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The Significance of Bi-Films

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The Complete Castings Handbook*,2nd Edition, 2011, Elsevier
Castings, 1st Edition, 1991, Butterworth-Heinemann (An Imprint of Elsevier)
The New Metallurgy of Cast Metals: Castings 2nd Edition, 2003; Elsevier

*Although the whole of this work is given over to the concept of bi-films, so that, much experimental evidence is presented as a matter of course, this short section lists compelling logic of the concept and the inescapable and important consequences.

Since the folded oxides and other films constitute cracks in the liquid, and are known to be of all sizes and shapes, they can become by far the largest defects in the final casting and can be dauntingly numerous. They can be easily envisaged as reaching from wall to wall of casting, causing a leakage defect in a component required to be leak-tight, or causing a major structural weakness in a product requiring strength or fatigue resistance.

In addition to constituting defects in their own right, if they are given the right conditions during the cooling of the casting, the loosely encapsulated gas film can act as an excellent initiation site for the subsequent growth of gas bubbles, shrinkage cavities, hot tears, cold cracks etc. The nucleation and growth of such consequential damage will be considered in later sections. The important message to take on board at this stage is that without the presence of bi-films, such defects would probably be impossible. Liquid metals are free from bi-films could make castings free from defects. This is a message never to be forgotten.

Entrainment creates bi-films that may never come together properly and hence constitute air bubbles immediately; alternatively, they may be opened (to become thin cracks, or opened so far as to become bubbles) by a number of mechanisms:

1. Precipitation of gas from solution creating gas porosity;
2. Hydrostatic strain, creating shrinkage porosity;
3. Uniaxial (tensile) strain, creating hot tears or cold cracks;
4. In-service strain, causing failure by fracture in service.

Thus bi-films can be seen to simplify and rationalize the main features of the problems of castings. For those who wish to see the logic laid out formally this is done in Figure 1a for metals (1) without films, such as liquid gold, (2) with films that are liquid, (3) with films that are partially solid, and (4) with films that are fully solid.

Figure 1a Framework of logic linking surface conditions, flow and solidification conditions to final defects

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	Pouring		Quiescence		Casting Defect
	Entrainment event by surface turbulence Weber Number (W_e) > 1	Compacting mechanism by bulk turbulence Reynolds Number (R_e) > 1	Liquid at rest	Solidification (unfurling mechanisms)	
1	Film free →	Coalesced matrix liquid →	Rapid flotation of bubbles →		No defects (small possibility of minute retained bubbles)
2	Liquid film →	Coalesced droplets of surface liquid →	Rapid flotation of large droplets →		Few defects (Residual small droplets in castings). Locally thickened slag layer on cope
3	Partially molten film →	Furled bi-film partially welded closed →	Rapid flotation of compact bi-films →		Complex macro-inclusions on cope surface
4	Solid Film	Buoyant bubbles →	Rapid flotation →		Gas (air) bubbles (solid film gives detrainment problems) Bubble trails
		Furled bi-films →		Gas precipitation out of solution →	Gas porosity
				Hydrostatic strain →	Shrinkage porosity Hot tears
				Uniaxial strain →	Cold cracks
				Crystalline precipitate straightening →	Centerline cracks in precipitates Matrix 'decohesion' cracks
				Dendrite pushing →	Inter-dendritic cracks and hot tears Grain boundary cracks and hot tears

Figure # 1 b
The engineering metals listed according to the ratio elastic/bulk modulus and Poisson ration showing the range of ductile to brittle behaviour. From this figure, lead (Pb) might be expected to be the most malleable element, but is denied this place as a result of its bi-film content. Gold (Au) is the world's most malleable metal at this time.

Ductile → Brittle

	Liquid	Pb	Au	Nb	Pt	Pd	Hf	Ag	Al	Cu	Zr	Ti	Ni	Co	Fe	Mg	Mo	Nd	W	Re	Ir	Cr	Be
μ/B	0	0.12	0.15	0.22	0.22	0.23	0.27	0.29	0.35	0.35	0.39	0.42	0.43	0.45	0.48	0.49	0.48	0.50	0.52	0.54	0.56	0.72	1.42
v	0.50	0.44	0.42	0.40	0.39	0.39	0.37	0.37	0.34	0.34	0.33	0.32	0.31	0.30	0.29	0.29	0.29	0.28	0.28	0.26	0.26	0.21	0.02

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Note that the defects on the right of Figure 1a cannot, in general, be generated without starting from the bi-film defect on the left. The necessity for the bi-film initiator follows from the near impossibility of generating volume defects by other mechanism in liquid metals.

The classical approach using nucleation theory predicts that nucleation of any type (homogeneous or heterogeneous) is almost certainly impossible. Only surface-initiated defects (i.e. porosity or cracks growing in to the casting from locations on the casting surface) appear to be possible without the action of bi-films. In contrast to the difficulty of homogeneous or heterogeneous nucleation defects, the initiation of defects by the simple mechanical action of the opening of bi-films requires nearly zero driving force; it is easy to say that in all practical situations it ***is*** the only initiating mechanism to be expected.

We are therefore, forced to the fascinating and enormously significant conclusion that in the absence of bi-films castings cannot generate defects that reduce strength and ductility. In other words, defects that lead to mechanical impairment are not produced by solidification, but only by casting. To restate once again for emphasis, in general, there is no such things as a solidification defect. There are only casting defects.

As noted previously, this hugely important fact has to be tempered only very slightly because porosity, and possibly cracks, can also be generated easily by surface initiation if a moderate pressurization of the interior of the casting is not provided by adequate feeders. However, of course, adequate feeding of the casting is widely understood and applied in foundries, and we can therefore assume its application here.

The wide application of good feeding, especially since the advent of good computer simulations, means that shrinkage porosity is ***not*** to be expected in castings. In fact, nearly all porosity I see in castings or on radiographs is usually ***never*** shrinkage, despite its appearance. It is usually a mess of bi-films and their selected tangled layers of air resulting from a poor filling system or technique. It is extremely important therefore for the reader to never to utter the phrase 'It is shrinkage'. The reader is urged to learn by heart and repeat often the phrase 'It ***appears*** to be shrinkage' but then add the rider' but probably is not!'

Alloy Type	Possible bi-film defects type in different alloy systems
Al-Si Alloys	Centerline and matrix cohesion cracks in plate-like inter-metallics (Si particles, Fe-rich precipitates, etc.) Planar hot tears with dendrite raft morphology of fracture surface
Flake Cast Iron	Nitrogen fissures
Ductile Irons	Plate fracture (spiking) defect
Steels	Rock-candy fractures on Aluminium Nitride (AlN) at grain boundaries
Nickle base super alloys (vacuum cast)	Intergranular facets on fracture surface Initiation of stray grains and high-angle grain boundaries in single crystal castings
Note	The causes of defects in cases of higher temperature alloys, irons, steels and Ni-based alloys are based only on circumstantial (although strong) evidence at the time of writing.

The author has pleasant memories of the early days (c. 1980) of the development of the Cosworth Process, when the melt in the holding furnace has the benefit of days to settle, becoming clear from bi-films because production at that time did not occupy more than a few production shifts per week. The melt was therefore unusually free from bi-films, and the castings were found to be completely free from porosity. As the production rate increased during the early years the settling time was progressively reduced to only a few hours, causing a disappointing reappearance of micro-porosity, and a corresponding reduction in mechanical properties. This link between melt cleanliness and freedom from porosity is well known. One of the demonstrations of this fact was the simple and classic experiment by Brondyke and Hess (1964) that showed that filtered metal exhibited reduced porosity.

An important point to note is that a subsequently generated defect which may be large in extent, may be simply initiated by and grow from a small bi-film. On the other hand, the bi-film itself may be large, so that any consequential defect such as a pore or a hot tear actually is the bi-film, but simply opened up. In the latter case, no growth areas of the subsequent defect are involved, only separation of the two halves of the bi-film. Both situations seem possible in castings.

Standing back for a moment to view the larger scene of the commercial supply of castings, it is particular sobering that there is a proliferation of standards and procedures throughout the world to control observable defects such as porosity and shrinkage porosity in castings. Although once widely known as quality control (QC) the practice is now more accurately named quality assurance (QA). However, as we have seen, the observable porosity and shrinkage defects are often negligible compared to the likely presence of bi-films, that are difficult, if not impossible, to detect with any degree of reliability. They are likely to be numerous, more extensive in size, and have more serious consequences and repercussions.

The significance of bi-films is clear, and worth repeating. They are often not detectable by normal non-destructive testing techniques, but can be more important than observable defects. They are often so numerous and / or so large that they can control the properties of the castings, sometimes outweighing the effects of alloying and heat treatment.

The conclusion is inescapable: it is more important to specify and control the casting process to ***avoid*** the formation of bi-films than to employ apparently rigorous quality assurance procedures, searching retrospectively (and possibly without success) for any defects they may or may not have caused.

Casting free from bi-films probably do not exist at this time. However, in principle, technologies exist that would enable the production of products with significantly stronger, totally reliable, and ultimately lower in cost than those made by our present production techniques. The first steps are being demonstrated for a number of alloy systems as I write.

Furthermore, there are good reasons for believing that Griffith's cracks, universally blamed for the start of failures of all our engineering metals, may cease to exist if bi-films can be eliminated because it seems atomic-sized voids and cracks are not easily formed in metals because of the extremely high inter-atomic forces. There are valid reasons for believing that every Griffith's crack originates from a bi-film, as I have argued in detail elsewhere (Campbell, 2011). No other volume defects seem available or possible. This conclusion would revolutionize the science of metallurgy and the attainments in engineering. It is indeed an awesome and fascinating thought, even now possibly within the grasp of currently available technology,

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to produce metals which are resistant to failure by cracking and fatigue, and resistant to failure by concentrated forms of corrosion such as pitting corrosion and stress corrosion cracking (scc). Our new generation of casting engineers will probably will have the pleasure and satisfaction to achieve this long-sought goal.

The Four Common Populations of Bi-films

Summarizing the efforts to obtain a clean melt, it is important to remember that there are commonly four sources of bi-films nearly always and in general require to be dealt with separately. The following considerations are targeted mainly at the melting of aluminium alloys, but will be seen to apply to other metal alloys.

1. The most serious crop of bi-films are what I call the primary oxide skins. They arise during melting because the charge materials are gradually submerged beneath the rising metal. The liquid rolls up the sides of the chunks of charge, rolling up against the thick oxide already in place on the surface of the charge to form he bi-films of the exact size and shape of the individual pieces of the charge. These massive bi-films can be the size of newspapers, floating about in the melt like plastic bags, with compositions of their oxides denoting their age. The dry hearth furnace is invaluable in this respect since the 'primary oxide skins' are automatically separated from the melt by remaining on the dry hearth of the furnace, from where they can be scraped off at intervals. When melting in crucible furnaces these massive defects must be removed by other techniques such as, perhaps rotary degassing; it is expected that the removal of primary oxide skins is probably the most valuable action of the rotary degassing treatment of liquid Al alloys. If not removed before attempting to pour a casting, and if a filter is in place in the filling system, it can be imagined that these huge and strong skins will block filters with great efficiency.

2. An unpredictable population of oxide bi-films in metals is that which is naturally inherited from previous melting and casting operations which the metal has experienced. This population is often dense, but the oxides are often unpredictable in size, in the range of centimeters down to micrometers, and probably characterized by a chemistry typical or 'older oxide such as spinel's.

3. The third source of oxide bi-films are those manufactured by turbulent processes during metal transfers such as the filling of the ladle and the filling of the mould. Those made in the channels of the filling systems are likely to be limited size as a result of the powerful churning action of the high velocity metal in these regions, probably shredding and tearing oxides many of which will be partially attached to the walls of the channels. These bi-films will be thing and 'young'.

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4. Those bi-films made in the mould cavity itself, where the melt is starting to reduce in velocity, will not suffer such forces, and so will retain their large size, measured in centimeters, but not large in thickness as a result of their rapid submergence in the turbulence and splashing. These bi-films will also retain their pure chemistries associated with their 'youth'.

It is common to overlook the presence of the primary skins. Such oversights were unknowingly routine in the Al casting industry for many years, explaining the horrendous failures which were occasionally reported. The finer population of inherited oxide bi-films requires to be dealt with by sedimentation (possibly aided by heavy element addition), or so far as possible, by filtration. The use of filters can only address bi-films, usually in their compact form, of size larger than the filter pore size (10, 20, 30 ppi), and even this can only take place at low velocities (filters in filling systems for castings are of practically no use for filtration because of the overwhelming high metal velocity). Also, of course, the bi-film is likely to unfurl from its compact form after passing through the filter, so as to maximize its area as a crack in the casting.

Having cleaned the melt from population one (1) and two (2) so far as possible, only counter-gravity casting is usually completely reliable to avoid re-introducing bi-films as in two (2) and four (4). However, gravity pouring can be improved significantly, especially if air is excluded by contact pouring, and if the geometry of the filling system corresponds to a good naturally pressurized design, delivering metal into the mould at or near 0.5 m/s, deemed be critical velocity.