The complex behaviour of refractory under thermal load and process conditions poses many challenges for engineers. While the use of thermomechanical analysis assuming either linear elastic conditions or non-linear fracture mechanics bases (brittle/plastic failure behaviour) is valuable, results can still lead to incorrect conclusions. It is a common belief that the use of plastic tips on anchors assists by accommodating differential expansion between the refractory and anchor thus reducing cracking or spalling of the refractory. In a variety of cases where plastic anchors were not used, no evidence was found of cracking induced by longitudinal growth of anchors.

The behaviour of refractory material under stress at low temperatures has not been previously reported. It is shown here that there is a step before high temperature primary and secondary creep known as stress induced shrinkage that occurs in a green refractory under load and temperature, in the range of 150–300 °C. Similar nonlinear creep and shrinkage effects that occur during drying has been found in civil concrete by Picket [8]. This shrinkage/creep deformation is larger than the sum of the individual shrinkage and creep values. The authors show that the magnitude of these effects is sufficient that linear elastic modelling of differential thermal strain cannot be considered valid.

1 Introduction

There is no doubt that the behaviour of refractory structures in processing environments is very complex. Refractory linings must perform at high temperatures and under these conditions these materials exhibit a range of complex phenomena. Industry aims to continually improve refractory reliability and extend runtimes between maintenance stoppages, but in-service degradation of refractory through mechanisms such as dilation, shrinkage and reactions with process constituents make this task difficult.

Improving the reliability of high temperature process equipment requires a different way of thinking and a move away from trial and error approaches. This approach is expensive, takes a long time to assess and outcomes or performance are never clear. More often than not such trials are not successful. Improving refractory lining reliability requires engineering and process knowledge, they are inextricably linked and must be considered at the design stage.

The reliability of alloy anchors in refractory lined vessels is one part of the structure becoming more critical as companies chase greater efficiencies and safety. Therefore, understanding the failure mechanism of alloy steel anchors is key to improve production efficiencies and better safety. The most common anchor failure point is at the interface between the hot face and insulation layer.

Thus in high temperature environments the selection of appropriate anchor material is vitally important for longevity. Equally important is consideration of the load condition that is imposed on the anchor over the time in service.

In the design of static refractory structures, the most common selection parameter for anchoring has been the published metal scaling temperature and the use of linear elastic static analysis for stress calculations. However, such calculations do not satisfactorily predict what happens in situ.

We present an outline of some key factors affecting anchor failure and the reason why plastic covers on anchors are not necessary.

2 Anchor-refractory behaviour

There is still significant debate within the industry about the role of refractory anchors and their contribution to refractory concrete failure.

Published research on anchor failure shows the failure mechanism varies and analysis results are mixed, but many authors believe that anchor/refractory expansion mismatch can result in refractory damage. Early research by Chen et al. [1] used a non-linear transient analysis to evaluate the anchor interactions for a single layer dense refractory lining in a cylindrical duct at 760 °C. In the heating stage, they conclude that the difference in the thermal expansion between the steel anchor and refractory concrete can result in cracking and spalling of the surface. They concluded: 1) if the re-
The term flexible anchor is commonly used and commonly misunderstood. It is generally used to describe a two-piece anchor linked in such a way that one piece moves relative to the other, like a knee joint. This joint sits near the interface of the dense and insulation layer but due to its configuration the point of rotation sits within the dense concrete. Thus, the term flexible is quite misleading; as it implies that the anchor can move somewhat freely with laterally movement of a refractory panel. Given the fact that the anchor “eye” and vee is well above the refractory interface line and encased in dense concrete, combined with alternating anchor layout pattern, it means the anchor base will be stressed by any lateral movement of the hot face. Fig. 1–2 show the effect of lateral refractory movement. In this case the anchor base was displaced and failed.

Another factor which is debated is the benefits of plastic covers on anchors. The basic hypothesis for the use of plastic covers on an anchor is to decrease the stress around the tip under thermal load which is thought to contribute to cracking and failure of the refractory concrete. The stress is believed to develop due to the differences in the thermal expansion coefficient between alloy steel and the refractory concrete. In general, the anchor alloy expansion coefficient is ap-
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approximately twice that of the refractory concrete depending on refractory composition. It is believed that the use of plastic tips on anchors assists by accommodating differential expansion between the refractory and anchor thus reducing cracking or spalling. It has been reported that this practice may reduce the overall holding power and strength of the anchoring system [2]. The authors agree that too much “burn out” coating on the anchor vee section, particularly straight vees, in the hot face can reduce the ability of the anchor to hold the hot face in place at operating temperature.

Published literature uses a linear elastic approach despite its limitations. Due to the calculated stresses it is thought that coating the anchor tip with a plastic cover can reduce the “pushing” effect of the anchor [1]. This is not illogical, because the thermal coefficient mismatch between the anchor and the refractory materials can induce thermal stresses in the refractory under thermal load.

Recent work [3] presented a linear elastic analysis for a 16 mm diameter anchor encased in a cylinder of concrete. The results show both hoop and radial stresses develop due to the thermal expansion difference far exceed the concrete strength in both tension and compression for a zone of 10 mm to 20 mm around the anchor and “null values are only reached at distance close to half the anchor spacing (150 mm)”. This would cause severe damage to the refractory and would be visible on inspection. In their case it was concluded that “too short anchor spacing can also lead to an interaction between the thermal stresses, which may increase the likelihood of crack generation”.

If the anchor and refractory concrete are in intimate contact, which is true assuming no quality defects, then as the concrete (hot face layer) is heated a number of process converge. The strain in this region is quite linear up to a temperature of approximately 120 °C [11]. Thus at the anchor tip, the steel will start to expand radially outwards as will the refractory. As the anchor expansion coefficient is greater than the refractory it will expand into the concrete resulting in a small tensile hoop stress and radial compressive stress in the concrete adjacent to the anchor. Using linear elastic analysis at this temperature it can be shown that the refractory’s tensile and compressive strength would be exceeded. The axial anchor strain at that stage will still be very small due to the low average temperature with thickness. As the temperature increases the radial stress will increase significantly and cause localized damage unless the stress is relieved by some other mechanism.

Fig. 3 shows the layout and steady state temperature profile for a “flexible” anchor in an isotropic two-layer refractory system. Three temperature lines in the thickness are presented. At the corner far away from the anchor, vertically adjacent to the anchor centre and inclined parallel to the anchor vee.

The results are shown in Fig. 4. In this case the hot face is 145 mm and an insulation layer is 80 mm. The steady state hot face temperature is 1000 °C, the shell ambient temperature is 25 °C and the shell convection coefficient is 20 W/m²-K. The results show the effect of the anchor thermal conductivity and the heat flux increases the shell temperature at the base by ~30 °C. Near the heated surface the temperature of the refractory and the anchor converge.

The anchor base acts as a heat bridge causing a localized cooling effect of the refractory hot face. The resultant nonlinearity within the lining plane induces local tensile stress and hoop compressive stress in the far-field. This mechanism was discussed in [1], where it was found that induces stresses peaked at the anchor tip in one-shot dense linings. The authors results find that, in two layer linings, the effect is largest at the hot face insulation interface. Due to an increased cross-section, the heat bridging effect of the anchor base in a “flexible” anchor exceeds that of a typical Y anchor.

In order to evaluate the damage of the refractory around the anchor tip zones and the condition of the anchor tip itself, site samples have been inspected. Fig. 5 shows the condition of the anchor tip and surrounding refractory concrete. In each case the hot face was the same material. Inspection using a loupe found no significant refractory damage, shear cracks or pop-outs in the hot face, when plastic covers were used or not used. However, metallurgical analysis of the anchor with a plastic tip found significantly degradation of the anchor metal occurs in an oxidizing environment. Fig. 6 shows the different level of oxidation corrosion that can occur to the tip. Thus, inspection of numerous refractories with and without plastic tips on the anchors has found little visual evidence of damage to the refractory concrete due to differential expansion. If plastic covers on anchors were critical in preventing refractory damage, then it should be possible to visually detect damage when they are not used. In instances where plastic covers are not used on anchors we have not detected any detrimental damage to the castable concrete. Fig. 7 shows a closer view of an anchor without a plastic cover, embedded in the dense hot face castable. Visual inspection did not detect any gap around the anchor at the tip or the stem. This is in-line with many other observations we have made of the years.

It also seems reasonable, if thermal expansion mismatch always occurred then it seems reasonable to expect a predominance of hot face spalling in-line with the anchor tips. As much as we have tried, we have not been able to establish this relationship over the years.
The physical evidence shows that not using plastic tips on anchors does not cause spalling of refractory concrete due to differences in material thermal expansion and the existence of a gap between the refractory. The visual evidence also shows the use of plastic tips will increase the oxidization/carburization of the anchor tip in high temperature areas.

Also, with respect to anchor/refractory concrete behaviour, particularly material thermal mismatch, the theory does not match physical site observations. There are many instances where it has been observed that anchors without plastic tips are not used and there is no wholesale or even minor damage or failure of the refractory. The majority of the refractory damage we have observed near anchors is due to thermal transients or reactions with process constituents.

What has been overlooked is the differences between the green\(^2\) and fired\(^3\) refractory states when loaded in compression or tension. It is the anisotropic nature of a green concrete that causes the material to creep when loaded. Shrinkage also occurs during the drying stages which occurs due to stress balance between capillary tension and surface tension in the pores. Thus, during a stressed drying stage it is impossible to separate drying and creep.

The difficulty that engineers face is due to the complexities of refractory under thermal load and process conditions. While the use of thermomechanical analysis assuming either linear elastic conditions (brittle behaviour) or nonlinear fracture mechanics bases (plastic behaviour) is valuable, results can still lead to incorrect conclusions.

3 Refractory castable behaviour with embedded anchors

It has been known that refractory lined vessels like secondary reformers and gasifiers which are lined with unfired\(^4\) high alumina dense castable monolithic linings, without any expansion joints, in compression do not catastrophically fail. While prefired dense refractory rings can fail catastrophi-
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cally when heated [4]. Using a thermal linear elastic analysis, the stresses developed far exceed the material’s tensile strength even at a very low temperature. Thus, there must be a material state, apart from elastic strain and shrinkage (PLC) that absorbs the stress developed by thermal strain.

Refactoriness Under Load (RUL) test is a good method for testing a material’s behaviour in a constrained state as opposed to an unconstrained state (dilatometry). The constrained state better represents what happens in the case of constrained refractory lining.

Using a RUL test it can be shown that green castable refractory behaves in a plastic manner when loaded in uniaxial compression under increasing temperature and testing further shows that dense refractory concrete behaves very differently between the green and fired state. By green it is meant that the material has cured but has not yet been dried or fired [5]. Bray [6] tested a number of castables which had been unfired and prefired at 1425 °C to establish the primary creep curves. Their procedure indicates the samples were soaked for 5–10 h before being loaded. The test results show the non-fired castable has a significantly larger primary and total creep compared to the fired sample. No explanation was offered as to the change in the creep between the unfired and fired samples, however, it indicates the non-fired sample can deform under load and temperature significantly more than when it is fired. Bray et al. [7] reported that creep on a high (90 %) alumina refractory concrete over the range of 538–1204 °C for loads of 6.9 MPa and 13.8 MPa (heated to temperature and soaked for 5–10 h) then loaded. The results for the low temperature samples show a very little deformation and it is not until the sample has been heated to greater than 1100 °C that deformation increases. They concluded refractory concrete exhibited normal creep behaviour consisting of a primary and a steady-state region. It was also concluded that creep, specifically during the initial application of stress or temperature, is attributed to changes in the microstructure of the refractory concrete due to the combination of stress and temperature.

However, the behaviour of refractory material under stress at low temperatures has not been previously reported. It can be shown that there is a step before high temperature primary and secondary creep that occurs in a green refractory under load and temperature, typically in the range of 150–300 °C. Similar, nonlinear effects of creep and shrinkage during drying has been found in civil concrete and is referred to as the Pickett effect [8–10]. The experimental facts are that there is an acceleration of compression creep, including bending and shear. In civil concrete the shrinkage/creep deformation is larger than the sum of the individual shrinkage and creep values. A similar relation in refractory concrete is expected.

The Pickett effect is a component of creep that is not observed unless the concrete is exposed to drying conditions while under sustained load, resulting in the apparent drying creep exceeding the sum of the separate basic creep and shrinkage effects. For a constrained structure under elevated temperature conditions (e.g. a containment structure), the total deformation of concrete is due to simultaneous actions of loading and drying (Pickett effect), stress induced thermal strain and hydro-thermal strain called Loading Induced-Thermal Strain (LITS) [11]. This research found the sustained load of 30 % of the compressive strength f’c, was enough to totally suppress free thermal expansion and cause shrinkage (Fig. 8). In the authors’ study, a 1600 grade refractory concrete sample was prepared under laboratory conditions according to the manufacturer’s recommendations. The green sample was tested for dilation and RUL and the results for strain vs. temperature and the derivative of normalized strain are plotted in Fig. 9–10, respectively.

The unconstrained sample shows an initial shrinkage zone starting at approx. 160 °C and finishing at approx. 320 °C. The shrinkage is due to dehydration of cementitious hydrates, CAH₉, C₆AH₈, ADH, and C₃AH₆ and removal of capillary pore water. The second zone starts at approx. 800 °C where shrinkage due to sintering out paces thermal expansion. This stops at approx. 1100 °C, and typical thermal expansion resumes.

The sample is also simultaneously loaded in compression at 0.069 MPa, 0.35 MPa and 2 MPa, respectively, while heated. The applied stresses were lower than that used in the civil concrete case due to limitations of the equipment.

For the refractory material, the results show there is little stress sensitivity during initial heating but the derivative graph shows the rate of thermal expansion is approximately constant until 125 °C to 130 °C, after which the dilation gradual transitions to shrinkage. The difference in the peak for the unloaded sample is due to settling of the sample in the test rig. The derivative curve also shows the temperature at which the peak strain value occurs decreases with increasing load. It is further shown the extent the material will creep and shrink in the dehydration zone increase with compressive load, but is finished at 300 °C. From this point, the material starts to thermal expand again at about the same rate and independently of load. The inflection at 574 °C correlates with quartz α => β inversion. From this point to approx. 750 °C the rate of expansion is decreasing almost independently of load. At approx 770 °C there is a second transition to shrinkage, with a high degree of temperature and load sensitivity. This temperature range coincides with the onset of sintering.

While there is a difference between the refractory and civil concretes due to the different cement hydrates the same behaviour is seen to occur, i.e. as the uniaxial compressive force increases with heating, the sum of dilation effects in the 150–300 °C region decreases.

It is concluded that a green refractory concrete has a shrinkage/creep state in the temperature range of approx. 150–300 °C where a material’s linear thermal expansion during heating is not followed. If the “green” concrete is under compression, during heating, and the level of compression is high enough then the material at that location can have a ~ve strain value. It is concluded that a linear elastic region is only applicable up to a temperature of approx. 150 °C. It is further concluded, that if a refractory concrete is in compression due to no expansion joints or in the case of alloy anchors embedded in the concrete, then linear elastic analysis will over predict the strain and stress state.  

5) Low stress tests by CSIRO. A special acknowledgment to Orton Laboratory USA for collaborating and performing the RUL test at 2 MPa.
4 Conclusions

It is known that the behaviour of refractory in process conditions is very complex but with advances in material science and engineering techniques it is possible to make significant improvements in refractory design and reliability.

It has been found that the physical evidence does not support the theory that anchors without plastic covers cause premature failure of the refractory concrete. The reason why an anchor without a plastic tip does not cause refractory failure, is due to loading-induced thermal strain.

Refractory when loaded in compression in the temperature range of approx. 150–300 °C does not expand in a linear elastic manner following the material’s thermal expansion coefficient, but expands non-linearly and if the compressive stress is large then shrink will occur.

It has also been found that a plastic cover is more likely to cause oxidation of the anchor tip. When selecting anchor alloy material, failure under creep rupture must be taken into account. Selecting an anchor material due to sigma phase formation only is likely to cause decrease refractory reliability.

It is concluded that using simple linear elastic analysis will always predict material failure when in practice failure due to the analysis doesn’t occur. Using traditional or historical approaches in the design or maintenance phase, in our opinion, is more likely to result in a lining that under performs or prematurely fails.

References

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