Helicopter Drive Train Failures

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Abstract

The dangers of using vacuum arc remelted (VAR) steel for the drive trains of helicopters are described. The steel can contain serious cracks, and historical helicopter failures are listed. An equivalent material recommended for use is that produced by the electroslag remelting (ESR) process which is expected to be fundamentally free of major defects.

Background

The drive trains of helicopters, including principally shafts and gears, are acknowledged to need the highest possible steel quality. Generally, therefore, twice-melted steels are used, known as secondary remelted steels. There are a number of different processes, including such esoteric processes as electron beam melting and plasma melting, but by far the most used are the VAR and ESR processes. In general, it seems that all the vacuum processes, including VAR and vacuum induction melting (VIM) have largely similar problems. Only ESR is substantially different, being the only process in which the metal is melted and transferred into the ingot is submerged in a liquid oxide slag, making the use of vacuum unnecessary to prevent the formation of oxide films as will be discussed.

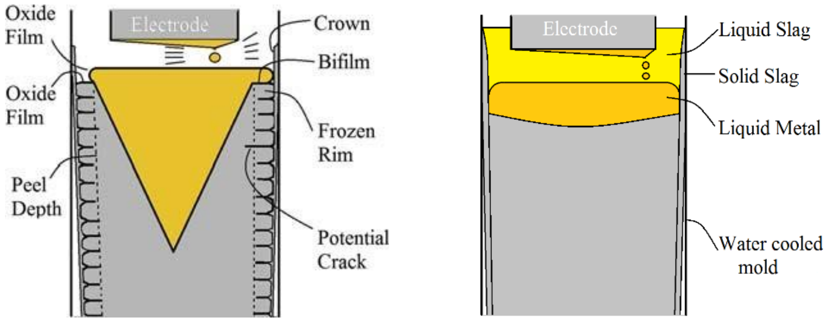

Figure 1. Sections of the VAR and ESR Processes

Both VAR and ESR processes produce ingots of steel and Ni alloys which are regarded as ultimate achievers of the cleanest metals. It is true that, in general, their microstructures appear impressively clean, with fine inclusions finely distributed. Thus, when small samples of the materials are taken for tests, such as tensile strength or fatigue resistance, they display excellent results. Such small samples, however, usually cannot alert the user to faults which are bigger than the samples. This is the subject of concern in this account.

The design engineer whose task it is to make the choice between these two processes is naturally attracted to the VAR materials. The use of the word ‘vacuum’ strongly suggests ‘cleanness’ or ‘purity’.

Furthermore, the VAR steel is considerably more expensive than ESR, its high price suggestive of high quality. The marketing advantage screw is turned further because “vacuum arc remelted” is often referred to by the producers as “vacuum arc refined.” This is not altogether untrue, but rather than using the word “refined,” we shall stay with the descriptive name “remelted” and shall attempt to assess the process more objectively.

In contrast, the name ‘electroslag remelted’ has none of the hi-tech overtones of VAR, containing in particular the word ‘slag’ which is most used in the term ‘slag heaps’ – generally implying rubbish dumps. It is a great pity that the ESR process labours under such a commercially unattractive name, when the process and the product can offer some important superior benefits.

The misleading marketing advantages for VAR have been unfortunate for the aerospace industry. This short account seeks to uncover the true reliability of each of these expensive multiply-melted materials. We shall see how neither are truly reliable, but ESR is very nearly so, and has the potential to be made fundamentally and totally reliable, whereas VAR is fundamentally and dangerously unreliable.

Supporters of the status quo will point to the years of the successful use of VAR material in many critical applications. This is certainly true, but seems to this author to have been the result of good fortune, inadequate non-destructive testing, excessive over-design, or the tendency never to question the cast-in defects of the steel. When VAR products have failed, the steel itself appears never to have been blamed.

In the case of helicopters, the situation is especially critical: parts are only reluctantly over-designed because of the direct disadvantage to load carrying capability. More importantly, the single drive train, with its many components, could hardly be more vulnerable. It is a system which is hypersensitive to any failure of the steel. Although many markets may choose to continue to employ VAR steels, believing (mistakenly in the view of this author) the material to have a good safety record, the helicopter industry needs to reassess the risk the continued application of a key structural steel which is predicted to be susceptible to serious defects [1], now confirmed in a recent Korean failure.

The author has written about the VAR and ESR processes, describing their metallurgy in some detail [1]. These technical details are not repeated here. Only the bifilm, the crack-like defect which can arise during casting processes is described briefly below, and its potential involvement in helicopter failures is described.

The Bifilm Defect

The central defect which has been previously overlooked in metals is the doubled-over oxide film on the surface of the liquid metal [2]. The double film is known as a bifilm. This pair of oxide films, with dry surfaces face-to-face, cannot bond, and so acts as a crack in metals (Figure 2). The bifilm is a ubiquitous feature of current engineering metals because nearly all metals are at some stage melted and cast by pouring. During the turbulence of pouring liquid metals, the time for the growth of the oxide film is only a few milliseconds, with the result that the films have no time to thicken, and therefore often so thin as to be invisible to normal inspection. Their area, however, is quite another matter, and can vary from microscopic to dinner plates. Although bifilms have been known about and researched for over twenty years, this knowledge is not yet widely disseminated in the metals industries.

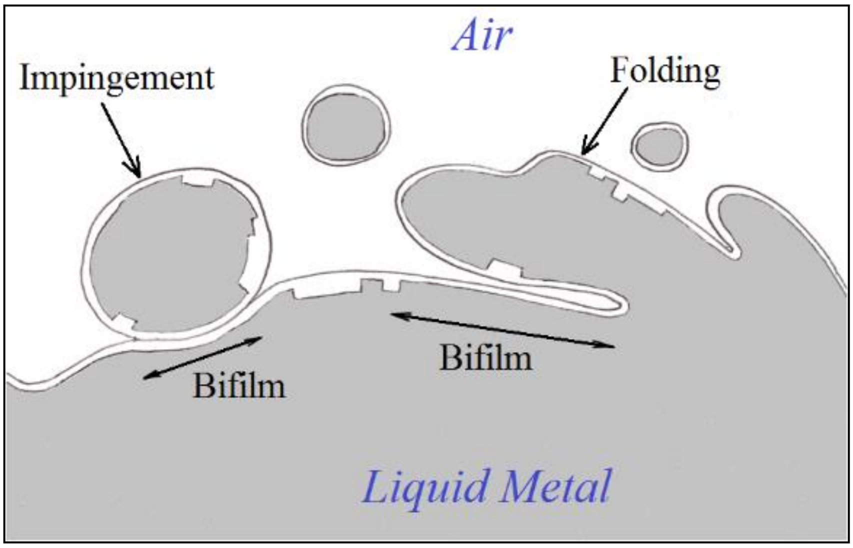

Figure 2. The creation of bifilms by folding and impingement [1]

The VAR Process

The VAR process is unfortunate and unique in having several mechanisms which can guarantee the generation of large bifilm cracks, and its cracking behaviour during forging, if its surface is not machined away, leaves its content of major defects in no doubt. In contrast, ESR is naturally completely free of these issues regardless whether its surface is as-cast or machined; its good-natured forging behaviour emphasises its defect-free condition.

The universal experiences of bifilm problems in metals is seen in other areas of aerospace. For instance, *every* failed turbine blade which the author has studied appears to be the result of a bifilm crack. The repeated stresses applied to the blade during its service gradually extend any cast-in bifilm, gradually growing it until complete failure. This seems to be a relatively common occurrence, only rarely causing total engine failure. More serious are the failures of turbine discs made from forged VAR ingot. This is clearly a concern in view of the unreliability of VAR steel; the failure of a disc always destroys the engine and can, of course, result in the loss of the aircraft.

The failures of blades and discs from bifilms is naturally questioned at this time because the presence of bifilms is not part of mainstream metallurgy as taught in colleges and universities. In addition, they are not easily detected, especially to an observer who is not aware of their existence. Parts of fracture surfaces illustrating bifilms are routinely attributed to ‘quasi-cleavage’ (a process which is clearly not cleavage, but is otherwise inexplicable) or slip-plane generated facts (which occasionally do appear to be facets generated by slip action, but on many occasions are facets generated by the straightening of bifilms by the growth of dendrites and grains during freezing).

These catastrophic failures promoted by bifilms are preventable. Whereas the metallurgical industry has traditionally sought ever-stronger alloys in an attempt to avoid failure, such lengthy and expensive enterprises overlook the major benefits to properties resulting from a defect-free condition, often achievable with minimal cost. In principle, the unbelievably simple requirement for success is the control of the casting process, so that the oxide films on the liquid metal surface are prevented from folding over or splashing to create bifilm cracks.

During the production of a VAR ingot, bifilm formation conditions are easily introduced and often difficult to avoid, so that VAR steel can be littered with defects. The growth of oxide films on the surface of the liquid metal during melting under 'vacuum' arises because the vacuum is not sufficiently free from oxygen to avoid the formation of oxides of highly oxidizable elements such as Al, Cr, Hf etc. The formation of nitrides is also common.

The ESR Process

The ESR process naturally avoids the incorporation of folded-over solid oxide films because the melting and transfer of the liquid metal to the ingot all occurs in an environment of a liquid oxide, which can take into solution any thin films of solid oxides which might fold to create bifilms.

The only threat to the ESR process is the common current practice of using electrodes which have been top-poured, and which therefore contain major bifilms. Such top-pouring can be carried out in air, but even when carried out in vacuum, in the commonly-used VIM process, the generation of large oxide bifilms in the so-called 'vacuum' environment cause major damage to the electrode. The damage to the electrode is in the form of large cracks, which, during the melting process, occasionally cause pieces of electrode to detach and fall into the ingot. These pieces are unmelted, and contain the unaltered bifilm population from the electrode. The unmelted chunks will be expected to tumble into the center of the liquid pool as a result of its V-shaped profile, keeping the defects away from the more vulnerable edge of the ingot. The final condition is expected to be a far less serious defect than the large planar bifilm cracks expected around the edges, and spreading towards the centers, of VAR ingots.

The resulting unmelted and unrefined regions in ESR are clearly not the fault of the ESR process. They can be totally eliminated by the provision of electrodes cast by counter-gravity, or by improved gravity pouring processes which are now developed and available at negligible additional cost [1, 2]. The provision of correctly cast electrodes would eliminate this minor and unnecessarily potential defect in the ESR material.

Metallurgists may point to freckle defects which are not easily avoided in large ESR ingots, but this author is of the opinion that the main problem with such segregation channels is not so much the segregation (the relatively large change in chemical composition) but the enhanced content of bifilms. Improved electrodes will reduce the bifilm content and render the freckle defects largely harmless.

Naturally, these predicted disadvantages relating to poor electrodes and channel segregates require to be tested, but, essentially, they are second-order considerations merely designed to finesse an already robust and reliable process. ESR, even when carried out sub-optimally as at this time, is still expected to be immensely reliable.

Helicopter Failures

The catastrophic failures of helicopters is difficult to understand in view that drive trains in particular are designed with substantial safety factors (sometimes a factor of 5 stronger than necessary), and has the backup of substantial quantities of fatigue testing to ensure that fatigue lives should never be exceeded during the lifetime of the craft. But failures stubbornly recur. Clearly, there is something profoundly in error with our engineering or metallurgical understanding.

The substantial safety factors commonly arise because if a component fails, the designer assumes it was not sufficiently strong, and makes it stronger – usually thicker and heavier. He never suspects the steel.

The 2012 and 2016 failures listed in Table 1 are classic VAR bifilm consequences [3, 4]. The accident investigation teams of each of these three failures discovered a minute corrosion pit which appeared to have initiated a fatigue crack which in turn led to the catastrophic failure. However, they were unable to understand how such a minute defect could have provided sufficient stress raising ability to initiate the fatigue crack.

This author proposes an alternative explanation. The prior presence of a bifilm crack is to be expected in VAR steel components. Such a crack would permit the ingress of corrodents, probably sea water, to open the entrance to form a corrosion pit. Thus, the corrosion pit is merely the witness of the presence of an underlying, pre-existing crack. The corrosion pit is the consequence not the initiator of the crack. The crack was clearly of sufficient size to initiate the fatigue failure. The presence of large bifilm cracks in VAR material is described elsewhere [1, 5].

The Korean failure is certain to be a VAR bifilm issue, because the weakness of all three rotor shafts were only detectable by the testing of the whole shaft, exactly as would be predicted for the large scale but invisibly thin defects expected in the VAR material.

European Accident Rate

The use of VAR steels for the drive trains of helicopters has led to a number of identifiable catastrophic failures. Some data for Europe is presented in Table 1.

Table 1 indicates, in the 42 years up to 2020, 4 probable VAR failures and 4 definite VAR failures in Europe (including an interesting and important Korean failure linked to Europe, to be discussed below). Because of the incompleteness of the failure information the probable numbers of total failures in Europe due to VAR material is almost certainly larger.

In Europe, therefore, since 1978 at least 1 failure due to VAR material has occurred at approximately every 10 years, with the probable rate being 1 every 5 years, and with the possibility, of course, of the real rate of failures being higher.

However, looking at the rather more complete records over more recent years 2012 to 2020, in the past 8 years the 4 helicopter failures in Europe (including the 1 Korean/Europe case) are *all* attributable to the use of VAR steel, and occur at the average rate of 1 every 2 years. This higher result may reflect better accident recording data over recent years, allowing causes to be identified with greater precision.

The one Korean failure is included because of its highly unusual and important circumstances, linking it to Europe. After the failure of the rotor shaft leading to the loss of the rotor and the fatal crash, the spare rotor shafts supplied by Airbus Europe held in stock by the Koreans were examined. The two spare shafts were both found to be highly defective, failing well below their specified strength. This is a finding of major significance. It is rare for the whole component to be tested, as in this case. Normally, VAR material is tested using some pieces cut from the main ingot. These small samples naturally have a reasonable chance of missing any significant crack, and if they were to fail early because of intersecting a crack, most approved testing specifications allow a second sample to be taken and the first result to be discarded. A test of the whole component is probably rarely carried out. Only such a complete test will guarantee to reveal the extensive VAR defects. In this case the Korean experience revealed the problem in all three of their rotor shafts. This result could not be clearer.

The Korean result is important in additional ways. For instance, there is much obfuscation in the technical literature about the failure mechanism involved. There are elaborate theories about how etch pits can develop, which are assumed to lead to some kind of stress corrosion cracking (SCC), which in turn develops into the final fatigue failure. However, in the case of the Korean spare drive shafts, no corrosion and no stress was experienced by the components. The cracks were already present. They must have originated in the VAR casting process.

Table 1

Year	Flight	Location	Helicopter Type	Fatalities	Fatigue Details
1978	Service flight 165	Norway North Sea	Sikorsky S-61	18	Rotor blade loosened after fatigue of the knuckle joint*
1986	Service flight	Shetland Isles	Chinook	45	Bevel ring gear failure*
2002	Bristow Service flight	North Sea	Eurocopter Super Puma AS332L1	11	Loss of rotor head*
1997	Service flight 451	Norway Norwegian Sea	Eurocopter AS 332L1 Super Puma	12	Multiple fatigue cracks in the Bendix spline which ultimately caused the power transmission shaft to fail and overspeed engine failure*.
2009	Service flight	North Sea	Super Puma	14	Main rotor separation following catastrophic gearbox failure due to fatigue of a planet gear*
2012 May	Service flight	North Sea	Bond Super Puma Eurocopter EC255	0	Gearbox cracks due to corrosion pit.**
2012 October	Service flight	North Sea	Bond Super Puma Eurocopter EC255	0	Gearbox cracks due to corrosion pit in a second stage planet gear.**
2016	Service flight	Norway Coast TurØy	Eurocopter Super Puma EC255	13	Micro-pit in a planet gear causing fatigue of rotor shaft **
2018	Military test	Korea	Marineon MUH-1	5	Fatigue of rotor shaft (1 of 3 faulty shafts from Airbus) **

*Fatigue failures probably attributable to VAR steel. ** Fatigue failures attributable to VAR steel.

Conclusions

1. VAR steels cannot be recommended for use in helicopters.
2. ESR steels are recommended.
3. Enhanced reliability ESR steels can be envisaged if provided with an appropriately cast electrode at negligible additional cost.

References

1. J Campbell 'The Mechanisms of Metallurgical Failure – The Origin of Fracture' 2020 Elsevier, Oxford, UK.

2. J Campbell 'Complete Casting Handbook' 2nd Edition 2015, Elsevier, Oxford, UK.

3. Air Accidents Investigation Branch Report AAR 2/2014 Eurocopter EC225 LP Super Puma, GREDW and Eurocopter EC225 LP Super Puma, GCHCN, 22 October 2012.

4. Report on the air accident near Turøy, Øygarden municipality, Hordaland county, Norway 29 April 2016 with Airbus Helicopters EC 225 LP, LN-OJF, operated by CHC Helikopter Service AS

5. J Campbell; Critical Review of VAR and ESR processes. To be published 2022.