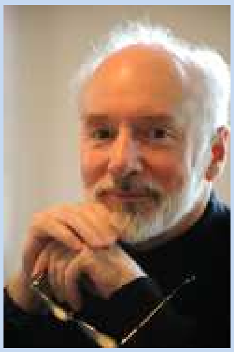
Steel, Stainless Steel, High & Super Alloy-
Heat, Wear, Abrasion, Pressure & Corrosion Resistant
Castings, Spares, Replacement Parts, Custom-Made Components
Manufacturer-Supplier to OEM's, Plants, & Process Industry
Machined, Proof-Machined, CNC/VMC Precision Machined Components
Conversion to Castings from Fabrications, Forgings & Welded Assemblies
Engineering, Materials & Metallurgical Consulting

WH-76, Mayapuri Industrial Area
Phase-I, New Delhi 110 064, India

T: +91-(0)11-2811-5021
F: +91-(0)11-2811-5021
E: acmecast@acmealloys.com
W: www.acmealloys.com



Professor Dr. John Campbell on The Consolidation of Metals: The Origin of Bi-Films

Novel insights into the mechanism of metallurgical failure-a paradigm shift in understanding metal failure analysis

Dr. John Campbell
OBE, Professor Emeritus of Casting Technology, University of Birmingham, England, UK

OBE (born 1938) is a British engineer and one of the world's leading experts in the casting industry with approximately 150 papers, and 20 patents. Campbell holds two Masters degrees from University of Cambridge and University of Sheffield, as well as two doctorates from University of Birmingham. He is a fellow of the Royal Academy of Engineering, and he was appointed to the chair of casting technology at University of Birmingham. The Institute of Cast Metals Engineers has named the "John Campbell Medal" after him.

John Campbell is a leading international figure in the castings industry, with over four decades of experience. He is the originator of the Cosworth Casting Process, the pre-eminent production process for automobile cylinder heads and blocks. He is also co-inventor of both the Baxi Casting Process (now owned by Alcoa) developed in the UK, and the newly emerging Alotech Casting Process in the USA.

Dr John Campbell's new book released in June 2020 amidst COVID19 outbreak, a global pandemic after 100 years of occurrence of Spanish Flu, that has immensely affected globally peoples- living, life and work behaviors; likewise the book's new insights ushers in a paradigm shift in our present thinking about metallurgical failure analysis of metals and alloys. Attributing reasons of metallurgical failure based on bi-film theory reveals new approach much needed from past understandings of metal failure, origin of cracks, poor mechanical properties in wrought and cast alloy products, microstructure disparities and consequences thereof, weld cracking in heat affected zones (HAZ) and corrosion issues from hydrogen embrittlement to stress corrosion cracking that had been vexing engineers, metallurgist, manufacturers and end users for a long time.

This document consists of a brief abstract at the outset and discusses main propositions explained in detailed in the full technical paper. It touches on consolidation of metals, suggests mechanism of metallurgical failure(s), origin of crack(s) and crack population that take our thinking forward that we have been oblivious in the past. Time has come when we must embrace our new found understanding and make knowledge work by putting into practice remedies, suggestions and metallurgical & engineering solutions in manufacturing bi-film free - metals, alloys, ingots, castings, forgings and weld fabrications that deliver high performance in end applications.

Abstract

During their processing from ores, all metals go through a particular stage. These separate pieces have to be consolidated usually with heat and pressure to form useful engineering forms. In the case of metals which undergo a melting stage, the pouring and stirring actions which are commonly employed disintegrate the liquid into splashes and droplets which appear to mutually assimilate, creating a consolidated bulk liquid. However, in every case, whether the consolidation mechanism takes place in the solid or liquid states, the consolidation mechanism naturally includes an oxide-to-oxide interface (although occasionally other surface films such as nitrides and pure carbon are involved). The concept of the meeting of oxides is of course assumed to be trivial and therefore universally overlooked. However, the consequences seem to be far from trivial. The creation of opposed double (never single),

WH-76, Mayapuri Industrial Area
Phase-I, New Delhi 110 064, India

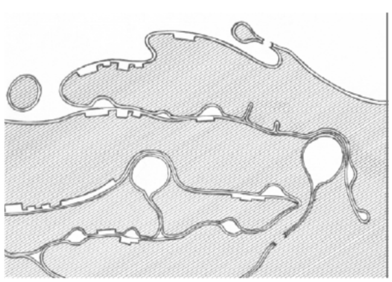
T: +91-(0)11-2811-5021
F: +91-(0)11-2811-5021
E: acmecast@acmealloys.com
W: www.acmealloys.com

unbonded oxide films, called '**bi-films**' by the author, acts as cracks. They can survive extensive plastic working and seem to be prolific throughout metallurgy.

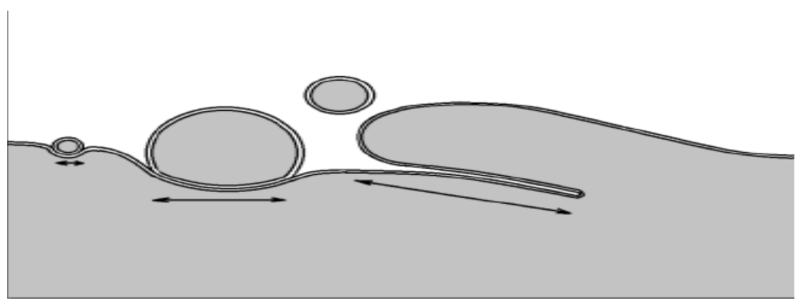
They appear to exert significant control over the failure properties of metals, by both cracking and corrosion. They are proposed to constitute the Griffith cracks required for the failure of metals by fracture and fatigue. Bi-films may now be eliminated from some our liquid processing routes, enabling for the first time the production of crack-resistant and corrosion-resistant metals and alloys.

Introduction

Turbulence during pouring of liquid metal folding over the surface oxide to create bubbles (pores) and bi-film cracks



Different sizes of bi-films being created in a splash of metal, from a surface fold, and from impingement of droplets



There are more than one steps in the production of metals in which the metal is consolidated from smaller fragments to make larger pieces for engineering purposes. In almost every case, the fragments have an oxide

skin on their outer surface, so that on consolidation, the oxides 'get in the way', obstructing the creation of a welding type of contact; in fact, oxide impinges on oxide to create an unbonded interface between these two ceramic layers. This phenomenon happens even when consolidation takes place in vacuum since most industrial vacuums are not sufficiently good enough to prevent oxidation. The hardness and great chemical stability of this interfacial feature ensure its longevity; it becomes part of the metal, and can remain an

unbonded, crack-like feature for the life of the metal. I have termed this double film feature a bi-film. The purpose of this paper is to draw attention to this phenomenon which appears to be have been overlooked for the past 6000 years. It is proposed that the presence of a population of bi-films is a general microstructural feature of metals, explaining much observed behavior.

Early investigations into the strength of metals have assumed clean metals and continuum concepts such as in (i) the use of surface tension of any embryonic bubble and (ii) the derivation of the Van der Waals equation. These studies have demonstrated huge strengths of the liquid or solid (the atoms are quite similarly spaced so it is not surprising that the theoretical tensile strengths of the solid and liquid phases are quite similar). More recently, these studies have been reassuringly confirmed by molecular dynamics (MD), in which aggregates of several thousand atoms are simulated by computer, resulting in fascinating insights into the theoretical properties of metals. In general, of course, the theoretical predictions are far higher, sometimes by an order of magnitude or more, than are observed for real metals. As will be discussed in this paper, these fundamental considerations predict that pores and cracks cannot form in metals at normal stresses involved in the manufacture and processing of metals: the inter-atomic bonds are far too strong to allow this.

Since all the studies confirm that atoms are extremely difficult to separate, inter-atomic forces being simply too strong, we can conclude that grain boundaries should also be strong. Traditionally, they have often assumed to be weak as a result of their de-coherence, often seen to provide the path for the propagation of crack. However, MD simulations have confirmed that grain boundaries have enormous strength. Boundaries with a twin orientation have 100% of the strength of the matrix because their atomic positions are identical to that of the matrix. However, even high angle boundaries appear to have approximately 80% of the strength of the matrix, reflecting the approximately 80% density of atoms at the boundary compared to the bulk. However, of course, grain boundaries are commonly observed to de-cohere at relatively modest stresses. Clearly, therefore, these exists a major disparity between theory and practice.

In a related critical study of solidification, it is clear that solidification has no mechanism for the creation of pores or cracks; it merely a phase change involving a minute re-arrangement of atoms; the atoms are held closely by powerful interatomic forces and would never normally separate to form any kind of void. However, as is commonly known, solidified metals are notoriously crammed with defects such as pores and cracks. A so-called ductile fracture surface commonly displays a dense array of microscopic ductile dimples, each dimple representing the site of failure of an apparently brittle inclusion, despite that prediction (regrettably significant counter-intuitive) that solidification will be incapable of producing inclusions which can act brittle because of pores or cracks cannot be generated in inclusions which have been formed, atom by atom, from the liquid state.

The great divide between theory and practice in current metallurgy is reminiscent of the early days of materials science when invisible agents, first atoms, then dislocations, had to be discovered and proven, amid vide denial of such features, before an understanding of metals and alloys became possible. The invisible agent which is now suggested to be practically universally present in metals is ***the bi-film***. Its presence will be seen to explain many aspects of failure behavior by fracture and corrosion.

In the same way that dislocations were essential to the understanding of plasticity, bi-films are proposed to be essential for the understanding of failure mechanism of metals including fracture and corrosion. The upheaval in our metallurgical thinking which follows from a realization of the presence of bi-films is indicated in Table # 1.

We have much re-thinking and re-learning to do. This paper is an attempt to illustrate the new scenario.

Source: The Journal of Material Science (2016) 51:96-106; Springer
DOI 10.1007/s10853-015-9399-9
50th Anniversary

The consolidation of metals: the origin of bi-films

Dr. John Campbell
jc@campbelltech.co.uk

WH-76, Mayapuri Industrial Area
Phase-I, New Delhi 110 064, India

T: +91-(0)11-2811-5021
F: +91-(0)11-2811-5021
E: acmecast@acmealloys.com
W: www.acmealloys.com

Table # 1

Examples of traditional metallurgical concepts which require to be corrected in the light of the new concept of the consolidation of metals and other recent findings such as those from molecular dynamics

Traditional metallurgical wisdom	New proposals
'The microstructure controls the properties'	At worst not true, and at best a half truth. More probably 'defects (actually bi-films) control both the microstructure and properties'
'Weak grain boundaries'	Grain boundaries are immensely strong, as confirmed by recent molecular dynamics (MD) simulations, unless, of course, they contain a bi-film
The brittle particle existing in the matrix acted as a stress raiser, which when stressed, led to the nucleation of a crack	Grain boundary precipitates such as carbides, nitrides, borides, etc. are immensely strong and fracture resistant. The appearance of brittleness results from a partly opened bi-films on which the precipitates formed. Many observations of the plastic deformation of carbides and borides have been reported
Facets on fracture surfaces (particularly fatigue failures) are formed by the crack propagating along a slip band	A high proportion of facets appear to be formed from bi-films which have been nucleated and grown on the crack in the liquid state. No stress was involved (although the rack may extend later if the solid is stressed)
The cleavage fractures visible on a fracture surface, highlighting the grain structure of the metal, are a characteristic form of brittle fracture	A significant proportion of so-called cleavage fractures appear to have formed from bi-films which have segregated into grain boundaries. The smooth surface is the result of the bi-film taking up the smooth form of the grain boundary
Cracks initiate from pores, leading to failure of cast products	Pores and 'cracks' (bi-films) are both entrainment defects containing entrapped gas, oxidized surfaces and thus unbonded. It is therefore, almost certain that pores and bi-films will be present together, often contiguous, so that the real contributor to the initiation of cracking is the unseen presence of a bi-film, which might be of significantly larger area than the pore
Stress corrosion cracks initiate from the bottoms of corrosion pits	Corrosion pits form on the site at which a bi-film intersects the surface of the metal. The bi-film provides ingress for the corrodant, and second phases formed on the bi-film provide corrosion couples to accelerate local attack. The crack is therefore the bi-film, often extending to cover a large area away from the base of the pit. It should always be expected to be present
The development of texture during plastic deformation is a crystallographically driven phenomenon	The presence of a population of bi-films will be expected to dominate grain boundary movement since re-crystallizing and migrating boundaries will be unable to cross bi-films, which in general will tend to align with the deformation direction