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A Future for Vacuum Arc Remelting and Electroslag Remelting—A Critical Perspective

John Campbell

School of Metallurgy and Materials, Faculty of Engineering, University of Birmingham, Birmingham B15 2TT, UK; jc@campbelltech.co.uk

Abstract: In the secondary metals refining processes, vacuum arc remelting (VAR) and electroslag remelting (ESR), the consumable electrode is commonly produced by vacuum induction melting (VIM) which employs the regrettably primitive casting technique of simply pouring into the open top of the mold. Despite the vacuum, the resulting oxidizing conditions and the immensely powerful turbulence accompanying the top-pouring of the electrode is now known to create a substantial density of serious cracks. The cracks in the cast electrode are bifilms (double oxide films), which in turn are proposed to be responsible for the major faults of the VAR ingot, including undetectable, horizontal macroscopic cracks, white spots (clean and dirty varieties) and in-fallen crown. The remedial action to solve all these issues at a stroke is the provision of a counter-gravity cast electrode, cast in air or vacuum, or provision of any similar electrode substantially free from bifilm defects. The ESR process is also described, explaining the reasons for its significantly reduced sensitivity to the top-poured VIM electrode, but indicating that with an improved electrode, this already nearly reliable process has the potential for perfect reliability. The target of this critical overview is an assessment of the potential of these secondary refining processes to produce, for the first time, effectively defect-free metals, metals we can trust.

Keywords: vacuum arc; electroslag; defects; bifilms; cracks; reliability

Citation: Campbell, J. A Future for Vacuum Arc Remelting and Electroslag Remelting—A Critical Perspective. *Metals* **2023**, *13*, 1634. https://doi.org/10.3390/met13101634

Academic Editor: Jaka Burja

Received: 26 August 2023
Revised: 20 September 2023
Accepted: 20 September 2023
Published: 23 September 2023

1. Introduction

Both vacuum arc remelting (VAR) and electroslag remelting (ESR) processes (Figure 1) produce ingots of steel and Ni alloys which are regarded as ultimate achievers of clean metals. Both processes are in principle impressively simple, in which an electrode carries electrical current which can melt the tip of the electrode, gradually building up an ingot drop by drop. In VAR the heat is generated by an arc, whereas in ESR a layer of an oxide slag melts the tip by the resistive heating of the slag.

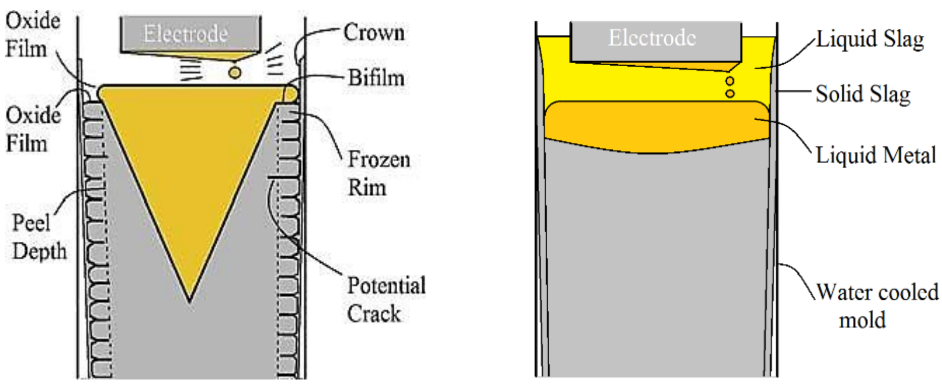

Figure 1. VAR and ESR processes.

In general, the microstructures of both processes are impressively clean, with fine inclusions evenly distributed. Thus, when small samples of the materials are taken for tests, such as tensile strength or fatigue resistance, they display excellent results for which the processes are prized. Such small samples, however, usually cannot alert the user to serious faults which are bigger than the samples. This is the subject of concern in this assessment.

This short account seeks to uncover the true reliability of each of these costly, multiply melted materials. We shall see how neither is truly reliable, but ESR is very nearly so. Nevertheless, both have the potential to be made fundamentally reliable. This account describes the defect production mechanisms built in as macroscopic integral features of the current VAR process (and to some much reduced extent, the ESR process) and the numerous defects which can litter VAR products. Future options for the elimination of these faults are recommended.

2. Background to Defect Formation

A breaking wave of water is an action in which the body of water turns to impinge on itself, with the two water surfaces coming together to assimilate seamlessly. This action is so obvious we do not trouble ourselves to think about it. However, in the case of liquid metals, the impact of two bodies of liquid is not a trivial or obvious event. In nearly all cases with our liquid metals and alloys (with some interesting exceptions which we have no time for here), the liquid has an oxide film on its surface, usually even under conditions of a normal industrial vacuum. Microscopically, the oxide film has a dry, rough, upper surface, which is the surface involved in the fold-over or impact collision, with the result that the two opposed surfaces, having impinged, do not wet, but remain unbonded, as a crack (Figure 2). The crack is submerged and suspended in the bulk of the liquid metal, where it can be frozen in place to become a crack in the solidified casting. Under very turbulent conditions, the cast metal can be filled with a dense snowstorm of cracks. They are found to vary in size from micrometers in diameter to the size of newspapers (such large sizes are not unusual; they are to be seen in tonnage nickel and steel castings), and thicknesses usually from nanometers to micrometers. Such thin cracks are a challenge to detect by NDT (non-destructive testing), but they can usually be detected on a fracture surface, and identified as bifilms by their wrinkles and folds characteristic of thin films originating on a mobile liquid surface [1].

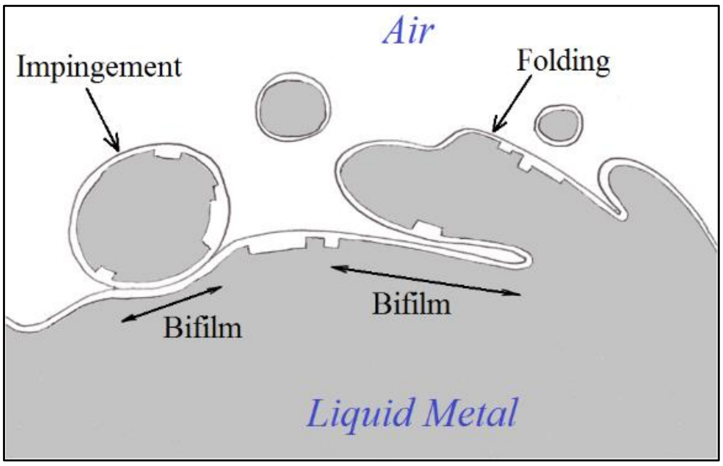

Figure 2. The creation of bifilms by entrainment mechanisms: folding and impingement [1].

The discovery that liquid metals can accumulate populations of cracks (the double oxide films formed by turbulence) which can be inherited by the solidifying metal has revealed the need for serious rethinking of some procedures in our metallurgical processing. In the casting of ingots, as for instance, electrodes for remelting, the act of pouring of the liquid metal into a mold, whether in air or vacuum, is now known to be damaging to the liquid, forming serious liquid crack defects which are incorporated into the solidifying metal.

3. The History of VAR Failures

The VAR process, in which the metal is transferred as droplets through an electric arc in a vacuum, has been accepted without question as providing the best possible engineering metals. Any failure of a component fabricated from VAR material has therefore been assumed, without thought or question, to be clearly some fault of design or manufacture. Consequently, the part is modified to ensure it avoids future failure, becoming stronger and heavier. Successive failures over the years have therefore resulted in gross over-design which has acted to protect the reputation of VAR. For instance, helicopter drive shafts now use safety factors of up to 5, but it is chilling to acknowledge that failures still occur. If the material had been reliable, in principle, a safety factor of 1 would have been acceptable. After all, funding of untold wealth has been lavished on fatigue research in the world's best metallurgical laboratories, so that a lifetime of the part should have been predictable with confidence. Clearly, there is a very serious mismatch between theory and practice. Some major unknown factor is present.

In an attempt to take an objective view of VAR reliability, it is clear the failures are not negligible. They are numerous, sometimes constituting major and tragic disasters. For aircraft since 1960, there have been over 600 failures due to the bursting of VAR gas turbine discs and the number is still rising [2]. In addition, the author has identified at least six helicopter failures in Europe over the past 20 years or more which appear to be the result of the use of VAR steels in drive trains [3] despite the use of large factors of safety.

Despite all the huge efforts world-wide in metallurgical laboratories to characterize properties in laboratories, it is easy to understand how macroscopic cracks have been persistently overlooked. The oxide films are often very thin, and not easily discerned or detected. In addition, there is the sampling issue—when preparing 100 specimens for fatigue testing, if several were to fall into two halves prior to getting them into the testing machine, they are likely to simply be ignored as some kind of 'mistake', and thrown into the bin. It is highly improbable they will be recorded as points on the zero axis of the final graphical reports as specimens with zero resistance to fatigue.

The successes of VAR products have been praised over the years, but blindness to its failures has led to widespread under-reporting. No-one has wanted to acknowledge or dwell on the failures. When we include the failures in our assessment, we are left with an image of an unreliable process.

This paper attempts therefore to lay out, for the first time, a rationale for the current operation of the VAR process, such that it might be understood, and its defects eliminated.

4. The VIM Process and Its Limitations

The metal intended for remelting by VAR is usually first vacuum induction melted (VIM) and cast under vacuum. In the VIM unit the melting crucible is tilted to pour the liquid alloy into a mold sited several meters directly below. More sophisticated industrial VIM melters tilt pour into launders which distribute the metal over several molds so that a number of ingots (electrodes) can be cast at once, and all under vacuum. Some of the large industrial VIM units are gigantic, impressive monuments of modern technology, often occupying major areas of the foundry.

It is all the more regrettable therefore that the products from such impressive production units are flawed [4]. The flaws occur because of the use of top-pouring to fill the mold. The considerable fall distance means that the liquid hits the base of the mold with immense energy, producing immensely powerful turbulence which creates masses of bifilms. Thus, the cast electrodes are automatically full of bifilm cracks. The cracks inflict major defects on the integrity of the VAR process and the final VAR ingot. It is interesting to note that Mitchell has drawn attention to the several shortcomings of electrodes in addition to their bifilm problems [5].

It gives this author even more concern to note that this situation is not easily rectified. The simple lip-pour into the mold is extremely simple, and has been assumed to be acceptable as a result of the 'vacuum' conditions. Almost any other casting technique is difficult to engineer in a vacuum chamber. The best solution to avoid pouring would be to up-cast, of which there are a number of valuable techniques, some of which are excellent, capable of delivering defect-free products. However, the siting of the melting furnace at the top of the vacuum chamber implies massive disruption to convert to some kind of counter-gravity filling of molds necessarily placed above the furnace. It will almost certainly necessitate the re-siting of the furnace at the bottom of the vacuum chamber; a move that will not be possible in many designs.

5. The VAR Process and Its Defects

VAR is a commendably simple process, as outlined in Figure 1, in which the electrical current flows down the electrode, arcs across to the top of the ingot, generating sufficient heat to melt the tip of the electrode. Droplets of liquid metal fall through the arc gap, gradually building up the ingot contained in the water-cooled mold. This clean, electrical processing of the liquid metal as droplets through a vacuum has been regarded as an iconic process, delivering a large ingot with low volatiles, especially hydrogen, but also low values of other undesirable residuals such as lead (Pb). With such a simple, elegant process, what could go wrong?

The problems start in the electrode (Figure 3). The high electrical current for melting is at a rather low voltage, and so in general the current is not able to cross the bifilm cracks—the cracks consisting of two insulating oxide ceramics separated by an 'air gap'. The 'air gap' being the colloquialism for the region where the two films do not touch face-to-face, but contain random regions of entrained environment, which could be air or vacuum, plus additional gases such as hydrogen which tend to diffuse in to this crack-like void, and argon which may be a remnant of the vacuum flushing gas, or the remnant 1 per cent of argon from the entrapped air after oxygen and nitrogen have reacted to thicken the bifilms with additional layers of oxide and nitride [1].

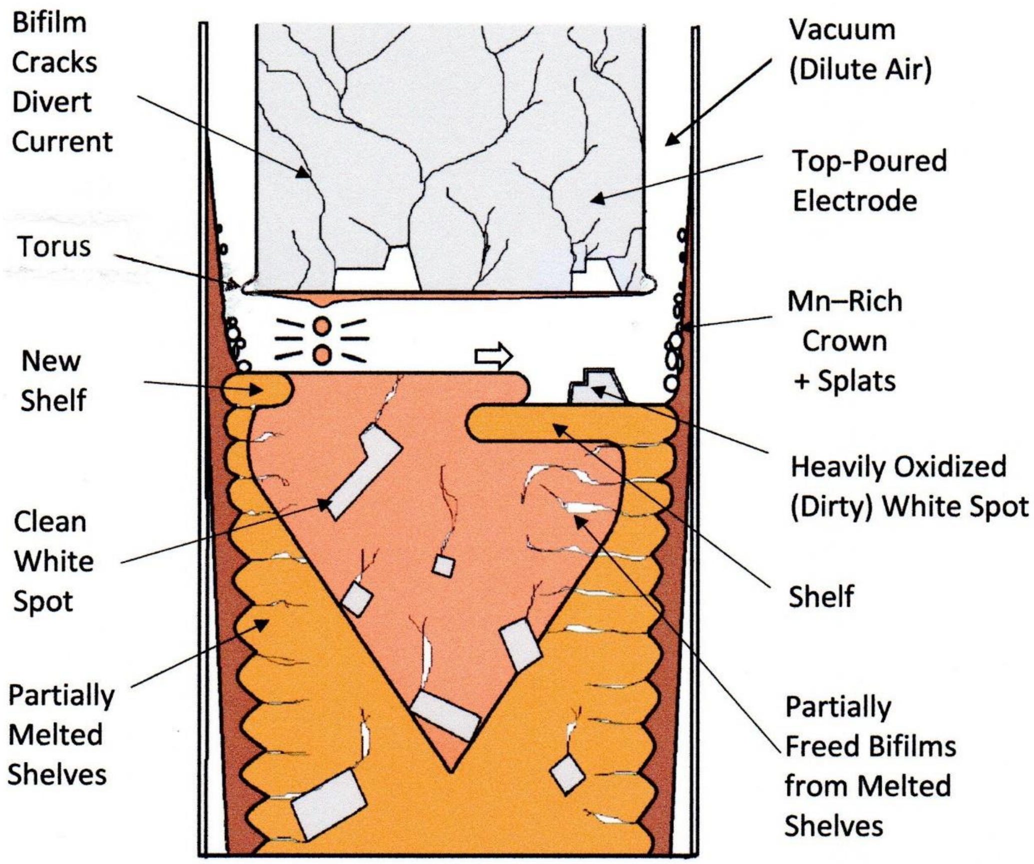

Figure 3. VAR process showing defect production.

The consequence for the flow of current down the electrode is that it becomes channeled in random directions, seeking out lengths of the electrode which happen to give a continuous conducting path. At times, this can be envisaged to be narrow paths well off center. This has serious consequences for the growth of the ingot.

The channeling of the electrical current via conductive pathways down the electrode seems likely to be the reason for the so-called 'constricted arc' into a narrow, concentrated jet, often well off-axis; an unwelcome condition causing the process loss of melting efficiency. The diffused arc, spread over the majority of the electrode surface is optimum for the process, but can prove difficult to maintain.

6. The Oxidizing Environment

The volume of the vacuum chamber of the VAR unit is small, and has few obvious outgassing sources such as, as in most other melting processes, porous refractories such as a crucible or rammed lining surrounding the molten metal. Thus, the strong vacuum extraction from this limited and relatively clean volume would be expected to result in a high-quality vacuum, sufficiently good to prevent the formation of oxide defects such as bifilms. Another reason why oxide bifilms might not be expected to be present is the huge temperature in the arc, which is sufficient to ensure that most oxides are unstable and are decomposed. With regret, these expectations are not met.

Because the electrode has been turbulently top-poured, it is now contaminated with a plentiful supply of oxide films—as double film (bifilm) cracks in addition to the oxide population it will have inherited from prior melting and casting operations. A cursory scan of the Ellingham diagram indicates immediately that the temperatures in the arc, of several thousand degrees Celsius, will reduce the oxides in the electrode, releasing oxygen gas into the environment.

Even so, despite this unwelcome source of oxygen in the high temperatures of the arc, how can oxides *re-form* in these conditions? The channeling of the melting power, taking the arc off center, means that the far side of the ingot will now cool to temperatures at which steel can solidify to create 'shelves', as have been observed and which we shall discuss below. These distant regions from the arc will be at approximately 1550 C, close to the freezing point of the steel, and well below the temperature at which many important oxides become stable.

7. Shelf Formation

The liquid pool is generally assumed to be in the top center of the ingot. To the writer's knowledge, all computer simulation studies have made this assumption. However, of course, the liquid metal pool will tend to follow the movement of the arc off center, particularly if the arc remains off center for a lengthy period (Figure 4). The far side of the ingot, solidifying against the water-cooled mold, now grows inwards, extending as a 'shelf'. Such shelf formation has been observed directly by Zanner [6] in an experimental VAR unit specially modified with a side window.

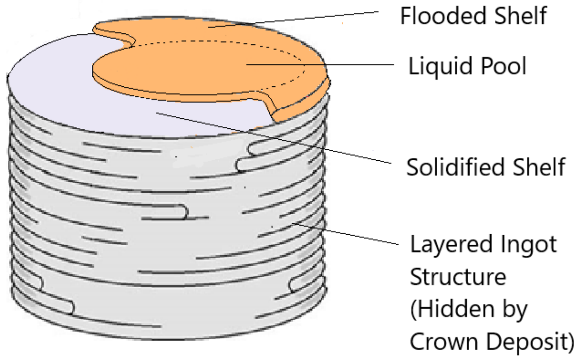

Figure 4. The build-up of a VAR ingot in layers, separated by deeply penetrating circumferential bifilm cracks.

The problem introduced by the growth of the shelf is that the surface of the shelf is now exposed to the oxidizing environment of the 'vacuum', and now has time to grow a thick oxide.

The upward advance of the liquid metal in the pool is now modified. The pool surface, particularly at its cooler outer edges, will have a thin oxide film, so that the combined action of surface tension and the surface film will hold the liquid metal together, preventing its spread over the shelf. However, as the liquid in the pool rises sufficiently high (about 8 mm, the height of a sessile drop of liquid steel) to overflow the shelf, it rolls over the oxide already formed on the shelf, rolling out and laying down its own oxide as a track-laying vehicle lays down its tracks as it progresses. The mechanism is well-known as a producer of major horizontal cracks in castings [1]. The result, therefore, is the creation of an extended area of thin dry oxide laid down face-to-face over an extended area of thick dry oxide, constituting an extensive bifilm crack which can occupy significant areas of the ingot. Its thin/thick film asymmetry is a common bifilm morphology. The horizontal cracks developed by the submerging of the shelves are likely to be serious defects. It is expected that they could extend over significant areas of the ingot.

There may be some evidence for the macroscopic depth of cracks. One study [7] has found evidence of oxygen (i.e., most probably overlooked oxide bifilms) at up to nearly 50 mm depth.

Such cracks could hardly be more serious because they can be predicted to be difficult to detect. As horizontal cracks, they will be parallel to the ultrasonic beam, and thus give no reflection. Even if the beam were angled, the sound would be reflected away to the far wall and dissipated, not giving any significant reflection.

These horizontal cracks around the circumference of the ingot are probably responsible for the fracture of the ingot if forged prior to machining or grinding away of the surface. Even after this costly diameter reduction, VAR ingots, especially Ni alloys, are known to crack on forging.

The presence of shelf cracks can hardly be doubted from other additional evidence. The author has clear memories of his early days in the 1960s steel industry when VAR and ESR were first introduced in the UK. In BISRA (the British Iron and Steel Research Association) laboratory, we would melt identical electrodes side by side in adjacent VAR and ESR units. If the surface was not removed by machining, I recall the VAR Waspaloy ingot fracturing on the first stroke of the forge, whereas the otherwise identical ESR ingot would forge like butter.

Nevertheless, to be fair, the fact that most ingots appear to benefit from the removal of 5 to 10 mm of surface indicates that most circumferential cracks are only 5 to 10 mm deep. It is only the serious random off-center dwell of the arc which leads to the random occurrence of more serious deep cracks. However, of course, we never can know when this has happened because the bifilm cracks, although serious, are practically or actually undetectable.

8. White Spots

As the melting current is funneled through narrow regions electrically isolated by cracks, the current will be concentrated in random connecting ligaments of the electrode. If the ligament is narrow, the concentration of current will cause the ligament to melt. For those fragments of the electrode being held in place by a ligament, its melting might permit the fragment to fall into the melt.

The cracked electrode, raining electrode fragments into the pool, develops the characteristic structure of VAR ingots, the fragments appearing as a scattering of 'white spots' in the darker matrix structure. The white spot is named from its appearance on a cut and etched section, in which the solute-lean dendrites which have remained unmelted from the electrode, are revealed as lighter etching than the slowly cooled or heat-treated matrix which etches more darkly as a result of its denser populations of precipitates.

It is sobering to reflect that the electrode creating white spots is perhaps the best outcome of the unsoundness of the electrode. At worst, the electrode can be so badly cracked that it fails catastrophically, falling into the melt and bringing the process to a stop.

Returning to the more normal sprinkling of white spots into the ingot, there are two locations where fragments may fall. They may fall into the liquid pool, or onto a solidified shelf.

If the fragment falls into the liquid pool, the fragment will automatically find itself enwrapped in a bifilm. This is because the fragment will have already grown its own (single) oxide film, and the liquid pool surface will also be covered (at least at its edges) by its own (single) oxide film. As the fragment falls through the surface of the pool, it will be enveloped in the oxide of the pool surface, thereby gaining a double oxide layer, dry-side-to-dry-side; a bifilm crack. This is a fundamental feature of all entrainment mechanisms in which the liquid has a surface film; a bifilm crack becomes wrapped around the entire perimeter of the introduced fragment.

The crack surrounding the fragment may be sufficiently reflective (i.e., have a sufficiently open 'air gap' which reflects elastic shear waves efficiently) to be identified by ultrasound. If not detected, the crack is a serious risk in the ingot, commonly measuring 5 to 25 mm across.

However, a detaching fragment of the electrode may not fall into the pool but may fall onto a shelf. This is a much more serious situation. The fragment now sits on the thick oxide of the shelf, and is exposed to the cooler, oxidizing conditions for the lifetime of the shelf which is likely to be one or two minutes. The fragment becomes heavily oxidized during this exposure. When the shelf is finally submerged and melts, the fragment subsides into the ingot together with the thick bifilm of the shelf, forming a massive defect. The heavy tangle of bifilms surrounding the fragment gives it its name: 'dirty white spot'. The nest of cracks surrounding the dirty white spot responsible for the disc failure of American Airlines flight 383 in Chicago O'Hare airport in 2016 is clear in the accident report [8].

9. The Torus

The torus appears to be a minor feature of VAR in which the metal droplets creep around the edge of the electrode and solidify. There has been some speculation that excursions of the arc might occasionally melt and detach portions of the torus which will add to the white spot population. This possibility is considered a minor issue compared to other defect-forming mechanisms and is neglected in this account.

10. In-Fallen Crown

During normal melting, when the arc is tolerably axial, the crown builds up on the water-cooled wall of the mold as a region of splatter and condensed vapors, mainly Mn vapor, making the crown rich in Mn (Figure 3). During normal operation, the rising melt submerges the crown, which then becomes the metallic skin of the casting, effectively coating the pancake stack structure of the ingot, hiding its intervening cracks under a smooth surface layer of Mn-rich metal.

However, if the arc is caused to stray off axis as a result of the diversion of current down the cracked electrode, then there is the danger of the base of the crown, now near to the arc, being melted by the increased heat, causing that region of the crown to collapse into the melt. It is a concern that on occasions, the crown falls not into the melt but onto a shelf, causing the final defect to become much worse. Crown inclusions can be very large and serious structural faults. They have been reported and described in detail [8].

11. A New Future for VAR

Standing back to view the list of problems with VAR, its problems are so numerous and serious it is amazing that any useful engineering products from VAR material ever avoided failure. However, of course, failure has been avoided in general because of the combined benefits of (i) luck, because not all parts of the ingot would suffer serious cracks, and (ii) over design. Neither of these reasons are recommended ways forward.

While viewing the problems as a whole, it is also clear that the problems are not necessarily with the VAR process itself. In fact, all the major problems can be traced back to the VIM electrode, as a result of it being unfortunately filled with cracks because it was top-poured. The cracks cause the current to be diverted, with the result that the off-axis temperature distribution leads to multiple defects including shelf formation with consequential deep horizontal cracks, detaching fragments as white spots and in-fallen crown, with all the in-falling debris enveloped in cracks.

It is interesting to reflect that an air-cast electrode would be significantly superior to the vacuum-cast electrode, provided a modern high technology casting system was employed. An air-poured electrode, if poured using good modern casting technology, could enjoy a significantly lower oxide content and near-zero content of oxide bifilms. In addition, of course, the electrode cast in air would be far less costly. Techniques for producing cast steels and nickel alloys by gravity are now capable of delivering castings with properties competitive to vacuum-cast steels and alloys [1].

Even so, of course, there may be other good reasons for wishing to retain vacuum conditions for melting and casting, as provided by VIM. However, if retaining VIM, it is essential to avoid top-pouring into the mold. It is only the top-pour which is at fault. The top-pour might be avoided by either (i) providing a kind of contact pour, bottom gated mold filling system [4] or (ii) counter-gravity filling the mold (some kind of up-casting system) [1,4].

The bottom filling of the ingot, channeled to the ladle nozzle as a contact pour technique, would be immensely better. If it could be made to work in vacuum (it would be a substantial challenge [4]), it would permit the continued use of the current VIM hardware, in which the furnace is sited high in the VIM vacuum chamber, and the molds are sited below. Contact pour works well in air because of the vacuum generated by the falling jet of metal in the downsprue (the vertical tube, channeling flow from the ladle nozzle to the base of the ingot to be cast). The internal generated vacuum sucks the falling liquid into the evacuating spaces, thus filling the whole downsprue, so that further reaction with air is prevented. However, the process only works in an environment of atmospheric pressure—the 'suction' action is the pressure difference between atmospheric pressure and the reduced pressure as a result of a scavenging (air entraining) action of the falling stream. Contact pour would not enjoy this benefit in vacuum. The downsprue channel would have to be accurately formed with a hyperbolic taper to match the shape of the falling stream as perfectly as possible to avoid oxidation of the metal during its passage through the downsprue. This is the basis of new filling technologies which are proving successful worldwide, but mainly used so far in air [1,4].

At the level of the base of the ingot there is an option to use a flush filter and spin trap technology [1], or tangentially entering the mold unchecked, to spin the metal up into the cylindrical mold. The high-speed tangential filling technology has already been tested by the author for a 50,000 kg round steel casting (a back-up roll), cast in air, resulting in a casting practically free from any significant defects [9]. The technique can be envisioned to work at least as well in vacuum.

Even so, the counter-gravity option is the simplest and by far the best casting technology. It could potentially deliver defect-free cast electrodes. The process can be operated in air or vacuum, probably with little or no detectable difference in cleanness. Nevertheless, of course, vacuum, or inert gas would be desirable for certain alloys for other reasons such as the prevention of loss of critical alloy elements by oxidation or evaporation.

The big disadvantage of counter-gravity for current VIM producers is that the relative location of the liquid metal source and mold are reversed, with the melter low in the vacuum chamber, and the mold(s) above. The reversal of current VIM furnace geometry would involve major cost to rebuild VIM units.

Amid the above concerns of the options, it is worth repeating that counter-gravity in air or vacuum counter-gravity would deliver an unexcelled quality of electrodes which can be predicted to eliminate at a stroke all the defect mechanisms which degrade current VAR metals.

12. Alternative Strategies

The immediate future for VAR is a concern. It will take time to rectify the serious faults of the process. During this period, now that its problems are clarified and brought into the public domain, it could be viewed as a lack of duty of care to continue to manufacture and sell VAR material using existing technology. A potential interim measure might be the mechanical testing of final machined products prior to them being accepted for service. A fairly recent example has offered, by chance, a clear example of this possible way forward. After a tragic helicopter disaster in Korea [2] in which the rotor was lost because of a failed drive shaft, the available unused drive shafts held in store were tested. All were found to be defective.

For the future, if a decision is made to continue to supply VAR products, mandatory testing of products prior to entering service seems unavoidable. If such testing could be carried out in-house, this might be a way forward. However, if carried out more appropriately by customers, this option gives no realistic commercial opportunity to move forward. It would be expected to fail from the instant that the first failed products were reported. Worse still, a run of failures may occur, as happened in Korea.

The provision of ESR products is an alternative, as all VAR manufacturers known to this author already manufacture and supply ESR metals. In general, comparative results of mechanical properties have shown VAR to be marginally superior in key properties such as fatigue resistance. This is commonly attributed to the faster cooling of VAR ingots leading to finer secondary dendrite arm spacing (SDAS). Even so, these are negligible differences compared to the central issue of overriding importance which is that ESR ingots are substantially reliable whereas current VAR ingots are not.

The VIM electrode can still create some problems for ESR. The author was once shocked by a fallen-in fragment approximately 100 mm in diameter in the center of a 500 mm diameter ESR ingot, but this unusual defect was detectable by ultrasound. Such defects are not the fault of the ESR process, but the process would clearly benefit from an electrode which was not top-poured and therefore not full of cracks. An ESR ingot manufactured with an electrode cast using good casting technology (in air) could be practically free from macroscopic defects and have a negligible oxygen excess, or at least a treatable oxygen excess by, for instance, a raised CaO content in the slag layer which would enhance the solubility of alumina bifilms.

Avoiding any hiatus in supply, producers could continue to supply ESR material while VAR manufacture was suspended.

13. The Potential for ESR Versus VAR

The comparative freedom of ESR from defects arises because the use of the conducting slag layer spreads heat, avoiding temperature distribution problems, and spreads conductive opportunities through the melting tip of the electrode, generally tending therefore to avoid the disengagement of fragments to create white spots or other entrained debris. The thermal inertia of ESR is also higher than VAR, facilitating control to avoid temperature excursions. Thus, the major problems of VAR are not suffered to nearly the same degree by ESR.

It is worth assessing the potential of ESR as a possible supplanter of VAR, pointing out that the usual criticisms of ESR are, in the view of this author, largely irrelevant or invalid. For instance:

The higher hydrogen content can be dealt with, if necessary, by control of the environment above the slag layer. However, there are good fundamental reasons why, in the absence of significant bifilms, hydrogen is almost certainly irrelevant [4].

The lower rate of heat extraction results in channel defects in larger ingots, but channel defects are almost certainly harmless in the absence of bifilms (in current metals, bifilms will be pushed by dendritic growth, concentrated in channel defects, and so lowering properties in channels). In any case, heat extraction can be greatly improved by using a collar mold and cooling the ingot by direct impingement of water jets as the ingot appears out of the bottom of the mold. In this way the cooling rate of ESR could exceed that of VAR and channel defects could be avoided for similar large ingot sizes.

The risk of break-out of liquid metal below the collar mold has been an inhibition on its use, but improved mold technology is available. Relatively low-cost air-slip systems or more costly magnetic levitation are available. In addition, breakouts may be, once again, the result of bifilms in the solidified skin providing an openable crack bridging the solidified layer (as this author also proposes [4] to be the major problem in the break-outs during the continuous casting of steel), whereas with an electrode with minor or zero bifilm content, such a danger may be avoided.

In this way ESR manufactured in improved collar molds could become a far more serious competitor to VAR on all fronts, possibly exceeding VAR in reliability and properties because of its many intrinsic advantages [4] (in addition to its lower cost). An ESR process exceeding the performance of VAR in every respect would be an opportunity to quietly phase out VAR production, avoiding the costs of revising the VIM and VAR processes, while embracing the new opportunity of expanding production of an upgraded, superior ESR.

14. Conclusions

1. Specialized, reliable metals will always be in demand for the manufacture of critical components such as those produced by ESR and VAR.
2. It is with regret that in the 21st century the VAR process is failing to provide reliable products because of its top-poured electrodes produced by VIM. The VIM process needs to be abandoned or it will be difficult and/or costly to improve its casting technology to produce crack-free electrodes. VAR is currently in serious need of improvement, whereas the ESR process already enjoys significant reliability.
3. Both VAR and ESR, with minimal investment and risk, could become totally reliable if VIM electrodes were abandoned and electrodes were produced by proven low-cost but superior high-technology gravity casting in air, which can be made immediately available [1]. More advantageously, the adoption of counter-gravity would permit substantially perfect, defect-free electrodes to be manufactured in air or vacuum. ESR cast in collar molds should be reconsidered as a potentially superior and permanent replacement of VAR.
4. At this time, the world continues to need metals we can trust.

Funding: This research received no external funding.

Conflicts of Interest: The author confirms no conflict of interest.

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