John Campbell

Complete Casting Handbook

Metal Casting Processes, Metallurgy, Techniques and Design

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Preface

Metal castings are fundamental building blocks, the three-dimensional integral shapes indispensable to practically all other manufacturing industries.

Although the manufacturing path from the liquid to the finished shape is the most direct, this directness involves the greatest difficulty. This is because so much needs to be controlled simultaneously, including melting, alloying, molding, pouring, solidification, finishing, etc. Every one of these production steps has to be correct since failure of only one will probably cause the whole product to be unacceptable to the customer. In contrast, other processes such as forging or machining are merely single-step processes. It is clearly easier to control each separate process step in turn.

It is no wonder therefore that the manufacture of castings is one of the most challenging of technologies. It has defied proper understanding and control for an impressive five thousand years. However, there are signs that we might now be starting to make progress.

Naturally, this claim for the possible existence of progress appears to have been made by every writer of textbooks on castings for the last several hundred years. Doubtless, it will continue to be made in future generations. In a way, it is hoped that it will always be true. This is what makes casting so fascinating. The complexity of the subject invites a continuous stream of new ideas and new solutions.

The author trained as a physicist and physical metallurgist, and is aware of the admirable and powerful developments in science and technology that have facilitated the progress enjoyed by these branches of science. These successes have, quite naturally, persuaded the Higher Educational Institutes throughout the world to the adoption of *physical metallurgy* as the natural materials discipline required to be taught.

This work makes the case for *process metallurgy* as being a key discipline, inseparable from physical metallurgy. It can explain the properties of metals, in some respects outweighing the effects of alloying, working and heat treatment that are the established province of physical metallurgy. In particular, the study of casting technology is a topic of daunting complexity, far more encompassing than the separate studies, for instance, of fluid flow or solidification (as necessary, important and fascinating as such focused studies clearly are). It is hoped therefore that, in time, casting technology will be rightly recognized as a complex and vital engineering discipline, worthy of individual focus.

Prior to writing this book, the author has always admired those who have published only what was certain knowledge. However, as this work was well under way, it became clear to him that this was not achievable in this case. Knowledge is hard to achieve, and often illusive, fragmentary, and ultimately uncertain. This book is offered as an exercise in education, more to do with thinking and understanding than learning. It is an exercise in grappling with new concepts and making personal evaluations of their worth, their cogency, and their place amid the scattering of facts, some reliable, others less so. It is about research, and about the excitement of finding out for oneself.

Thus the opportunity has been taken in this new book to bring the work up to date, particularly in the new and exciting areas of surface turbulence, the recently discovered compaction and unfurling of folded film defects (the bifilms). Additional new concepts of alloy theory relating to the common alloy eutectics Al–Si and Fe–C will be outlined. These are particularly exciting. Perhaps these new paradigms can never be claimed to be 'true'. They are offered as potentially valuable theories allowing us to codify and classify our knowledge until something better comes along. Newton's theory of

gravitation was a welcome and extraordinarily valuable systematization of our knowledge for several hundred years until surpassed by Einstein's General Relativity.

Thus the author has allowed himself the luxury of hypothesis, that a skeptic might brand speculation. This book is a first attempt to codify and present what I like to call the 'New Metallurgy'. It cannot claim to be authoritative on all aspects at this time. It is an introduction to the new thinking of the metallurgy of cast alloys, and, by virtue of the survival of many of the casting defects during plastic working, wrought alloys too.

The intellectual problem that some have in accepting the existence of bifilms is curious. The problem of acceptance does not seem to exist in processes such as powder metallurgy, and the various spray-forming technologies, where everyone immediately realizes 'bifilms' exist if they give the matter a moment's thought. The difference between these particle technologies and castings is that the particulate routes have rather regular bifilm populations, leading to reproducible properties. Similar rather uniform but larger-scale bifilms can be seen in slowly collapsing metallic foams, in which it is extraordinary to watch the formation of bifilms in slow motion as one oxide film settles gently down on its neighbor (Mukherjee 2010). Castings in contrast can have coexisting populations of defects sometimes taking the form of fogs of fine particles, scatterings of confetti and postage stamps, and sometimes sheets of A4 and quarto paper sized defects.

The new concept of the bifilm involves a small collection of additional terms and definitions which are particularly helpful in designing filling and feeding systems for castings and understanding casting failure mechanisms. They include critical velocity, critical fall distance, entrainment, surface turbulence, the bubble trail, hydrostatic tensions in liquids, constrained flow, and the naturally pressurized filling system. They represent the software of the new technology, while its study is facilitated by the new hardware of X-ray video radiography and computer simulation. These are all powerful investigative tools that have made our recent studies so exciting and rewarding.

Despite all the evidence, at the time of writing there appear to be many in industry and research still denying the existence of bifilms. It brings to mind the situation in the early 1900s when, once again despite overwhelming evidence, many continued to deny the existence of atoms.

The practice of seeking corroboration of scientific concepts from industrial experience, used often in this book, is a departure that will be viewed with concern by those academics who are accustomed to the apparent rigor of laboratory experiments and who are not familiar with the current achievements of industry. However, for those who persevere and grow to understand this work it will become clear that laboratory experiments cannot at this time achieve the control over liquid metal quality that can now be routinely provided in many industrial operations. Thus the evidence from industry is vital at this time. Suitable confirmatory experiments in laboratories can catch up later.

The primary aim remains, to challenge the reader to think through the concepts that will lead to a better understanding of the casting process – the most complex of forming operations. It is hoped thereby to improve the professionalism and status of casting technology, and with it the castings themselves, so that both the industry and its customers will benefit.

As I mentioned in the preface to *CASTINGS 1991*, and bears repeat here, the rapidity of casting developments makes it a privilege to live in such exciting times. For this reason, however, it will not be possible to keep this work up to date. It is hoped that, as before, this new edition will serve its purpose

for a time; assisting foundry people to overcome their everyday problems and metallurgists to understand their alloys. Furthermore, I hope it will inspire students and casting engineers alike to continue to keep themselves updated. The regular reading of new developments in the casting journals, and attendance at technical meetings of local societies, will encourage the professionalism to achieve even higher standards of castings in the future.

JC
Ledbury, Herefordshire, England
23 November 2010

Introduction from *Castings* 1st Edition 1991

Castings can be difficult to get right. Creating things never is easy. But sense the excitement of this new arrival:

The first moments of creation of the new casting are an explosion of interacting events; the release of quantities of thermal and chemical energy trigger a sequence of cataclysms.

The liquid metal attacks and is attacked by its environment, exchanging alloys, impurities, and gas. The surging and tumbling flow of the melt through the running system can introduce clouds of bubbles and Sargasso seas of oxide film. The mould shocks with the vicious blast of heat, buckling and distending, fizzing with the volcanic release of vapours that flood through the liquid metal by diffusion, or reach pressures to burst the liquid surface as bubbles.

During freezing, liquid surges through the dendrite forest to feed the volume contraction on solidification, washing off branches, cutting flow paths, and polluting regions with excess solute, forming segregates. In those regions cut off from the flow, continuing contraction causes the pressure in the residual liquid to fall, possibly becoming negative (as a tensile stress in the liquid) and sucking in the solid surface of the casting. This will continue until the casting is solid, or unless the increasing stress is suddenly dispelled by an explosive expansion of a gas or vapour cavity giving birth to a shrinkage cavity.

The surface sinks are halted, but the internal defects now start.

The subsequent cooling to room temperature is no less dramatic. The solidified casting strives to contract whilst being resisted by the mould. The mould suffers, and may crush and crack. The casting also suffers, being stretched as on a rack. Silent, creeping strain and stress change and distort the casting, and may intensify to the point of catastrophic failure, tearing it apart, or causing insidious thin cracks. Most treacherous of all, the strain may *not quite* crack the casting, leaving it apparently perfect, but loaded to the brink of failure by internal residual stress.

These events are rapidly changing dynamic interactions. It is this rapidity, this dynamism, that characterises the first seconds and minutes of the casting's life. An understanding of them is crucial to success.

This new work is an attempt to provide a framework of guidelines together with the background knowledge to ensure understanding; to avoid the all too frequent disasters; to cultivate the targeting of success; to encourage a professional approach to the design and manufacture of castings.

The reader who learns to guide the production methods through this minefield will find the rare reward of a truly creative profession. The student who has designed the casting method, and who is present when the mould is opened for the first time will experience the excitement and anxiety, and find himself asking the question asked by all foundry workers on such occasions: 'Is it all there?' The casting design rules in this text are intended to provide, so far as present knowledge will allow, enough predictive capability to know that the casting will be not only all there, but all right!

The clean lines of the finished engineering casting, sound, accurate, and strong, are a pleasure to behold. The knowledge that the casting contains neither defects nor residual stress is an additional powerful reassurance. It represents a miraculous transformation from the original two-dimensional form on paper or the screen to a three-dimensional shape, from a mobile liquid to a permanently shaped, strong solid. It is an achievement worthy of pride.

The reader will need some background knowledge. The book is intended for final year students in metallurgy or engineering, for those researching in castings, and for casting engineers and all associated with foundries that have to make a living creating castings.

Good luck!

Introduction to *Castings* 2nd Edition 2003

I hope the reader will find inspiration from this work.

What is presented is a new approach to the metallurgy of castings. Not everything in the book can claim to be proven at this stage. The author has to admit that he felt compelled to indulge in what the hard line scientist would dismissively label 'reckless speculation'. Ultimately however, science works by proposing hypotheses, which, if they prove to be useful, can have long and respectable lives, irrespective whether they are 'true' or not. Newton's theory of gravitation was such a hypothesis. It was, and remains, respectable and useful, even though eventually proven inaccurate. The hypotheses relating to the metallurgy of cast metals, proposed in this work, are similarly tendered as being at least useful. Perhaps we may never be able to say for certain that they are really 'true', but in the meantime it is proposed as a piece of knowledge as reliable as can now be assembled (Ziman 2001). Moreover, it is believed that a coherent framework for an understanding of cast metals has been achieved for the first time.

The fundamental starting point is the bifilm, the folded-in surface film. It is often invisible, having escaped detection for millennia. Because the presence of bifilms has been unknown, the initiation events for our commonly seen defects such as porosity, cracks and tears have been consistently overlooked.

It is not to be expected that all readers will be comfortable with the familiar, cosy concepts of 'gas' porosity and 'shrinkage' porosity relegated to being mere consequences, simply macroscopic and observable outcomes, growth forms derived from the new bifilm defect, and at times relatively unimportant compared to the pre-existing bifilm itself. Many of us will have to re-learn our metallurgy of cast metals. Nevertheless, I hope that the reader will overcome any doubts and prejudice, and persevere bravely. The book was not written for the faint-hearted.

As a final blow (the reader needs resilience!), the book nowhere claims that good castings are easily achieved. As was already mentioned in the Preface, the casting process is among the most complex of all engineering production systems. We currently need all the possible assistance to our understanding to solve the problems to achieve adequate products. In particular, it follows that the section on casting manufacture is mandatory reading for metallurgists and academics alike.

For the future, we can be inspired to strive for, and perhaps one day achieve defect-free cast products. At that moment of history, when the bifilm is banished, we shall have automatically achieved that elusive goal, targeted by every foundry I know, '*highest quality together with minimum costs*'.

Introduction to *Casting Practice: The 10 Rules of Castings* 2004

The second book is effectively my own checklist to ensure that no key aspect of the design of the manufacturing route for the casting is forgotten. The Ten Rules are first listed in summary form. They are then addressed in more detail in the following ten chapters with one chapter per Rule.

The Ten Rules listed here are proposed as necessary, but not, of course, sufficient, for the manufacture of reliable castings. It is proposed that they are used in addition to existing necessary technical specifications such as alloy type, strength, and traceability via international standard quality systems, and other well known and well understood foundry controls such as casting temperature etc.

Although not yet tested on all cast materials, there are fundamental reasons for believing that the Rules have general validity. They have been applied to many different alloy systems including aluminium, zinc, magnesium, cast irons, steels, air- and vacuum-cast nickel and cobalt, and even those based on the highly reactive metals titanium and zirconium. Nevertheless, of course, although all materials will probably benefit from the application of the Rules, some will benefit almost out of recognition, whereas others will be less affected.

The Rules originated when emerging from a foundry on a memorable sunny day together with indefatigable Boeing enthusiasts for castings, Fred Feiertag and Dale McLellan. The author was lamenting that the casting industry had specifications for alloys, casting properties, and casting quality checking systems, but what did not exist but was most needed was a *process specification*. Dale threw out a challenge: 'Write one' The Rules and this book are the outcome. It was not perhaps the outcome that either Dale or I originally imagined. A Process Specification has proved elusive, proving so difficult that I have concluded that it will need a more accomplished author.

The Rules as they stand therefore constitute a first draft of a Process Specification; more like a checklist of casting guidelines. A buyer of castings would demand that the list were fulfilled if he wished to be assured that he was buying the best possible casting quality. If he were to specify the adherence to these Rules by the casting producer, he would ensure that the quality and reliability of the castings was higher than could be achieved by any amount of expensive checking of the quality of the finished product.

Conversely, of course, the Rules are intended to assist the casting manufacturer. It will speed up the process of producing the casting right first time, and should contribute in a major way to the reduction of scrap when the casting goes into production. In this way the caster will be able to raise standards, without any significant increase in costs. Quality will be raised to the point at which casting a quality equal to that of forgings can be offered with confidence. Only in this way will castings be accepted by the engineering profession as reliable, engineered products, and assure the future prosperity of both the casting industry and its customers.

A further feature of the list of Rules that emerged as the book was being written was the dominance of the sections on the design of the filling systems of castings. It posed the obvious question 'why not devote the book completely to filling systems?' I decided against this option on the grounds that both caster and customer require products that are good in *every* respect. The failure of any one aspect may endanger the casting. Therefore, despite the enormous disparity in length, no Rule could be eliminated; they were all needed.

Finally, it is worth making some general points about the whole philosophy of making castings.

For a successful casting operation, one of the revered commercial goals is the attainment of product sales being at least equal to manufacturing costs. There are numerous other requirements for the successful business, like management, plant and equipment, maintenance, accounting, marketing, negotiating etc. All have to be adequate, otherwise the business can suffer, and even fail.

This text deals only with the technical issues of the quest for good castings. Without good castings it is not easy to see what future a casting operation can have. The production of good castings can be highly economical and rewarding. The production of bad castings is usually expensive and damaging.

The 'good casting' in this text is defined as one that meets or exceeds the customer's specification.

It is also worth noting at this early stage, that we hope that meeting the customer's specification will be equivalent to meeting or exceeding service requirements. However, occasionally it is necessary to live with the irony that the demands of the customer and the requirements for service are sometimes not in the harmony one would like to see. This is a challenge to the conscientious foundry engineer to persuade and educate the customer in an effort to reconcile the customer's aims with our duty of care towards casting users and society as a whole.

These problems illustrate that there are easier ways of earning a living than in the casting industry. But few are as exciting.

JC
West Malvern
03 September 2003

Introduction to *Castings Handbook* 2011

Revised and expanded editions of *Castings* and *Castings Practice* were planned in a more logical format as *Casting Metallurgy* and *Casting Manufacture*. However, Elsevier suggested that the two might beneficially be combined as a single *Complete Castings Handbook*. I have warmed to this suggestion since encompassing both the science and the technological application will be helpful to students, academics, and producers. The origin of the division of the Handbook into volumes 1 and 2 therefore remains clear: Volume 1 is the metallurgy of castings, formally outlining for the first time my new proposals for an explanation of the metallurgy of Al–Si alloys, cast irons, and steels; Volume 2, manufacture, divides into the 10 Rules, manufacturing design, and finally the various processing steps.

As I have indicated previously, the numerous processing steps make casting a complex technology not to be underestimated. It is our task as founders to make sure the world, happily ignorant of this significant challenge, takes castings for granted, having never an occasion to question their complete reliability.

JC
Ledbury, Herefordshire, England
23 November 2010

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