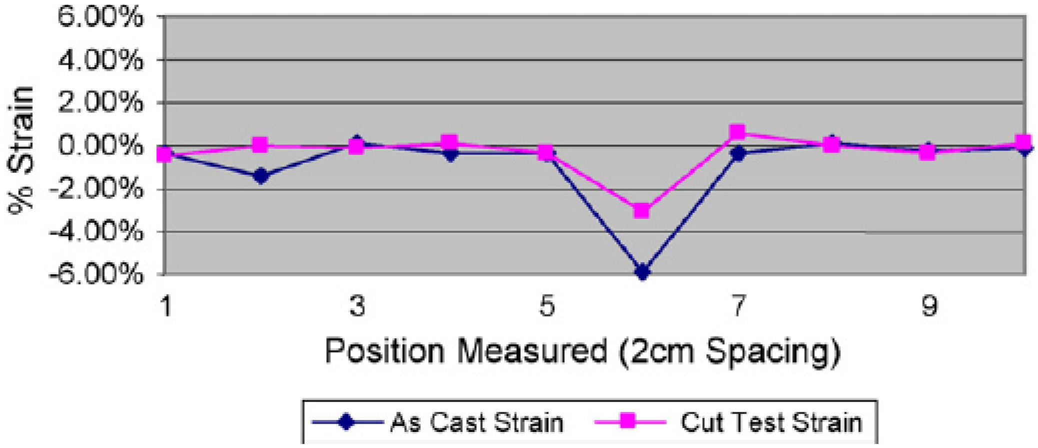


Figure 9 - Results of cut and thermally stress relieved casting. The residual stresses are calculated using Hooke's Law as described in ref.

Fig. 9. Results of cut and thermally stress relieved casting. The residual stresses are calculated using Hooke's Law as described in ref.

the value of the elastic modulus will not be significant although hardness will change. The change in the elastic modulus is of second order in magnitude, as elastic behavior depends only on the interatomic forces and does not involve plastic deformation

Surprisingly, levels of indicated strain are often higher for the thermal stress relief than for the specimens that were cut (Fig. 9).

Upon cutting, the material will redistribute the internal residual stresses in such a way as to require the least expenditure of energy. This when seen as the cut strain follows the same strain relief pattern as the full thermal stress relief, as well as having locally induced residual stress changes around the cut itself. Note that the strains measured at position six will include a summation of the residual stress relief across the entire section, as the gap produced by cutting is either opened or closed.

The thermal stress relief has been assumed to be a fully stress relieved case for the castings. From Fig. 4, it can be seen that the strains once again redistribute themselves upon thermal stress relief. This implies that cutting techniques do not reveal the full extent of large scale residual stresses, but merely the stresses concerned with the constraints of the geometry of the casting.

In addition the levels of stresses in the vicinity of the cut are especially high possibly indicating dangerous levels of stresses in the as cast state. It has been reported that spontaneous cracking can occur on removing castings from their molds

Conclusion

Although the strength of the material will be lowered by a slower quench, the strength of the component (i.e. the failure resistance of the complete casting acting as a load bearing part) in service will be increased.

If water quench is avoided with a view to avoiding the dangers of internal residual stress, it is common for the customer to complain about the 5 per cent or so loss of apparent properties. In answer to such understandable questions, an appropriate reply to focus attention on the real issue might be `Mr Customer, with respect, do you wish to lose 5 per cent or 50 per cent of your properties?'

In the experience of the author, a number of examples of castings that have been slowly quenched, losing 5 or 10 per cent of their strength, are demonstrated to double their performance in service .

Finally therefore, it remains deeply regrettable, actually a scandal, that many national standards for heat treatment continue to specify water quenching. This disgraceful situation requires to be remedied. In the meantime the author deeply regrets having to recommend that such national standards be set aside. It is easy for the casting supplier to take refuge in the fact that our international and national standards on heat treatment often demand quenching into water, and thereby avoid the issue that such a production practice is risky for many components, and in any case provides the user with a casting of inferior performance. However, the ethics of the situation are clear. We are not doing our duty as responsible engineers and as members of society if we continue to ignore these crucial questions. We threaten the performance of the whole component merely to fulfil a piece of metallurgical technology that from the first has been woefully misguided.

The fact is that our inappropriate heat treatments have been costly to carry out, and have resulted in costly failures. It has to be admitted that this has been nothing short of a catastrophe for the engineering world for the past half century, and particularly for the reputation of light alloy castings, not to mention the misfortune of users. As a result of the unsuspected presence of bifilms they have suffered poor reliability so far, but as a result of the unsuspected presence of residual stress this has been made considerably worse by an unthinking quest for material strength that has in fact reduced component performance.

The use of a low cost technique for the measurement of the residual stresses in a casting is viable.

Cutting techniques demonstrate partial stress relief as the constraints within the casting are removed thereby affecting the section being investigated.

This questions the validity of hole drilling as the micro-hardness indents produce insignificant stresses when compared to the large size of the component.

The values of residual stress recorded here are dangerously high and may account for the spontaneous failures of castings of certain geometry on removal from their molds.
The work here presents the initial findings and observations of an ongoing study into residual stresses in cast components

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