Chapter

Perspective Chapter: A Personal Overview of Casting Processes

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Abstract

Casting processes are reviewed from the point of view of the type of defects they produce and their consequential properties of the castings they produce, particularly resistance to fracture, and therefore, their reliability in service. The ingot casting of steels is criticized for unnecessary degradation of the steel. The fundamental problems of continuous casting of aluminum alloys and steels are seen to be lying in inattention to the details of the processes. Vacuum casting, particularly vacuum arc remelting, as currently executed, is seen to be fundamentally unreliable for any safety critical purposes, particularly its history of helicopter tragedies resulting from its use in helicopter drive trains.

Keywords: metal casting, entrainment, oxide film, bifilm, defect, fracture

1. Introduction

I have written about casting processes extensively, some would say, over-extensively, but useful new concepts enshrining the new insights into this important subject are being only slowly realized and understood. Their awful importance to the reliability of engineering is yet to be fully adopted. It is useful therefore to offer a short summary in this appropriate volume. A personal reading list is appended.

Space unfortunately forbids any lengthy discussion of the influence of the melting processes on the quality of the resulting castings. However, of course, the quality of the metal prior to casting is of critical importance; a liquid metal, especially if a secondary metal (such as recycled metal, as is common in the aluminum industry) can be literally crammed with defects, so that despite the excellence of the casting process and the heat treatment process, the resulting casting predictably fails all mechanical property requirements and is scrapped. We shall have time to give only a brief mention of this important problem. Our subject is the casting process.

2. Fundamental issues

Castings have had a poor reputation as a result of their poor and variable properties. For many years this was thought to be somehow associated with the turbulence of the pouring process, but the details were not understood, and efforts to control turbulence, despite all claims to the contrary, were failures. No-one was aware of the degree of failure to control turbulence during mold filling because, of course, molds made or sand or steel were opaque: the awful internal damaging mechanisms were unseen and unsuspected.

The breakthrough in understanding came from X-ray video studies of mold filling. Although occasional demonstrations of this technique had been made a number of times over the years, it was only in the 1990s that intensive and systematic studies were carried out at Birmingham University, UK [1]. It was quickly realized that because the liquid metal practically always exhibited a surface oxide film, the mutual impingement of drops and splashes, or the folding of the liquid surface, occurred as oxide film to oxide film. The liquid metal, in general, never made contact with itself. Furthermore, the upper surface of the film in contact with the air was dry. Thus, the mutual impingement processes occurring during turbulence of the surface occurred as dry-film-to-dry-film (**Figure 1**). No bonding occurred between these two ceramic films which for many metals and alloys, including steels, consisted of alumina (Al_2O_3) and similar very stable high melting point oxides.

The practical result of this impingement of two unbonded ceramic films, is the effective creation of a crack in the liquid. This defect is called a bifilm. The turbulent pouring of a liquid into a mold can fill a liquid with cracks. The properties of the subsequent casting are, of course, significantly impaired. This is the fundamental problem of all casting processes. It affects nearly all processes in a major way. It is an issue which cannot be ignored.

Throughout this chapter, it should be kept in mind that if oxides in metals are mentioned, it necessarily means double oxides, in other words, bifilms, which implies cracks. Careful consideration of the entrainment mechanism will convince the reader that the surface oxide cannot be entrained and submerged without it occurring as a doubled oxide to create a bifilm crack; all oxides indicate the presence of cracks in the metal. As will be discussed in detail, the bifilm cracks survive plastic working, and so enter the world of the metallurgist and engineer. Because nearly all our engineering metals are intrinsically ductile, all cracks observed in metals almost certainly originate from the turbulence of the casting process.

The presence of bifilms in most metals comes to the rescue of the reasons why metals fail by cracking. After extensively surveying the metallurgical and fracture literature it was a tremendous surprise to this author arrive at the realization that there was no metallurgical mechanism to explain fracture. The lattice mechanisms such as the dislocation pile-up leading to the initiation of a crack were widely believed but have over recent years seen to be in error. Thousands of pile-ups have

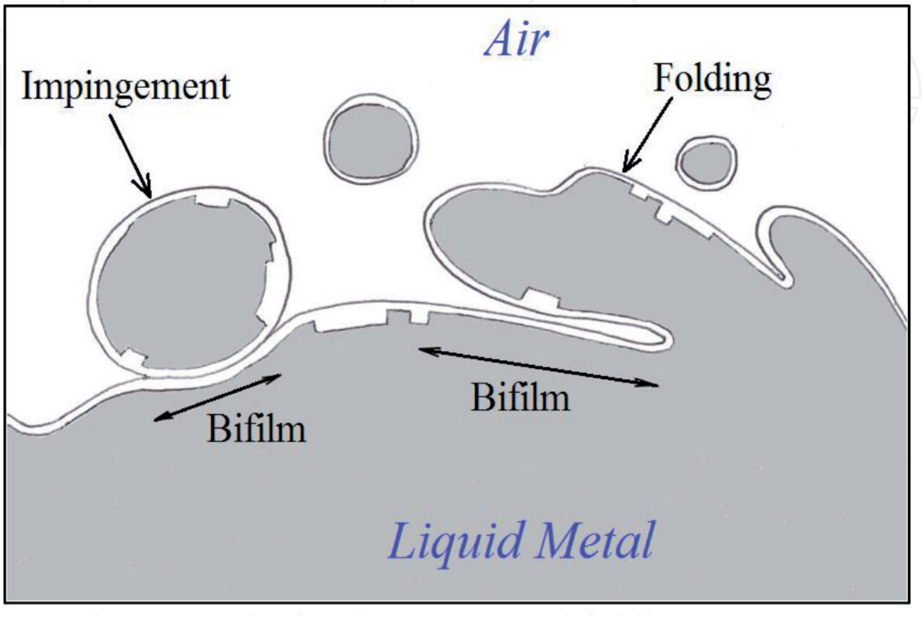

Figure 1.
The impingement and folding processes to produce bifilms as cracks in the liquid metal.

been observed by electron microscopy and studied in detail by computer simulation, but a crack from a pile-up has never been reported. Other theories such as the condensation of vacancies has been known for many years to result not in cracks but in totally collapsed lattice features such as dislocation rings and stacking fault tetrahedra, depending on the stacking fault energy. In brief, the bonds between atoms are simply too strong. Atoms cannot be separated mechanically by any normal forces; pores and cracks cannot be opened up by atomic or lattice mechanisms [2].

The fact that fracture occurs in so many ways and often at modest stresses cannot be explained by conventional metallurgy. This amazing fact is, however, obvious when it is realized that bifilms are present in most metals, usually as a result of poor casting techniques. It follows that if bifilms could be eliminated from metals, there would be no residual mechanism for fracture. Failure by fracture could not occur. This was a sobering realization to this author which it is hoped the reader will be convinced by this short account. If the short account fails to convince, the references at the end of this chapter are recommended.

Before moving on to the discussion of the techniques of casting processes, in addition to the bifilm, a further serious entrainment defect must be described.

In the maelstrom of pouring processes, in addition to the entrainment of oxide films as bifilm cracks, bubbles of air can also be entrained. The bubbles are serious defects in themselves, but their buoyant flotation makes a bad situation worse. Their buoyancy force causes the oxide film at the crown of the bubble to tear, so that it moves to one side, but is immediately replaced by fresh oxide film (**Figure 2**). It can

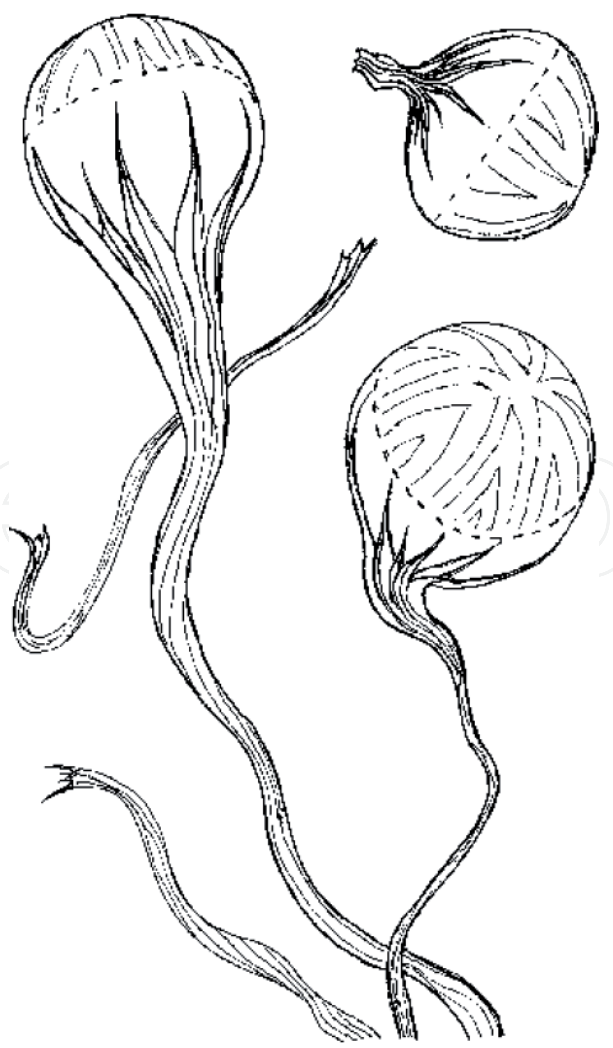

Figure 2.
Bubbles and bubble trails as collapsed oxide tubes.

be seen therefore that the skin of the bubble effectively slides around the bubble, coming together underneath to form a kind of collapsed tube, which extends back to where the bubble was effectively tethered, the point where it first entered the liquid; probably some early location in the channels of the filling system. This bubble trail is a kind of long bifilm. It can be metres long. Thus, bubbles can create macroscopic crack-like defects out of all proportion to the original size of the bubble. Furthermore, it is common for hundreds or thousands of bubbles to make their way up through the metal, creating masses of tangled defects [1, 3].

The reader may by now be already appalled, realizing the reality of grossly poor metallurgical processing which still bedevils our casting world today. The fact is that as a result of these fundamental entrainment mechanisms, most casting processes are bad. Books are full of the descriptions of casting processes, but none state that nearly all of them usually are capable of delivering only badly defective products.

This short summary will attempt to redress this key issue, illustrating how engineering and the world copes at this time simply by accepting the mediocre properties of metals, often by building in substantial safety factors. For the future, impressive improvements in properties and reliability are forecast for fundamentally improved casting technology.

3. Gravity casting

If liquid metal is allowed to fall under gravity, after a fall of about 10 mm the metal has accelerated to near 0.5 m/s. This is the critical velocity at which the liquid now has sufficient energy to jump or splash up to about 10 mm high, and so be in danger of entraining its own oxide skin during its fall back under gravity. Thus, fall heights and speeds less than these values are safe from the introduction of damage due to surface turbulence. Above these heights and speeds, entrainment of air and oxides becomes increasingly severe [1]. Therefore, when pouring an average sand casting, which might be 500 mm tall, the falling stream reaches speeds of over 3 m/s, far higher than is wanted, so that, in general, copious amounts of defects are entrained. The situation is worse still for the pouring of steel ingots where a fall of 3 or more meters creates speeds of near 8 m/s, generating conditions similar to emulsification with air and oxides.

The skill in the filling of shaped castings by gravity pouring is to limit air ingress into the filling system and limit the velocity at which the metal enters the mold cavity. Only in the last few years have these problems been solved for the first time [3].

The sand casting process (of which there are very many variants) and investment casting processes similarly require these new solutions for design of filling system if, as is usual, filling is by pouring under gravity. Interestingly, these processes both exhibit rather low properties compared to castings poured in metal molds. The improved properties of faster cooled metals are traditionally attributed to a refinement of the dendrite arm spacing (DAS). In steels and Mg alloys there is some truth in this as a result of their limited number of slip planes. However, for Al alloys, with its extremely ductile face centered cubic (FCC) structure, the benefit from DAS is negligible.

The benefit to the faster freezing of Al alloys is a bifilm mechanism. Bifilms arrive in the mold in a compact raveled state because of the dramatically vicious bulk turbulence (high Reynolds number) in the filling system, so that their crack-like morphology is initially suppressed to some extent. Metal molds solidify quickly and freeze in these favorably compact and convoluted defects. In comparison, slow solidification in sand and investment molds allows more time for the bifilms to unfurl. This opening-out process, in which the crumpled bifilms unfold and straighten, resembling the opening of a flower, in which the petals adopt the morphology of planar engineering cracks. The unfurling process generally takes several minutes, and is driven by a number of mechanisms, including gas in solution which precipitates into the 'air-gap' inside the double film, or because of dendrite pushing and other factors [1, 3]. When all the bifilms have straightened out to resemble engineering cracks, the metal properties are at an all-time low. The metal now contains a snow-storm of cracks.

Turning to steelmaking, the technology of casting includes some astonishingly retrograde techniques. In an electric arc furnace, the steel quality is probably quite good as a result of the length of time available for the flotation of oxides. However, the metal quality is ruined by the tilting of the furnace and the fall of metal by several meters into a ladle. The turbulent churning of the steel has to be seen to be believed. However, it takes several minutes for the ladle to be lifted from the pit and taken to the casting station, during which time its quality recovers somewhat because of the very different density of the oxides compared to the dense liquid metal. But this improvement is destroyed a second time by ingot casting. Although some of the damage during casting floats out, not all escapes. The ingot is permanently degraded.

The move to ladle metallurgy is a valuable modern step in steelmaking, but the final pour into the ingot mold is unchanged and undoes much of the good achieved in the ladle.

This problem is especially acute for the casting of special steels, in which the tonnage is often too low to consider the use of the rather superior continuous casting process. Special steels are therefore mainly cast as ingots. At the time of writing, this is a poor process, in which steels which may be required to be especially good for a special purpose are actually made especially badly.

All castings which are top poured under gravity, including many sand castings, nearly all investment castings, and nearly all ingots, suffer the maximum damage from entrainment of air and oxides (**Figure 3**). All top pouring is bad.

In an effort to upgrade the ingot casting process, a bottom gating (sometimes known as uphill teeming) is carried out (**Figure 3**). The reduced splashing by uphill

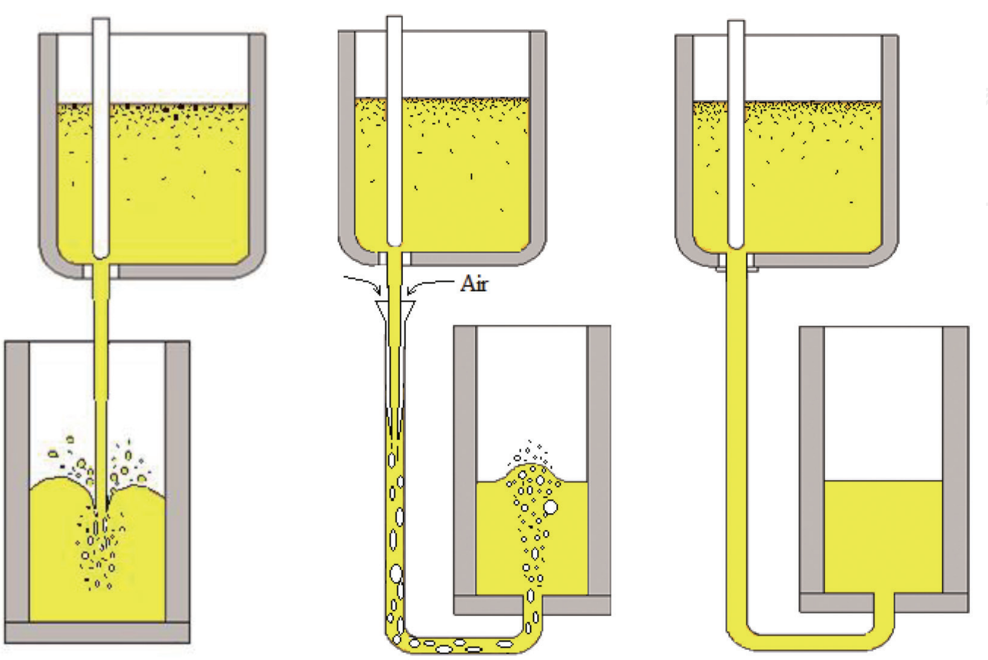

Figure 3.
Illustrating top pouring; uphill teeming; and contact pouring of steels.

teeming improves the surface finish of the ingot. However, unfortunately, the interior quality of the steel is little improved. The falling stream jetting from the base of the ladle enters the start of the filling system at conical intake (often known as the trumpet). The trumpet and following channels need to be oversized with respect to the falling jet to avoid back-filling and over-flowing. This geometry results in at least 50 per cent of the fluid entering the conical basin as air. In the filling system pipe-work, the 50/50 air/steel mix is substantially thrashed together at speeds of up to 10 m/s, ensuring that the bifilm mix will never properly de-segregate, and the bubble trails will further contribute to the copious residual inclusion population, each trail contributing an impressively long crack.

At the high temperatures of some steels, and because of the compositions of some oxides, the crack can evolve to reduce its surface energy. The double film coarsens by diffusion, finally forming sheets of granular solid particles of oxide. The final product is therefore sometimes oxide fragments attached to a void, or gas-filled cavity such as an argon bubble, the residue of the bifilm 'air gap'. The argon bubble remains after the oxygen and nitrogen have been taken into solution in this energetic mixing, leaving the 1 per cent argon in the air as the insoluble residue.

The overall result is that the internal quality of the bottom gated ingot is hardly any better than the top poured ingot.

A dramatic improvement to gravity pouring is achieved by contact pouring (**Figure 3**). The author now insists on contact pouring for all his shaped castings of any metal. The foundries which use this technique find that their cast products are transformed, including cast steels, Ni alloys, Al alloys and bronzes.

Returning to the casting of bulk steels, the continuous casting process certainly delivers a superior product to those steels cast as ingots. This is partly because the ladle take time to be delivered to the top of the casting machine, and then only slowly releases its melt from the base of the ladle – the steel at the base of the ladle having the best quality as a result of the melt cleaning automatically by flotation, and the extended time which is available for flotation, which can easily be 10 times longer than the time required to cast an ingot.

The continuous casting process could probably be much improved by paying attention to important details. The use of tapered nozzles for ladles and launders (the tapering avoids air entrainment into the nozzle which is probably the reason that nozzles block by oxide accumulation [1, 2]). Any fall exceeding 10 mm has to be controlled, so as not to occur in air but submerged under metal or slag. There is a huge amount of research concentrating on the *detrainment* of inclusions from launders, when the research really needs to be spent on the prevention of *entrainment* of inclusions because the inclusions should never be in the launders in the first place. The fall of the metal into the initially empty mold is a massive retrograde step which has to be eliminated – the piling of scrap metal into the mold is a poor starting technique not helping at all. The initial fall creates masses of bifilms which then pollute the whole length of the cast strand because of the progressive dilution of the initially badly damaged metal [2]. These are all simple, negligible cost techniques for which there is no excuse for not implementing immediately.

4. Counter-gravity casting

All the difficulties of mold filling by pouring under gravity, at which metals are accelerated to unwanted high speeds, and so creating masses of unwanted defects, are avoided by not employing gravity.

If now, by some means, the metal can be pumped uphill into a mold, its velocity can be controlled at every point, and need never exceed the critical velocity 0.5 m/s at which entrainment becomes possible. Furthermore, air need never be entrained, so that bubble damage from bubble trails cannot occur. The contrast between conventional gravity pouring and counter-gravity filling is seen in **Figure 4**. In the counter-gravity process the surface oxide film is never entrained; as the metal rises, the surface film simply splits and moves to one side, but instantly reforms and splits, moving aside etc. The surface film becomes the skin of the casting. It is never entrained. In principle, the counter-gravity casting of metals promises perfection.

However, attempts to achieve this perfection are, unfortunately, often not conspicuously successful.

The most disappointing process which nominally adopts counter-gravity filling is the low pressure permanent mold process for the casting of automotive castings, particularly wheels. Most embodiments of this process currently employ a large melting furnace to tip metal into a ladle, in which it falls at least a meter. This damaged metal is then driven by forklift truck to a treatment station, then to the furnace of the casting unit, into which it is tipped again, falling another meter and suffering more damage. The consequence is a really poor quality of metal, full of bifilm cracks, giving poor strength and toughness. If this were not bad enough, there is worse to come! The furnace is pressurized to displace the metal up the riser tube and into the mold (**Figure 5(i)**). After solidification of the casting the release of the pressure causes the melt to fall down the riser tube, thereby displacing all the oxide sediment, which has taken its time to settle at the bottom of the furnace, back into suspension, just in time for the next casting to be made. In addition, the depressurizing action causes bubbles to expand from pressurized gas trapped in crevices in the refractory walls, and the creating of generous quantities of bubble trails. Sufficient bubble trails can sometimes be created to make the metal uncastable; the furnace becomes filled with a slurry of metal and oxide films resembling concrete. Crucible furnaces (**Figure 5(ii)**) appear to be somewhat more resistant to the worst excesses of this problem because of the finer pore sizes from use of isostatic consolidation during their manufacture.

A more recent development is the application of pressure to the mold, pressurizing the incoming metal, and therefore acting to keep bifilms closed, with a benefit to properties. Naturally, this pressure effectively acts to counter the pressure used to pressurize the metal up the rise tube, hence the name 'Counter-Pressure Casting.' However, if counter-gravity is employed to cast good quality metal, in which the bifilm population has been reduced or eliminated prior to casting, the counter-pressure becomes redundant. The counter-gravity counter-pressure process seems

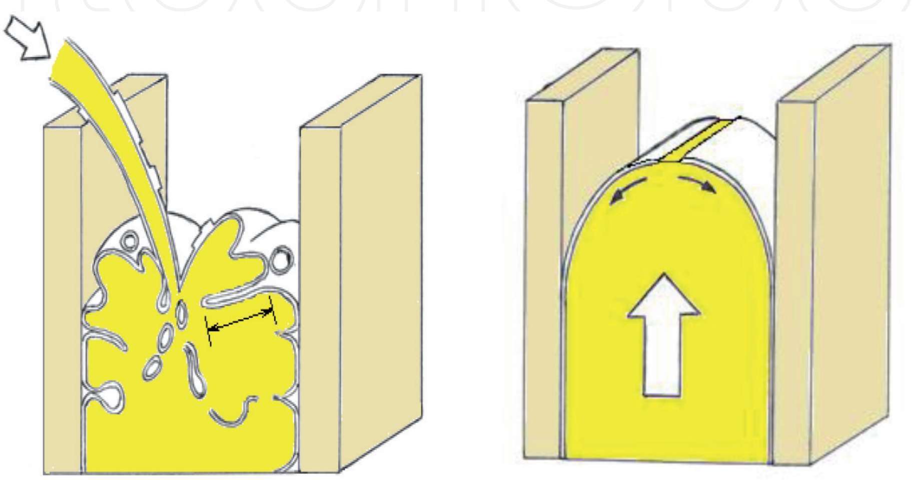

Figure 4.
Conventional gravity casting and counter-gravity casting.

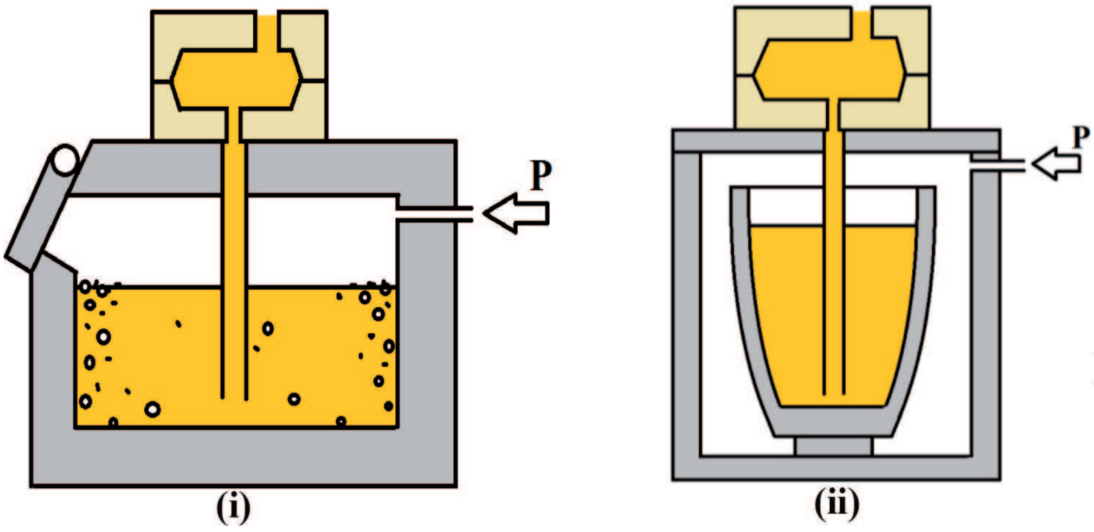

Figure 5.
Low-pressure casting in (i) a refractory lined pressurized furnace, compared to (ii) a pressurized crucible furnace.

to this author to be a step too far. Liquid metals, like all liquids, is effectively incompressible, and cannot be improved by pressure.

When counter-gravity casting is carried out well, with cleaned metal free from dense populations of bifilms, and when transferred uphill, against gravity, carefully controlled by a pump, the resulting castings can be spectacularly excellent.

In his early days in the casting industry, when the author first set up the Cosworth counter-gravity process, the castings requiring aerospace quality were cast in the half of the foundry containing the counter-gravity system using an electromagnetic pump for the liquid aluminum alloy. The other half of the foundry was retained for less important gravity cast products. Eventually however, it was found that with counter-gravity it was difficult to make a bad casting, whereas with gravity casting it was difficult to make a good casting. After 6 months, the gravity area was closed, and all castings were made on the pump.

5. Metal injection casting

The production of castings by high pressure die casting (HPDC) are generally limited to the low melting point metals Al, Mg, Zn and Pb. Some brasses are cast by this technique but attempts to cast stainless steels seem to have been abandoned. This brief description will concentrate only on the casting of Al alloys.

Although the term ‘high pressure’ seems to offer reassurance of a well-consolidated pore-free product, as most readers will be aware, this can be far from the truth and should never be forgotten by potential users. In general, the HPDC process can never guarantee freedom from porosity and leakage. Nevertheless, the process has valuable features and capabilities which distinguish it widely from other casting methods.

The process is often described as high productivity. It is true it benefits enormously from its ability to cast thin sections which can freeze quickly. But in common with all metal mold casting processes, the metal mold cannot be opened until the casting has frozen, or nearly frozen. This waiting time for the casting to solidify is a major contribution to the production cycle. High production sand casting systems can be much faster for any thickness of casting section, because after pouring, the mold can be moved away, allowing the immediate pouring of a second mold, and so on. Both sand and die systems can benefit from multiple impressions, giving multiple castings per filling.

For most HPDC machines, metal is spooned from an open holding furnace, and poured into a shot sleeve, from where it is rammed into a steel die by a piston. The steel die is sunk into a massive steel bolster, which is kept closed during the shock of the filling process by hydraulic rams developing hundreds or thousands of tons of force. This brutal description is not too far from reality, although the injection stroke and filling pattern is now often optimized by computer simulation to reduce air entrainment, which has resulted in significant improvements to the reduction in porosity in castings.

The turbulence during the injection process, in which the metal velocity usually exceeds 50 to 100 m/s, is so great that defects are necessarily created but are accepted as a feature of the process. Interestingly, the high density of bifilms is not necessarily the disadvantage that might be imagined; the long oxide flow tubes (the oxide tubes which surrounded the jets of metal entering the mold cavity) and other bifilms are aligned along the flow direction, giving a fibrous microstructure whose properties somewhat resemble the directional features of wood. The rapidity of the filling process, being completed within milliseconds, probably also suppresses the degradation of the casting by bifilms, whose constituent films have so little time to grow and are necessarily extremely thin. Their limited thickness may permit some bonding between the two films as a result of atomic rearrangements during their transformation from pure alumina to spinel as Mg in the alloy diffuses into the bifilm. The high pressure, keeping the two sides of the bifilm closely in contact is a further aid to bonding and, in any case, provides strength by the bifilm being enabled to resist shear force, because of jogs and wrinkles, if not direct tensile force. Even so, the HPDC castings can never be relied on not to leak, and sometimes, not to fail unexpectedly. Their use for safety critical purposes should therefore only be accepted with very great caution. (In contrast, gravity sand and gravity die castings [permanent mold castings] are typically favored for safety critical components).

Traditionally, small HPDC machines provide high productivity for small thin-walled products. The accuracy and surface finish are good, often eliminating machining, making the process favored by engineers. Recently, extremely large HPDC machines have been built to produce castings of several square meters area with walls only a millimeter or two in thickness, creating large pieces of automobiles in one shot.

6. Vacuum casting

There are some genuine reasons why vacuum is needed for the melting and casting of certain alloys and certain products. Sometimes, a limit on the oxidation of reactive metals or alloying elements is required. At other times the vacuum is needed to ensure the filling of extremely narrow and tapering sections as in turbine blades.

Alternatively, vacuum casting is used, imagining that this will prevent the formation of defects during a top pour. This appears to be a widespread but dangerously incorrect assumption. The entrainment defects resulting in bifilm creation appear to be the same no matter what environment is used, whether this is air, inert gas or vacuum. The reason is that both the inert gas and the vacuum environments always contain sufficient oxygen and/or nitrogen to create oxide or nitride films on the surface of the pouring liquid, so that defects of identical size and geometry are formed if entrainment of the surface occurs – the only difference being the thickness of the resulting bifilms. Bifilms are generally so thin that they are not easily seen when cast in air, but are, of course, far more difficult to detect in vacuum castings. The vacuum casting has a lower oxygen content, and is assumed to be cleaner, which in a way it is. But the distribution and sizes of its population of cracks appears to be unchanged [2].

7. Vacuum induction melting (VIM)

The formation of bifilms in vacuum casting is practically universal, because ingots and castings poured in a vacuum furnace are nearly always top poured. In huge industrial VIM installations, the fall can be many meters, creating much damage to the metal. For instance, all the metal used by the aerospace industry for remelting for the casting of turbine blades is damaged during VIM preparation of the Ni-base alloys; the metal is top poured, falling many meters, down long vertical steel tubes; the larger the diameter of the tubes the worse the damage to the alloy by splashing and entrainment.

In probably all the leading R&D institutions in the world, metals and alloys for research are melted and poured in laboratory VIM furnaces, the top pouring, with the metal falling by a meter or more, fundamentally undermining or complicating nearly all metallurgical R&D worldwide (**Figure 6**). It has greatly contributed to the lack of understanding of more complex failure forms of metals such as fatigue, stress corrosion cracking and hydrogen embrittlement among others as a result of all researchers being unaware that their research materials were densely pre-cracked [2].

It is with great regret therefore that we have to conclude that the preparation of most metals and alloys by vacuum casting is a snare and delusion. It would be easily possible to make castings in air of far greater perfection by simply avoiding surface turbulence during the casting process. This is most effectively achieved by

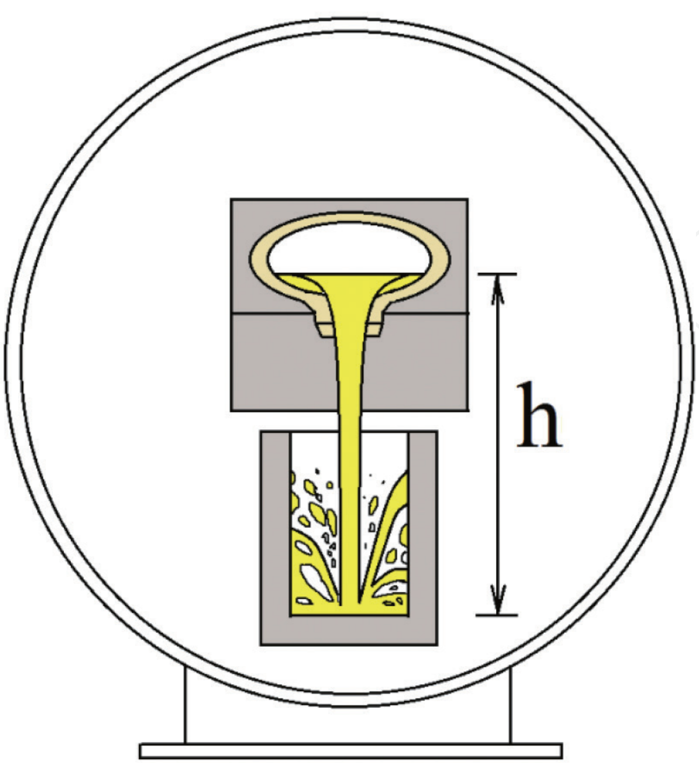

Figure 6.
A simple laboratory vacuum induction furnace illustrating the awful top pouring, creating damaged products.

abandoning gravity pouring and adopting counter-gravity filling of the mold. The world needs to convert its casting operations to counter-gravity casting. The suffering of the casting world from the ubiquity of casting defects will then be of interest only for historians.

8. Secondary remelting

The secondary remelting processes for steels and Ni alloys are designed to deliver a premium quality of metal in the form of an ingot. Their starting material is a reasonably good metal in the form of a consumable electrode which is slowly and progressively remelted by arc, plasma, electron beam, or joule heating in a liquid slag layer etc. As the tip of the electrode melts, a new ingot is then slowly built up drop by drop within its protective environment of vacuum or slag. The ingot solidifies tolerably rapidly because of the use of a water-cooled mold.

At the time of writing, it requires to be noted, with regret, that none of the secondary remelting processes are totally reliable. All can have serious crack defects which can survive the subsequent forging or rolling, and the heat treatment, making these products unreliable in service. Some, as we shall see, can be seriously unreliable.

9. Vacuum arc remelting (VAR)

VAR is probably the most widely used of all the secondary remelting processes (**Figure 7**). The marketing of VAR benefits from its name: engineers are attracted to the concept of 'vacuum' suggesting cleanness.

However, the VAR process is particularly susceptible to its slightly oxidizing vacuum conditions, growing an oxide skin on the horizontal ledges formed by the slow layer-by-layer advance of the solidifying liquid. This variety of advance occurs because of the strength of the oxide on the advancing meniscus as it rolls over the solidified or solidifying metal around the edge of the ingot. The vertical advance occurs by the horizontal flow of the liquid front, gradually spiraling upwards, advancing vertically by the 8 mm high steps corresponding to the height of the meniscus. This is the height which surface tension can support against the hydrostatic pressure due to this depth [1]. As the meniscus rolls over the oxide film on the

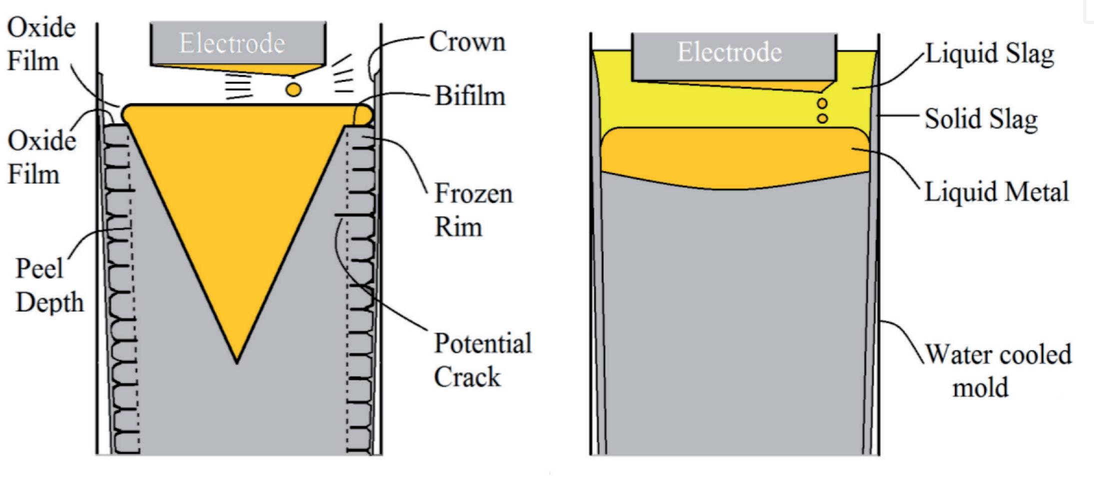

Figure 7.
VAR and ESR secondary remelting processes.

freezing ingot, the meniscus lays down its own oxide film on top of the surface oxide film, creating a bifilm. It is a substantial crack, possibly extending up to 50 mm deep [2].

The presence of cracks around the circumference of VAR ingots is widely known. It is proven by the cracking of the ingots in forging (in contrast to ESR ingots which forge like butter). The manufacturers machine off around 5 mm depth of the outer surface as a token gesture to remove cracks. Because ingots forge better after the removal of the 5 mm it is certain that most cracks are removed. However, of course, it is unlikely, given the variability of conditions during arc melting, that all will have been removed.

The falling-in of the 'crown' of spatter and evaporated metal (**Figure 7**) into the forming ingot may introduce additional macroscopic bifilms. A further source of major bifilms is the electrode. The electrode is typically made by top pouring into an ingot mold, sometimes in air and sometimes in vacuum (the VIM/VAR process combination) but as we have seen, whether air or vacuum, the seriously deleterious defect distribution will be essentially the same. A bifilm taking up a substantial area of the cross section of the electrode may cause a large piece of the electrode to detach and fall into the melt. This unmelted fragment will be effectively surrounded by a bifilm (its own oxide surface collecting a covering of the oxide on the liquid as it plunged through the surface) together with its own internal oxide bifilms.

10. Electroslag remelting (ESR)

Nearly all producers of VAR material also produce ESR. The ESR process is probably the next most popular secondary remelting process. The tip of the electrode is heated by the passage of an electrical current through a slag layer (**Figure 7**). The thin film of melted metal, gathering over the base of the electrode, and finally detaching and falling through the slag droplets of metal, ensures that metal arriving in the melted pool contains only rather small bifilms. Any bifilm which happens to touch the slag will be sucked out of the liquid metal and into the liquid slag by capillary attraction: the solid oxide will be wetted by the slag, a mainly oxide liquid. It will then be dissolved in the slag and disappear. This sets a limit of around 1 mm for the maximum size of bifilm defect which could be present in an ESR ingot (contrasting interestingly with the potential for 50 mm defects in VAR). This ability of ESR to actively extract oxides and dissolve them is a fundamental and unique benefit of the ESR system. (In the early days of the process, no-one could understand how the ESR process improved the properties because no significant changes to the metallurgical structure could be seen!).

There remains a threat to the integrity of ESR material through no fault of the ESR process itself. The threat lies once again with the desire to provide only the cheapest electrode, and so, once again, electrodes are usually cast by top pouring. An electrode top-poured in air contains bifilm defects as surface-appearing laps which can be seen by the unaided eye from 100 m distance. It is no wonder therefore that, once again, large fragments can detach from the electrode during melting and can fall into the melt. These defects contain unmelted and unrefined material. The author has personally seen such a defect the size of his hand on the section of a 600 mm diameter ingot.

For the future, if completely reliable metal is required, the ESR process is the only currently available source, but requires the provision of an electrode cast by a reliable process. Such a process includes low-cost ingots cast by contact pouring (especially if enhanced by flush filters and spin traps), or perhaps an improved continuously cast material, or, ultimately, counter-gravity casting of some kind.

The world would then have, for the first time ever, a totally reliable metal process free from macroscopic cracks, but containing only microscopic cracks of maximum size perhaps 1 mm.

11. Metal processing

The result of entrainment of bifilms during casting production results in huge losses in metals processing such as forging, rolling and extrusion. All these processes suffer from cracking of the processed metal, sometimes to the extent that the metal cannot be processed. Many steel ingots suffer from cracking during cooling. For this reason, fluted molds assist to disperse stresses across the faces of the ingot, although the technique is not especially successful for some steels. The break-outs of liquid steel from the cast strand during continuous-casting are almost certainly bifilm problems which is the reason this rather common disaster has remained unsolved. A number of Ni-alloy ingots are known for cracking at the first stroke of the forge, and rolled steels suffer edge cracking, longitudinal cracks, transverse cracks, internal cracks. Many metals suffer edge cracking during extrusion and rolling. Aluminum alloy semi-continuously cast slabs suffer cracks of all sorts, some measuring their length in meters across the slab face.

For those working in metal processing, valuable R&D has often been carried out to provide process 'windows' defining the limits of successful processing. Many such limits have been set by the onset of cracking. Processors would be delighted to see these limits eliminated. The processing of metals remains to be revolutionized.

12. Metal properties

If the metal is successful to survive processing, it then can suffer from its internal bifilm population during its service life. All its mechanical properties and failure modes are affected by its bifilms. Some of these aspects are discussed below.

12.1 Ductility

Practically all of our engineering metals are intrinsically ductile. Basic dislocation theory predicts that if a stress is applied to a crack in most engineering metals, dislocations are emitted prior to the advance of the crack tip. The result is that the crack blunts, and crack propagation cannot occur.

(This behavior contrasts with the rather few intrinsically brittle metals, including W, Cr and Be, for which the imposition of a tensile stress causes the crack to propagate first, without the emission of dislocations. Fracture by cleavage is a variety of brittle failure but is only known for certain to exist in zinc).

In theory, therefore, tensile overload in the majority of our metals should result in plastic necking down to 100% reduction in area (RA) despite the metal possibly having high strength, resulting in high stress supported during the plastic failure.

Cast aluminum alloys fail this expectation lamentably, having typical elongations to failure in single figures, typically 3 ± 3%. Al alloys generally contain a dense populations of bifilm cracks because the alumina bifilms are slightly denser than the liquid, but contain some entrained air lending some buoyancy, causing bifilms to be close to neutral buoyancy, and thus remaining in suspension for hours or days. Conversely, steels typically reach 50% elongation because the rapid flotation of bifilms within minutes results in much cleaner metal. Other factors leading to some bonding across the central interfaces of bifilms in some steels further contribute to improvement [2].

In contrast to steels, the lack of a definitive yield point in Al alloys is probably due to the presence of bifilms, raising the stress around the bifilm because of the loss of load supporting area and the sharpness of the bifilm crack. Thus, plastic flow occurs early, spreading from scattered locations throughout the matrix of an Al alloy before the macroscopic yield point is reached. Similarly, the lack of a fatigue limit in Al alloys compared to steels can be similarly explained.

12.2 Fatigue

In the experience of the author, much of the area of many fatigue fracture surfaces is comprised of bifilms. The genuine fatigue areas characterized by 'beach marks' appear to be generally confined to a few regions which happen to be devoid of bifilms. The remainder of the surface is often described as quasi-cleavage failure, which is simply a polite admission of ignorance – no-one seems to know what quasi-cleavage is, except that it is definitely not cleavage. These regions appear to be bifilms, hiding in plain sight. The regions often outline grains because the bifilms tend to be trapped intergranularly between grains or are straightened by dendrite growth transversely across grains. When the advancing fracture reaches the limit of one bifilm and has to migrate out of its plane to continue its advance by opening the next bifilm, the plastic shearing process between bifilms outlines the grains.

A typical well-known example is the fatigue failure of the main bearings of wind turbines. These huge steel rings are forged from a single large ingot. The interior surface of the ring is naturally composed of the center of the ingot. Bifilms will have been segregated here by dendrite pushing. Because of the huge size of the ingot, the plastic deformation involved in forming this into a ring is modest; the bifilm cracks are merely pushed around a little but are by no means 'welded' closed. Large tangled masses of bifilms are therefore present on the inner surface of the bearing ring. These masses of pre-cracked regions are likely to be millimeters or even centimeters across. They experience the high (2000 MPa) rolling stresses, with the result that minute connections inside these regions, or linkages holding the masses to the matrix, will suffer even higher concentrations of stress, resulting in genuine fatigue failure of the tiny isolated connections holding the pre-fractured regions together. Ultimately, whole, macroscopic blocks of material break away among the rollers because of the minute, almost negligible amounts of fatigue, signaling the imminent death of the bearing.

12.3 Creep

There is excellent evidence for creep being significantly controlled by the presence of bifilms. In the comparison between polycrystal and single crystal turbine blades, it was traditionally explained that the overwhelming benefit to resistance to creep failure was the elimination of the transverse grain boundaries. It was assumed that the boundaries were weak. However, as much recent research has now demonstrated, grain boundaries are immensely strong. The traditional explanation is clearly unsatisfactory.

The realization that bifilms are present in the liquid alloy leads to a logical explanation. In the conventional polycrystalline casting grains nucleate and grow randomly throughout the cooling liquid. Bifilms in suspension therefore become trapped as grains collide, the bifilm effectively becoming coincident with the newly formed grain boundary. The boundary is therefore weak, effectively pre-cracked, and the polycrystalline casting is observed to have poor creep properties as a result of a high proportion of its boundaries harboring cracks.

In contrast, in the conditions for growth of the single crystal, the slow vertical advance of the freezing front will push bifilms ahead. Those that are not pushed may float. The result is a casting relatively free from bifilms, and displaying astonishingly good creep life.

12.4 Pitting corrosion

Bifilms can act as invasive pathways for corrodents into the interior of metals. The outside surface of a metal may be tolerably resistant to corrosion, but at the location at which a bifilm emerges, breaking the surface, the ingress of rain or salt water is likely to form an etch pit. The localized corrosion around the bifilm may be enhanced by precipitates of second phases and intermetallics which favor the wetted exterior surface of the bifilm (its wetted exterior surface contrasts with its dry, unbonded inner interfaces). These different compounds with different electrochemical potentials attached to the exterior surface of the bifilm can provide vigorous corrosion couples.

Figure 8 shows a typical etch pit. Although the conventional explanation of the image would be that the etch pit has initiated the formation of cracks, the reverse is true. The cracks are bifilms, as can be identified from their morphology and precipitates. They have initiated the etch pit.

In the past decade there have been at least three, perhaps four or more, helicopter crashes, some extremely tragic, in which items of the drive train appear to have failed by fatigue initiated from an etch pit. Experts from around the world have been puzzled because an etch pit was far too small to have initiated the fatigue crack. In the case of one main rotor shaft, which appeared to have failed in this way, the shaft was designed with a safety factor of five. It is not conceivable that such a robust shaft could be threatened by an etch pit.

It is easily appreciated, that the etch pit is merely the witness to the presence of a bifilm crack. Furthermore, the bifilm could have been extensive, such as possibly extending over a major portion of the shaft. The shaft was formed, of course, from VAR steel, so that the probability of its being pre-cracked is virtually certain. The crack

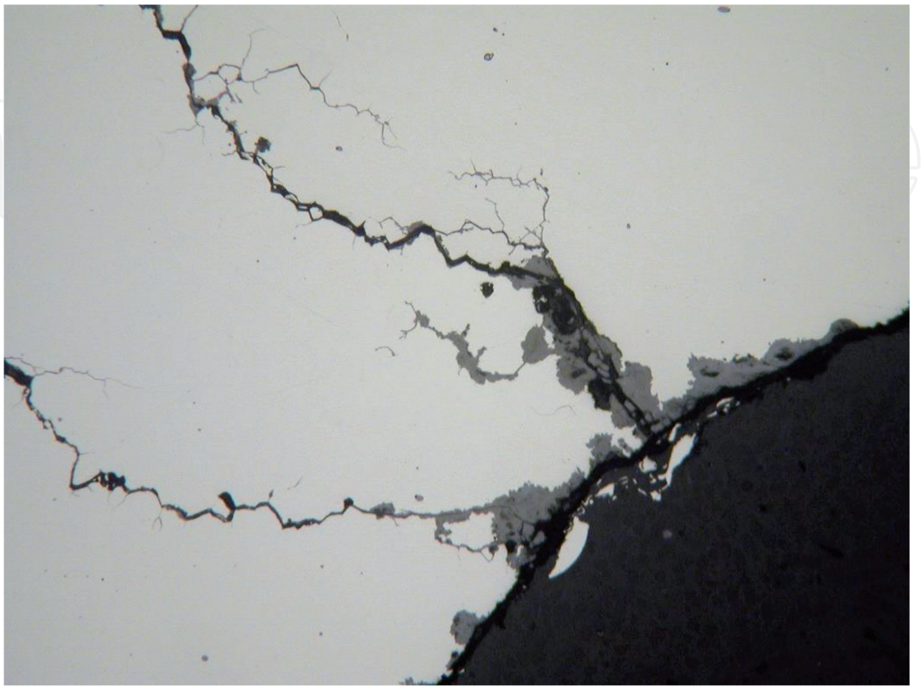

Figure 8.
Etch pit in a steel turbine blade. Courtesy Metallurgical Associates Inc.

would have evaded detection because, being formed by oxidation in vacuum, its oxide films would have been extremely thin. Also, as a universal feature of castings, and heat-treated products, especially if quenched, the interior is in tension, but the exterior surfaces are in compression. The crack on the outside of the shaft would therefore have been tightly closed.

Attempts to find bifilms by nondestructive testing (NDT) has proven to be tragically unreliable. As always in such difficulties, the clear way forward is to use only those processes which do not generate bifilms and which are therefore intrinsically reliable.

12.5 Stress corrosion cracking (SCC)

This dangerous failure mode involves almost no loss of metal by corrosion but can generate deep cracks by a time-dependent advance, often under only low stress. A metal can be sensitized to SCC by heat treatments.

There seems to be good evidence that SCC is a bifilm phenomenon, whereby the corrodent is simply moving through the 'air gaps' of the bifilms, linking bifilms by corrosion, driven by the stress concentration at the bifilm linkages [2].

The action of certain heat treatments to enhance SCC susceptibility is here proposed to arise from the precipitation of second phases on the bifilm. The favored formation of precipitates on bifilms seems to be the result of the reduction in the strain energy of formation, because the volume change and shape change of the new arrival can be more easily accommodated by the 'air gap' of the bifilm. The movement of part of the new phase into the air gap is likely to assist the forcing open of the air gap, so that percolation of the corrodent is facilitated [2].

12.6 Hydrogen embrittlement (HE)

There are numerous theories which have attempted to explain HE, but the phenomenon cannot yet be claimed to be clearly understood. In practice, the ingress of hydrogen into a stressed steel can result in gradual loss of ductility, and final fracture. The process has been identified as the slow progress of a crack until the final fracture when there is insufficient area to support the load. Hydrogen enters the steel as a proton released from certain corrosion mechanisms. For research purposes, hydrogen is introduced by electrochemical processes. Significantly, researchers complain about the interference of blistering which upsets their experiments during the charging processes, and report they are at a loss to know how the blisters can nucleate [2].

Once again, the bifilm seems more than adequate to explain all these observed characteristics of HE. The blisters are the observation of bifilms, inflated by hydrogen, near to the surface of the metal. Clearly, bifilms in the interior of the metal will also be experiencing the pressurization of hydrogen gas. Bifilms will almost certainly aid the progress of the gas into the interior of the metal, greatly accelerating the apparent rate of diffusion. However, it is probably mainly those isolated bifilms whose internal pressurization is leading to internal stress build up which is countering the ability of the metal to withstand tension.

There has been much interest in the attempts to desensitize a metal to HE by providing sinks for hydrogen. The sinks have been generally thought to be dislocations, and stress fields around carbide precipitates. This author has proposed that bifilms are probably significantly more capacious sinks, and the action of carbides is to precipitate onto bifilms and to prize them open, enabling them to accommodate even more hydrogen. He suggests that in an increasing supply of hydrogen, the bifilm would act as a temporary reduction in the deleterious effect of hydrogen, but this benefit would only exist at low hydrogen levels. When the hydrogen pressure in the bifilms equalled and the exceeded the yield stress, the damaging effects of HE would resume unchanged [2].

13. Conclusions

1. The entrainment of the oxide film on the liquid metal during casting processes leads to widespread damage to metals. Pre-cracking by a poor casting technique is central to the loss of properties, and to numerous failure modes, including those during solidification, during cooling to room temperature, during metal processing, and during service conditions.

2. Casting processes involving top pouring are especially damaging.

3. Casting processes using gravity pouring can be designed to yield significant benefits in bifilm reduction and are recommended if counter-gravity cannot be provided [3].

4. Ultimately, counter-gravity casting is strongly recommended to be the new casting norm, capable of delivering defect-free cast products.

5. The current use of VAR steels in all critical applications (especially such applications as helicopter drive chains) appears to be dangerously unreliable.

6. The reliable secondary remelting process could be ESR if combined with a reliable electrode. The implementation of this process combination would be greatly valued by the engineering world.

7. Both primary and secondary casting processes can now be made to deliver economic metals which cannot fail; metals we can trust.

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