

MATERIAL CHARACTERISTICS THAT HAVE THE GREATEST INFLUENCE ON THE SURVIVAL OF REFRACTORY ANCHORAGE SYSTEMS

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ABSTRACT

The fracture of refractory anchorage components is a recurring theme when furnace systems are repaired and replaced. It is often difficult for furnace operators to understand why the components fail. Considerations such as:

- Insufficient expansion/contraction allowance in the design of the anchorages.
- Local anchorage failures inducing excessive stress in adjacent anchors.
- Poor material selection has resulted in a low strength at elevated temperature.
- The presence of high temperature metallurgical phases that are brittle at lower temperatures causing brittle failure during thermal cycling.
- Anchorage component designs that introduce stress concentrations.
- Anchorage component manufacture that introduce stress concentrations.
- Anchorage component installation practices that induce unnecessary stresses in the components.
- Use of temporary weldments to hold anchorages in place during installation operations. These welds dramatically change the material responses of components that may otherwise be well designed and manufactured.
- Setting of specifications for design, manufacture and installation, and the diligence required to ensure compliance are equally critical to any of the physical parameters noted above.

The purpose of this paper is to consolidate the ideas associated with the above material items into a useful design tool that is accessible to all designers and the operators of refractory lined furnace systems.

1 INTRODUCTION

The development of monolithic refractory materials for casting, gunning and shotcreting has changed the speed of application and diversity of geometries that can be protected using refractory materials. Despite the developments in refractory materials, their ultimate success still hinges on metallic anchors. It has become commonplace to find perfectly good refractory material lying on the floor of a furnace after failure of the anchor system. Unfortunately, most of these failures could have been avoided by taking the time during the design of a furnace and thought given to the strength of materials at high temperatures, the strains induced due to thermal effects and the detrimental phases that can form in certain temperature bands.

Furthermore, welding dissimilar metals for ambient service conditions can be difficult enough, but stainless steel and nickel alloy refractory anchors are commonly fixed to carbon steel furnace shells and are expected to survive these harsh conditions. Again, very little thought is given to the design of the welded joint and it is common throughout the industry to simply weld the anchors to the shell without qualified welding procedures.

The design activities associated with furnace refractory installation needs to better consider the role

that the refractory anchor plays in the success of the refractory installation.

2 DESIGN

2.1 Restraint and Complex Stress and Strain Profiles in Anchor Systems

A refractory anchor must support the refractory under a combination of stress conditions. The primary stress is due to the weight of the refractory. Another source of stress includes the relative thermal expansion between the outer shell and the refractory panel sections, which only become relevant as the respective anchor gaps (wire within the anchor lug hole – Figure 1) and refractory construction/expansion joints close and induce high stresses in the anchorage components. The anchor wire and lug components will also have local stress concentration effects due to their specific geometries. The heating and cooling processes also have a significant bearing on the anchorage life and the transient stresses due to heating and cooling conditions must also be determined so that a maximum rate of heating/cooling can be defined for long life operations. The determination of these factors requires detailed finite-element analysis of the system as a whole including the take-up of gaps, and potential for non-linear material behavior because lug bending may become the only mechanism that allows for full refractory expansion.

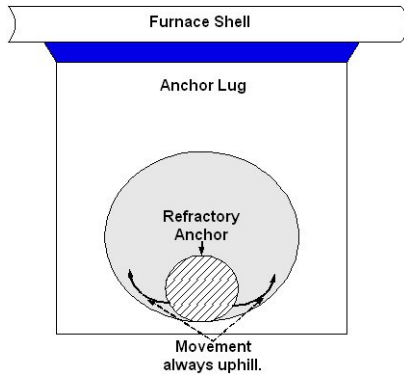


Figure 1: Restraint of a refractory anchor in an anchor lug.

2.2 Material Selection

2.2.1 Basic Principles

At room or moderate temperatures, generally predictable material behaviour over time can be expected. Such are the benefits of operating in the materials elastic range. At high temperatures, however, time dependent creep deformation and/or fatigue loading has to be taken into account. Often at high temperatures the fatigue strength of heat resistant alloys is greater than their creep rupture strength. The principles of designing material applications at elevated temperatures follow the same basic principles of designing applications at moderate temperature; they both must consider material strength and damage tolerance.

The strength of materials at temperature can be tested and quantitative results can be fed directly into the design of an anchor system. The next aspect of the material design is to consider what is happening metallurgically to the material as it is extended to temperatures above $0.6T_m$. The growth of detrimental phases and the segregation of some key alloy components to the grain boundaries of the material need to be considered in the overall material performance appraisal. A further discussion of the incidence of detrimental phases is provided in 2.2.3.

Finally, the corrosivity of the furnace environment needs to be considered. This should consider carburization, sulphidation, oxidation and the effects that trace elements in the atmosphere may have on corrosion resistance of the anchor materials. Trace elements such as the halides can dramatically reduce a materials corrosion resistance.

2.2.2 Creep Rupture Strength

Data for creep rupture is often presented in the form shown in Figure 2. This data is determined using smooth-bar stress rupture tests. In most refractory anchor applications, there are complex stresses and invariably the anchors contain some form of stress

concentration. The smooth bar creep data is therefore considered a good starting point for the design of refractory anchors. However, notched-bar stress rupture tests can provide information regarding a materials defect tolerance and how it will perform in real world applications. It is recommended that when selecting anchor materials that the designer not only considers the creep rupture strength of the material, but the tolerance the material has to creep when damaged

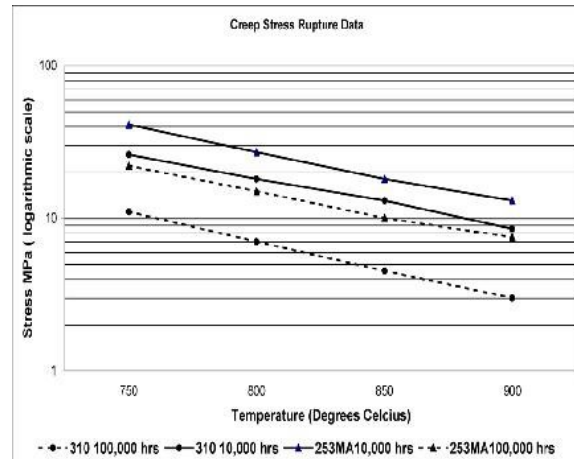


Figure 2: Typical creep stress rupture data for UNS S31000 and UNS S30815 (253MA) (Drawn by author with data from [2] and [3])

2.2.3 Formation of Detrimental Metallurgical Phases

There are a number of phase transformations and metallurgical changes that occur to materials when exposed to elevated temperatures. The most insidious and the one most commonly detrimental to the performance of anchor performance is sigma phase.

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

Sigma phase embrittlement only results in failure of a stainless steel anchor system when it is cooled down. The σ -phase dramatically reduces the low temperature toughness of the stainless steel and during cool down the anchor is exposed large thermal differentials and hence stresses.

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 band of σ -phase represented in the Iron-Chromium equilibrium

(phase) 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 stabilize 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-stabilizing 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 stabilize 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.

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.

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 σ -phase formation. The illustration in Figure 3 shows a typical lining configuration, and the resulting profile, highlighting the zone in which σ -phase would be expected to form. The size and extent of this zone will vary according to the lining design and configuration.

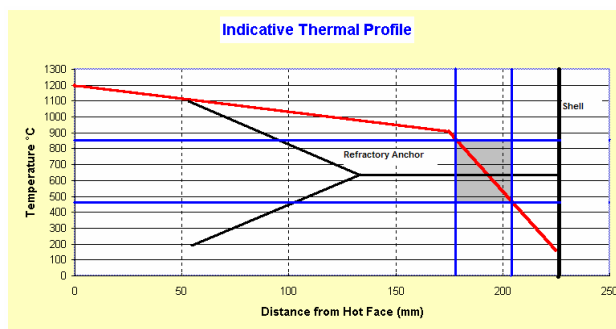


Figure 3: Thermal profile through typical lining, highlighting the critical zone for σ -phase formation. [1]

The designer when considering the selection of materials that are resistant to the formation of σ -phase should first consider the Schaeffler DeLong diagram. A typical example is shown in Figure 4. In general, metals occupying the upper left zone of this diagram can be expected to show better resistance to σ -phase formation. Specific attributes that contribute to improved σ -phase resistance would include high nickel equivalents and lower chromium equivalents, whilst remaining in the austenite zone of the diagram. The designer should be aware that the Schaeffler DeLong diagram does not consider the alloying of stainless steels with nitrogen or rare earths such as cerium. This is demonstrated clearly on the diagram in Figure 4 where the alloys 253MA (UNS 30815) and 353MA (UNS S35315) appear to be more susceptible to σ -phase formation than 310 (UNS S31000). Whereas in practice, the opposite is true, with the 310 based austenitic stainless steels subjected to a larger temperature range where σ -phase is formed.

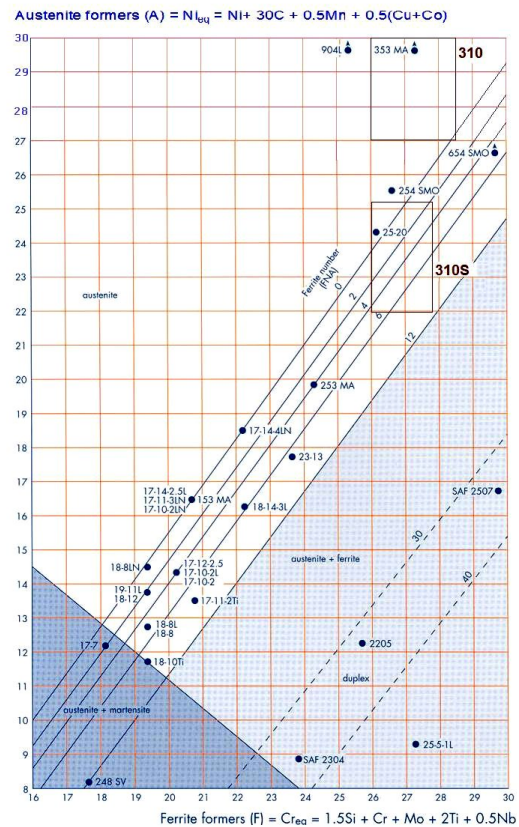


Figure 4: Typical Schaeffler-De Long Diagram [1]

2.3 Anchor Manufacture

Anchors are manufactured from a number of different product forms. Some are made from bar stock whilst others are made using plate/strip products. Refractory anchors are made in large volumes and are therefore formed by mass production techniques. It is for this reason that during the design phase, the designer must consider a refractory anchors tolerance to damage. Most wire/bar type refractory anchors are

cold formed and this will lead to strain hardening of the austenitic type materials. Strain hardening leads to recrystallization of the microstructure. When the service temperature is higher than the recrystallization temperature and the material has been highly strain hardened, a marked loss of creep rupture strength may occur [4].

Cold forming wire anchors can leave deep surface imperfections that can reduce the creep stress rupture strength of a material at high temperatures. Anchors if cold drawn to their final shape must be formed using a lubricant to reduce induced strains and surface damage caused by forming dies. All of these factors need to be considered during design to ensure the material selected for the anchor duties is damage tolerant.

3 INSTALLATION

3.1 Anchor Installation Arrangement

Anchor installation is critical to the longevity of the refractory system. Anchors must be installed so that they are able to behave as the designer intended. In this respect wires that are welded to lug plates (for initial positioning) must be designed to have the weld there and be tolerant of the weld failure when it eventually occurs. Similarly, anchor orientation must reflect the designer's intentions, otherwise large stresses may result and fatigue type cracks may develop at the base of the lug, ie. due to insufficient gap being provided and lug bending that results from unintended expansion take-up or through locking the refractory system up. Correct height setting of the anchor is also important to accurately reflect the design stresses and movements. If the wire is fully submerged in castable, then no movement is possible at the wire-lug connection, and the lug will be subjected to higher temperatures than it was designed for. Refractory anchors are often given room to move but the orientation of the respective anchor placement works to lock the system in place

3.2 Fixing Anchors by Welding

Welding of dissimilar metals for service at room or moderate temperature is quite onerous and the relevant industry standards insist that welding procedures be designed and qualified by testing. Unfortunately, the refractory installation industry often welds heat resistant material anchors to carbon steel shells without a written welding procedure.

A well-designed anchor system should include a welding procedure and that welding procedure must be qualified by testing. Testing of the weld procedure should include mechanical testing, metallographic examination and chemical testing. Chemical testing is critical as it will show the amount of dilution of the weld material and provide an indication of whether or

not the weld material will perform as well in creep as the anchor parent material. Without a qualified welding procedure, the entire design process to get the correct materials in place, ensuring the anchor system stresses are evenly distributed and ensuring the system can move are compromised by poor quality welds.

3.3 Installation Design, Surveillance and Quality Control

Finally, to top off all of the desktop design work that is done at the front end of the project, an equal amount of attention needs to be paid to the installation activities. Installation of refractory anchor systems should be controlled using an inspection and test plan (or quality plan) where the following activities are accounted for:

- Verify anchor materials are the correct material using positive material identification;
- Verify anchor manufacture has not created undue damage to the anchors;
- Ensure qualified welding procedure are in place for welding;
- Non-destructive testing should be planned for a sample on anchor welds;
- Final verification that all anchors have been fixed securely to the shell by complete welds and not just tack welds;

The inspection and test plan should be used to regulate the quality activities that ensure the anchor system is put in place in accordance with the design.

4 CONCLUSIONS

Refractory anchor systems are the most critical part of whether or not a monolithic refractory lining remains in place or falls off exposing the high temperature equipment to damage.

The design process needs to be rigorous and the following critical refractory anchor aspects must be covered:

- Ensure stress and strains are fully accounted for. Look for restraint in the system under thermal loads, don't just design for gravity stresses;
- Ensure the refractory system is capable of moving to normalize any residual stresses and strains;
- Ensure materials are capable of withstanding the stresses at the design temperature, review creep stress rupture data for the materials and consider the use of notched bar creep rupture specimens to better gauge creep ductility;

- Ensure the materials selected for anchors are resistant to the formation of embrittling phases, such as σ -phase.
- Sigma phase is most likely to cause brittle failure mode problems during heating and cooling operations, therefore transient and steady state thermal gradients must be considered in the design of the refractory system and the way that it is operated.
- Ensure the anchor is capable of withstanding the corrosive conditions;
- Ensure the anchor system is defect tolerant. The design process should account for manufacturing defects and specify a tolerance for these defects;
- Ensure welding procedures are designed and qualified by testing.
- Ensure design extends into the installation phase of the project and that inspection and test plans are put in place to regulate the quality activities during installation;

5 REFERENCES

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