When a Refractory Failure Isn't!- Some Anchor Issues

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ABSTRACT

In a number of instances Operators have refractory failures when the refractory itself is still in operable condition. This happens when a metallic anchor system gives way for various reasons. This paper discusses the possible mechanical causes of such failures, with specific reference to weld defects, and sigma phase embrittlement, with its deleterious effects on the creep strength of various stainless steels and alloys used in their manufacture. Recommendations are made as to the correct criteria for materials selection in these applications.

INTRODUCTION

In many refractory structures, failure occurs, not in the refractory component, but in the steel/alloy anchoring system. This failure can be attributed to numerous mechanisms, including poor choice of steel grade for high temperature strength and corrosion by aggressive species. However, this paper will focus on other issues, specifically welding practice, and mechanical failures attributable to so-called σ-phase embrittlement, which produces a fatigue failure within the anchor after extensive temperature cycling during the campaign life of the refractory lining.

In forensic assessment of refractory failure, the most infuriating is the case where the refractory components do not seem to have been damaged at all. For example, in some instances, high overhanging walls or roofs drop away from their original line, often by up to 50-70mm. This often occurs along the construction joints used during installation. These will normally be on an approximately 1-m grid. Eventually these faults will result in the effected material falling to ground if not rectified, usually by replacement. On examination, it is often found that the fault lies, not with the refractory components of the lining, but with the anchoring systems.

Anchors can fail in a number of ways. The most obvious, is that the weight of refractory was too much for the installed system, for example, too thin and/or at too great a pitch or the material was not adequate for other components of the environment, perhaps containing chloride or sulphurous gases.

Failures also occur with poor welding, in instances when there was an area of poor weld fusion between the anchor base and the vessel shell, or in some cases, no more than a tack weld was instigated before the refractory castable was installed. The most difficult type to predict, however, is the brittle fracture of the anchor in a zone generally between a third and two thirds along the anchor length.

Failures in these areas can be ascribed to various mechanisms, but the most probable is embrittlement caused by the formation, during service, of sigma phase in the steel.

WELDING DEFECTS

It would be very unusual for a refractory castable to be installed without anchors welded to the shell. It is therefore most important for this activity to be conducted in accordance with accepted standards, especially when affixing stainless/alloy steel materials to mild steel. The most obvious problem leading to failure is lack of weld fusion, that is the weld does not fully bond to the parent metals for a sufficiently strong joint. Figure 1 below shows an example of this. Lack of fusion is caused by unclean surfaces (scale, grease or dirt of the surface(s)); electrodes are too small for welding to a thick shell section; insufficient amperage; incorrect electrode angle and manipulation; and rate of travel is too fast, not allowing proper fusion and heat input.

Figure 1: Refractory with anchor showing partial weld fusion

Another common weld defect incurred when fixing anchors to a furnace shell, is lack of weld penetration. Lack of weld penetration is where the weld metal does not penetrate to the root of the joint thereby leaving a gap between the weld and the parent metal. This gap between weld and parent metal reduces the anchors overall bending and fatigue strengths by the introduction of a sharp notch at the transition between the anchor and the shell. Lack of penetration is caused by insufficient amperage; insufficient root gap (ie not large enough to get the electrode into the interface); and too large an electrode size;

There is also the case when the weld procedure has not been completed; perhaps only the initial positioning tack welding has occurred before the installation of the castable. This is illustrated by Figure 2 below. This can occur due to the number of anchors that need to be secured to the wall and is the result poor production or quality control.

For this particular circumstance controls should be inplace to weld-out each joint fully before installing the next anchor or to have a team of two welders working to first tack weld and then weld out each joint. There will still be a need for each anchor to be visually inspected to ensure it has been fully welded out.

Figure 2: V anchor with tack weld only taken from a "failed" castable system

There are a number of other welding defects that can occur when fixing anchors to furnace shells such as slag inclusions, porosity and cracking. All of which can be avoided by the use of proven welding procedures (ie current, voltage, weld preparation, consumable type and size etc) and clean welding surfaces.

EMBRITTLEMENT OF STAINLESS STEELS

EMBRITTLEMENT MECHANISMS

Iron-Chromium based steels are commonly used for high temperature service conditions. Unfortunately, these alloys are also susceptible to embrittlement when held within or cooled slowly through the temperature range 400°C to 980°C. There are in fact two significant embrittlement phenomenon that occur within this temperature range, the first is known as 475°C embrittlement (550°C to 400°C) and the second is known as Sigma (σ) phase embrittlement (565°C to 980°C).

The 475°C embrittlement phenomenon only occurs in ferritic and duplex stainless steels and not with austenitic stainless steels and can be reversed by heating to 675°C or above. Therefore 475°C embrittlement phenomenon is not expected to cause problems for austenitic stainless steel refractory anchor systems.

SIGMA PHASE EMBRITTLEMENT

Sigma phase embrittlement is the result of long term exposure to temperatures in the range 565°C to 850°C, although this temperature range varies with the composition and processing of the stainless steel.

Sigma phase is an Iron-Chromium intermetallic phase that is extremely hard and brittle. The formation of σ-phase is shown clearly in Figure 3, (Chromium - Iron equilibrium diagram).

The band of σ-phase represented in the Cr-Fe equilibrium diagram does not adequately represent the true incidence of σ-phase in commercial alloys. Commercial alloys show a wider range of incidence due to the presence of other elements in the alloy composition that stabilise and promote ferrite formation and hence promote the formation of σ-phase. Sigma phase forms more readily in ferritic than in austenitic stainless steels. Elements such as silicon, molybdenum, and to a lesser degree aluminium, tungsten, vanadium, titanium and niobium all promote ferrite and hence σ-phase formation. Small amounts of nickel and manganese, generally considered to be austenite stabilising elements, promote σ-phase formation. However, large additions of Ni and Mn retard σ-phase formation. Nitrogen, which is now used extensively in the austenitic and duplex stainless steels to stabilise austenite, also helps to retard σ-phase formation. Carbon additions decrease σ-phase formation as the carbon removes some of the chromium out of solid solution through the formation of chromium carbides.

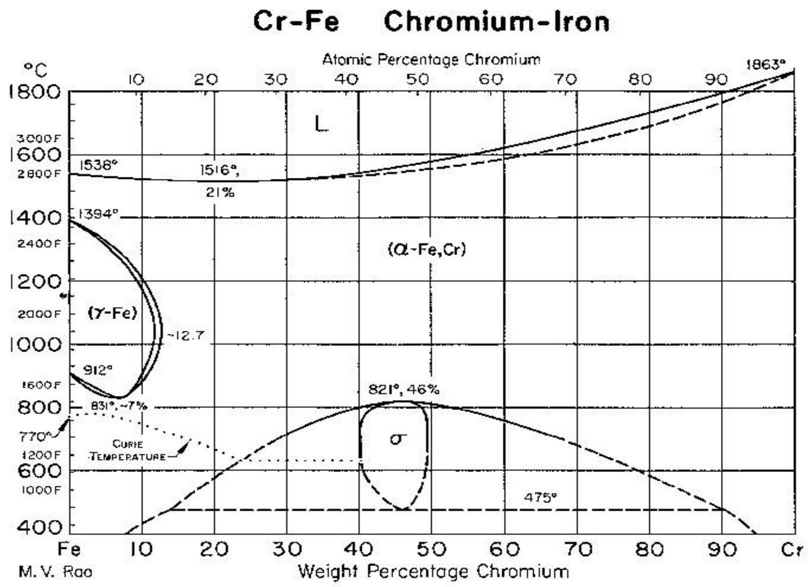

Figure 3: Iron-Chromium Equilibrium phase diagram

Sigma phase is not commonly incurred during manufacture of austenitic stainless steels, as the steels are rapidly quenched through the critical temperature zone thus leaving the austenitic structure. Stainless steels may also form σ-phase during fabrication operations such as welding where the steel is heated into the critical temperature zone and then allowed to cool slowly. The slow cooling through the critical temperature zone allows formation of large volumes of σ-phase.

Sigma phase reduces a steel's toughness, creep resistance and fatigue strength. Although σ-phase is one of the most prevalent embrittlement phase it is not always solely the cause of degradation of properties and therefore each situation must be evaluated to optimise performance.

HOW IS IT RELEVANT TO REFRACTORIES

In a typical refractory lining, there is always a thermal profile between the hot and cold faces. Therefore, there is nearly always a portion of the lining, and any support anchors, exposed to temperatures within the range of sigma phase formation. The illustration below shows a typical lining configuration, and the resulting profile, highlighting the zone in which σ-phase would be expected to form.

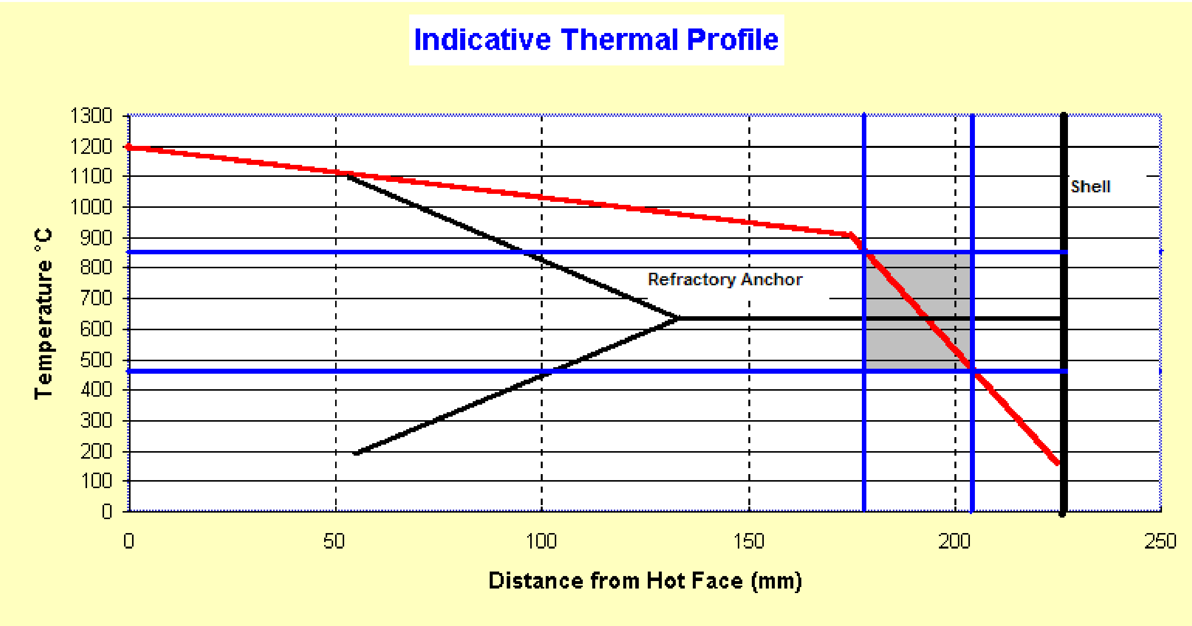

Figure 4: Thermal profile through typical lining, highlighting the critical zone for σ-phase formation.

The size/extent of this zone will vary according to the lining design/configuration

HOW DO YOU AVOID IT?

In many common austenitic steels, it is impossible to avoid the formation of this phase in its entirety. What is possible, however, is to choose a steel or alloy, to minimise the formation of the phase to a level where the effect does not significantly compromise the mechanical properties required by the lining design

One of the tools available to the design engineer for this purpose, is the Schaeffler-De Long diagram, which scans the range of alloys and steel by their Nickel and Chromium equivalents. By plotting these parameters for the common steels/alloys, their susceptibility to σ-phase formation can be assessed to a preliminary degree.

In Figure 5 below, several common steels have been plotted by these parameters. Resistance to σ-phase formation can be assessed by the "*ferrite number*" ascribed to the area of the chart in which the steel is plotted. In general, steels occupying the upper left zone of this diagram can be expected to show better resistance to sigma phase formation.

Specific attributes would include high Nickel equivalents and lower chromium equivalents, whilst remaining in the austenite zone of the diagram.

Small additions of Nitrogen appear to have a significant beneficial effect. Steels within the Austenite only region will have much lower susceptibility than those to the lower right quadrant, where most of the common ‘300’ series stainless steels will be found. It can be seen from this diagram that type 310 (UNS S31000) is largely within the austenitic field, and this is why it is a favoured material for these applications. In this figure the range of values for the steels UNS S31000 and UNS S31008 have been plotted.

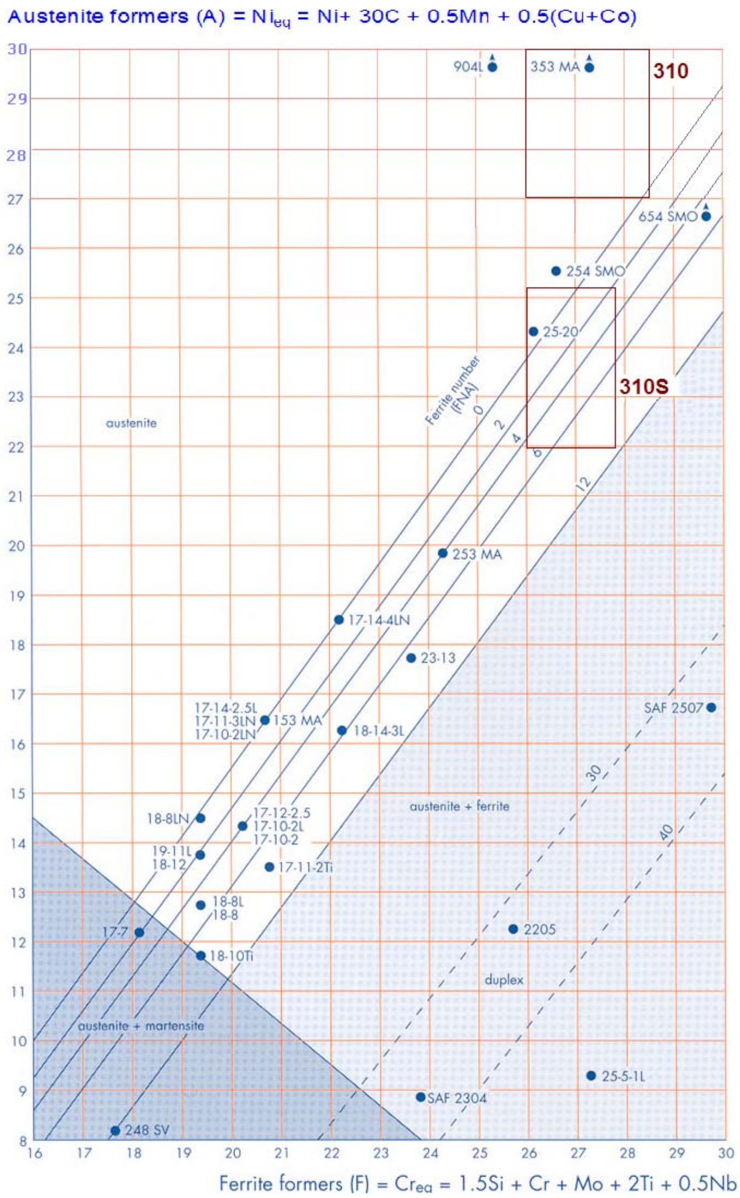

Figure 5: Schaeffler-De Long Diagram

These plots would indicate that 310 is less susceptible than its low Carbon variants 310S/N, which are often preferred for their better weldability properties.

The diagram would also indicate that 310 should also be less susceptible than UNS S30815 (253MA), yet this is not the case. The reason for this is thought to be the level of Nitrogen in the composition of the latter steel, not given adequate weight in the calculations used in the construction of the diagram.

The following table gives qualitative evidence of sigma phase formation after prolonged ageing, equivalent to approximately one years service (9000 hours) and failure for 310, 310S and 253MA steels.

Table 1: Relative Sigma phase formation after prolonged aging

	Test Temperature (°C)	% σ by Volume
253MA	700	3
	800	8
	900	0
310	700	15
	800	14
310S	700	44
	900	24

Source: Sandvik data

This indicates that 310 will form twice the sigma phase as 253MA under similar conditions. The low carbon 310S forms even more, due to the lower level of austenite stabilisation.

Recently there have been a number of newer high temperature alloys developed with higher nickel and chromium contents and stabilised with nitrogen and rare earth elements such as cerium. An example of these alloys includes 353MA (UNS S32315). The newer alloys tend to be more expensive than the 253MA and 310 stainless steels but are very stable at high temperature and from the Schaeffler De-Long diagram it can be seen that 353MA sits well within the austenitic range with a very high nickel equivalent.

OVERLOADING (UNDER DESIGN)

The calculations required to ensure that the size, type and spacing of anchors for a castable installation are not, in themselves, difficult. It is important, however, to make sure the appropriate data is used.

It is often necessary to complete a number of calculations, at different temperatures, particularly when the prevailing temperature predicted within the lining exceeds 800°C, where the mechanical strength of many steels starts to fall markedly.

Table 2 below illustrates the variation with temperature of the creep resistance of many such materials in terms of Stress (in MPa) to cause failure in 10,000 hours at the specified temperature.

Table 2: Creep Resistance of Various Common stainless steels.

Temperature °C	Steel Type 304	309	310	316	321	253MA*
480	-	379	-	-	-	-
540	248	252	223	296	176	-
590	153	169	138	183	171	145
650	95	99	76	112	105	96
700	59	53	48	68	63	60
760	37	30	31	41	39	38
820	23	17	23	26	23	25
850	N/A	N/A	N/A	N/A	N/A	19
900	N/A	N/A	N/A	N/A	N/A	14
950	N/A	N/A	N/A	N/A	N/A	10.5

(*Sources*: AISI Designer's handbook No 9004, *Sandvik commercial brochures.)

CONCLUSIONS

In a large number of instances, refractory systems fail, not because of any problem with the refractory material, but with the anchoring system. This is often related to poor welding in affixing the steel anchors to the vessel or other support wall. This can be eradicated by instigation of correct QA procedures and adequate supervision.

Another potentially significant problem is fatigue failure caused by sigma phase embrittlement. This is an insidious issue, as most anchors will see temperatures in which this phase will form during operation. The only solution is to choose a suitable high temperature steel or alloy, in which the formation of this phase is minimised.

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