The thermal contact resistance of a steel-ceramic interface with oxide intermediates

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Abstract: Metal structures covered by refractories are widely employed in high temperature processes such as incineration and metal production. The thermal resistance in refractories used in high temperature processes is associated with different phases, phase boundaries and porosity in the refractory and with the thermal contact resistance between the refractory and the metal interface. Here, a light flash method was used to evaluate the thermal contact resistance of the ceramic/steel interface at temperatures of 25, 100, 200, 300 and 400 °C. The material combinations studied were a commonly-used reference ceramic, Pyroceram 9606, and pressure vessel steel with oxidizing treatment at 450 and 650 °C for 50 h. Thermal resistance at a ceramic/steel interface increased significantly when a porous oxide layer was formed on the steel surface. The thermal contact resistance of the interface varied from 0.1 to 0.4 × 10^{-3} m^2K/W, depending on the temperature and the oxidation of the steel sample.

Subjects: High temperature processes; Incineration; Refractories

Keywords: refractory; oxidation; thermal contact resistance; light flash; heat conduction

1. Introduction

In heavy industrial processes such as power generation and metal refining, the construction materials have to withstand extremely high temperatures. Both ceramic and metal materials are needed for some applications; ceramic for their high maximum service temperature and metals for their malleability in structural parts such as tubing, fins and other load-bearing structures. Since...
these structures contain metal/ceramic interfaces, it is important to know the thermal resistance of the materials and material combinations when subjected to thermal gradients.

There are a vast number of engineering applications where heat is transferred through different interfaces. The materials in contact at the interface can be metal, polymer or ceramic, and they can be powder, granular or solid. In high-temperature applications, refractories are used at the hot end of the process to preserve the functionality of the construction metals and to prevent the structure from melting. Refractory castables are common lining materials in this kind of application.

For insulating purposes, it is clearly beneficial if the thermal conductivity of the material is as low as possible. This can be accomplished by incorporating a large amount of air with low thermal conductivity into the material, i.e. increasing its porosity. Additionally, by increasing the phase boundaries in a multi-granular material such as a refractory castable, the thermal resistance of the material increases, and therefore its effective thermal conductivity decreases. (Smith et al., 2003) Similarly, in installations containing different layers and interfaces, such as refractory/metal joints, thermal resistance is increased because of the thermal contact resistance between the layers. The thermal contact resistance in various applications has been under intensive studies recently. (Dhuley, 2019; Liu, Ma, Wang, Wang, & Yang, 2019; Lorenzini et al., 2017; Ngo, Byon, & Lee, 2018; Xian, Zhang, Zhai, Yuan, & Yang, 2018; Dongmei, Huanxin, Shanjian, & Limei, 2017).

The heat transfer in bulk material can be expressed generally by Fourier’s law of heat conduction (Mills, 1999)

\[ Q = -k \frac{dT}{dx} \]  
(Equation 1)

Where \( Q \) is the heat flux (W/m²), \( k \) the thermal conductivity (W/mK) and \( \frac{dT}{dx} \) the thermal gradient in the material.

Thermal conductivity \( (k) \) can be expressed as,

\[ k = \alpha c_p(T) \rho(T) \]  
(Equation 2)

where \( \alpha \) represents thermal diffusivity (m²/s), \( c_p(T) \) is the specific heat (J/kgK), and \( \rho(T) \) is the density (kg/m³). In single-phase ceramic materials, thermal conductivity typically decreases as the temperature increases. This is due to the restricted free mean path of the phonons, which are the main heat transport medium in ceramics. (Richerson, 2006) In metallic materials, however, there is also electron conductivity which is responsible for metals’ good thermal conduction properties. (Callister, 2011)

In a multi-granular or layered material, there is a specific thermal resistance involved at each grain boundary or interface along the heat flux. The temperature profile in bulk material of length, \( l \), without interfaces (Figure 1(a)), and with interfaces (Figure 1(b)), is shown schematically in Figure 1.

Consequently, case b) can be interpreted as a situation where two materials with different thermal conductivities are in close contact with each other and the temperature drop, located in the vicinity of the joint, is a measure of the contact quality itself. In a material with lower thermal

Figure 1. Temperature profile in a single-phase homogeneous material without (a) and with (b) interfaces. \( T_{1,1} = T_{1,2} > T_{2,1} > T_{2,2} \).
conductivity, the slope of the temperature curve would be steeper. A thin layer of a third material, such as metal oxide, can also be introduced at the joint, in which case there are two contact resistances at the joint plus the thermal resistance of the oxide layer.

If one part of the interface is a metal, the surface can be oxidized at an elevated temperature and a somewhat porous interlayer is formed perpendicular to the heat flux causing thermal resistance, which can be measured from the apparently lower thermal conductivity of the layered structure. Thermal resistance in a layered material \( R, m^2K/W \) can be expressed as:

\[
R = \sum \frac{l_i}{k_i} + \sum R_{c,i,i+1} \quad \text{(Equation 3)}
\]

where \( l_i \) is the length of material in the direction of the heat flux and \( k_i \) the thermal conductivity of the material. \( R_{c,i,i+1} \) is the thermal contact resistance between the materials. (Mills, 1999) Thermal contact resistance is associated with all granular-type materials such as ceramics and refractory castables. Ceramics typically contain grain boundaries, porosity and different phases, all of which increase the thermal resistance of the material and thus decrease its effective thermal conductivity. (Smith et al., 2003; Yang, Bai, Thompson, & Eastman, 2002)

In practical applications, thermal expansion mismatch can cause unexpected gaps between the layers in a construction and thus increase the thermal resistance in the vicinity of the joint. Thermal contact resistance is highly dependent on the quality of the contact, such as the roughness and flatness of the opposing surfaces. Refractory castables are typically cast on top of their metal counterpart, thus adopting the shape of the metal, so the contact between a castable and its metal counterpart is initially good.

Metal oxidation can play an important role in increasing the thermal resistance of a joint at elevated temperatures. In an oxidizing atmosphere, as the temperature starts to rise, an oxide layer begins to build up on the metal surface. The thermal conductivity of an iron oxide is typically significantly lower than the steel from which it is formed. However, at moderate service temperatures the layer of oxide is often only a few micrometers thick, and therefore the resistance of the layer itself is quite low. (Cooper, Yovanovich, & M, 1969) At high temperatures, on the other hand, the oxide layer can be tens of micrometers thick and may be composed of many different layers and phases. (Zambrana, Coronado, & Rodríguez, 2015) In this case, the different layers each form their own thermal resistance, and thermal contact resistance between the layers. Additionally, oxidization increases the surface roughness of the metal, which decreases the true heat-conducting contact area, especially if the roughened oxidized surface is in contact with a smooth surface.

When two surfaces are in contact, there are three ways in which the heat is transferred through the interface: conduction through contact spots, conduction through an interstitial gas medium (air), and radiation. Convective heat transfer is typically regarded as being non-existent in micrometer-sized voids. As the temperature rises, the radiative heat transfer increases since it is proportional to the fourth power of the absolute temperature. However, radiative heat transfer is typically neglected below 300 °C and if the temperature difference across the interface is small. (Cooper et al., 1969)

Past research has thrown up a variety of techniques for measuring the heat transfer properties of materials. These include guarded hot plate, hot wire, hot disk and light flash techniques. (Reif-Acherman, 2014) One of these methods, the light flash technique, is a transient technique where the radiation energy is used to heat up the sample material while the temperature increment as a function of time is recorded from the opposite side of the sample. This method has been used for measuring the thermal diffusivity of various materials including metals, polymers and ceramics. (Gaal, Thermitus, & Stroe, 2004; Hay, Filtz, Hameury, & Rongione, 2005; Min, Blumm, & Lindemann,
The light flash technique has also been used to determine thermal properties, i.e. the thermal diffusivity, specific heat capacity and the thermal conductivity of layered composite materials. In these applications, the contact between the layers has been seamless. (Cooper et al., 1969; Casalegno et al., 2010; Absi, Smith, Nait-Ali, Grandjean, & Berjonnaux, 2005) This technique can also be used to measure the thermal diffusivities of various materials, including solids, pastes and melts.

The way it works is that radiation from a Xenon flash is directed on to the graphitized surface of the measured sample, and the temperature rise detected on the other side of the sample is recorded. Thermal diffusivity can then be calculated according to Parker’s original equation (Gaal et al., 2004):

$$\alpha = 1.388 \frac{d^2}{t_{1/2}}$$  \hspace{1cm} (Equation 4)

where $d$ is the sample thickness and $t_{1/2}$ is the time for 50 % of the total rise in temperature. In this model, the heat transfer through the sample is assumed to be so quick that no temperature increase occurs at the edges, which could cause thermal losses. Cowan [12] among others has since introduced other mathematical models that take radiative losses into account.

The light flash method can be used for two layers of material to find their thermal diffusivity and consequent thermal conductivity of an unknown layer. In this approach, the thermal contact resistance between the known and unknown layer is included in the calculation. In this way, the layered sample can also be treated as a single solid material in order to measure its thermal diffusivity and thermal conductivity. This was the approach used in our study as it can be used to evaluate thermal contact resistance when measuring materials either individually, or as a stacked freestanding installation.

The purpose of our experiments was to evaluate the thermal contact resistance of a steel/ceramic interface by first measuring the thermal diffusivity of the individual steel and ceramic samples, and then measuring the diffusivity of free-standing stacked steel/ceramic samples. We then calculated the thermal conductivities of the samples using Equation 2. Once the thermal resistance of the individual and stacked samples had been calculated, Equation 3 was used to evaluate the thermal contact resistance. In power generation processes, the temperature at the interface between the metal tubing and its refractory lining is about 400 °C, so our measurements were taken at temperatures of 25, 100, 200, 300 and 400 °C.

2. Experimental procedure

2.1. Materials

The samples used in the experiments were commonly-used materials, i.e. pressure vessel steel, A387 grade 11, and a high temperature ceramic, Pyroceram 9606. The samples were 25.4 mm in diameter and 1–2 mm thick.

The specification for chrome molybdenum pressure vessel steel according to ASTM standard product analysis (A387 grade 11) is shown in Table 1. (Standard, 2000) This grade is designed for high temperature processes such as power generation boilers and it is classed as a low carbon steel with moderate alloying.

| Element | C (%) | Mn (%) | P (%) | S (%) | Si (%) | Cr (%) | Mo (%) |
|---------|-------|--------|-------|-------|--------|--------|--------|
| Amount  | 0.04–0.17 | 0.35–0.73 | 0.025 | 0.025 | 0.44–0.86 | 0.94–1.56 | 0.40–0.70 |
A common glass ceramic, Pyroceram 9606 (Corning Inc.) (denoted as PC) round plate (25.4x1 mm) was utilized as the ceramic counterpart. This is a commonly-used reference material consisting mainly of silica-based ceramic with some refractory oxides of aluminum, magnesium and titanium. (Salmon & Tye, 2010) Its thermal conductivity at room temperature is 3.8 W/mK. PC has long been known as a good reference material for thermal diffusivity measurements. It was used in this study because of its homogeneous microstructure, smooth surface and well-researched thermal properties. (Assael, Antoniadis, Kakosimos, & Metaxa, 2008) The heat transfer properties of PC are in the same order as those of low cement castables, which are commonly used in refractories.

The steel samples were given different surface treatments in order to evaluate how much the quality of the surface affects the heat transfer across the joint. Before oxidation the metal surfaces were polished with 320-grade abrasive grit paper. Some of the samples were then oxidized in a Lenton chamber furnace at temperatures of 450°C and 650°C for 50 h. The thickness of the formed oxide layer was measured visually using Leica DM 2500 M optical microscopy. The surface topography of all the samples was characterized using the Wyko NT1110 optical profiling system. This was used to measure the roughness average (Ra), the root mean squared roughness (Rq) and the maximum profile height (Rt) of the polished and oxidized steel and Pyroceram 9606 samples. Also a 3D plot of the surface topography was created. It was difficult to analyse the oxidized surfaces because of the poor contrast, so a thin layer of gold was sputtered over the top of all the oxidized samples. In the stacked PC/oxidized steel samples, there were actually two boundaries, PC/oxide and oxide/steel. The heat transfer was expected to be mainly determined by the number of contact points between the samples, and the amount of interfacial porosity. Therefore, the true contact area was only a small fraction of the theoretical contact area for the samples. In the study of stacked samples with an oxidized layer in the middle, three different samples were measured and their median value was reported in the results. The corresponding steel sample surfaces were also studied further to find out the effect of surface quality on thermal contact resistance.

2.2. Methods

The thermal diffusivities were measured with Netzsch LFA 467 light flash equipment with a gentle flow of N\textsubscript{2} as a purging gas. The thermal diffusivities were calculated using the Cowan+ pulse correction model, this model being the recommended one for the equipment software.

The principle of this method and the stacked sample set-up is shown in Figure 2. The samples were spherical disks with a 25.4 mm diameter and were originally manufactured to a thickness of 1 mm for the PC, and 2 mm the A 387 GR 11 steel. The samples were heated with a Xenon lamp and the speed at which the heat was dissipated through the sample was dependent on the material’s thermal diffusivity.
The measurements were obtained by first measuring the steel and PC samples individually, and then as stacked free-standing samples. The steel samples were then given oxidization treatment in order to find out the effect of the oxidation layer on the thermal contact resistance. Three shots of irradiation (duration 0.3 ms) were focused on the sample with a spot diameter of 17.8 mm, which was 70 % of the sample area. An MCT (HgCdTe) infrared sensor was used to detect the temperature increase, which was calculated using a linear baseline and reported as the median value of the three shots.

As explained above, the stacked sample was regarded as a single layer for the thermal diffusivity measurements. Before taking the measurements, a thin graphite layer was applied to both sides of the sample disk in order to replicate the behavior of a black surface under irradiation. The stacked sample was prepared so that one side of the PC and steel was coated with graphite while the other side remained uncoated. Then the PC was placed in a spherical sample holder and the steel sample was placed on top so that the polished or oxidized surface was against the surface of the PC. In this way, different contact situations were obtained between the ceramic and steel sample disks. No external force except gravity was exerted on the interface. The surface quality, oxide thickness/uniformity and consequently the number of contact points were expected to affect the measured thermal diffusivities.

When the thermal diffusivities were measured, it was possible to calculate the thermal conductivities and thermal resistances of the measured samples and consequently the thermal contact resistance between the steel and PC samples. The material density capacities that were needed to perform these calculations were taken from the tabulated values for steel, 7.85 g/cm³, and PC, 2.602 g/cm³. The specific heat capacities were measured at the same time as the thermal diffusivities for both the steel and PC at all temperatures using an alumina reference sample with known thermal properties.

The surface topography of the samples was studied with a Wyko NT1110 interferometric microscope to evaluate the contact quality between the steel and ceramic counterparts. Median filtering was used to analyze the measured data with a window size of three. The measured surface parameters were: roughness average (Ra), root mean squared roughness (Rq), and maximum profile height (Rt). The consistency of the surface curvature was also evaluated using a bearing ratio Htp curve with a peak offset of 5 % and a valley offset of 90 %. The Htp bearing ratio value therefore describes the average height between two planes when 5 % of the highest peaks and 10 % of the lowest valleys have been excluded.

3. Results and discussion
The steel samples were oxidized at temperatures of 450 °C and 650 °C for 50 h in an ambient atmosphere. After this heat treatment, the oxide layers visually observed were 2 µm and 50 µm thick respectively, as measured from the cross-sectional optical image, Figure 3.
The microstructure of the Fe oxide layer was lamellar and porous. The oxide layers in both samples (450 and 650 °C) were detached from the steel surface. The porosity and lamellar nature of the layer was clearly visible, especially in the thicker oxide layer formed at 650 °C (Figure 3(b)). Due to the different thermal expansion behaviors of Fe oxide and steel, the lamellar structure could also have been formed during the cooling stage. Lamellar structure can increase thermal resistance over oxide layer. The elemental composition of oxide layers was studied by EDS analysis. This analysis showed elements of Fe, Cr, Mn and Si, and increasing oxygen content when approaching the outer edge of the oxide layer.

In thermal diffusivity measurements, it is important that the surfaces on both sides of the sample are in parallel. In practice, the topography of these surfaces will typically have some features that are inherited from the material processing, or occurred during installation. In the stacked samples, the contacting area was expected to be only a fraction of the total apparent surface area and the heat flux is assumed to flow mainly through the contact points of the surfaces. The gaps between the contact points were filled by fluid, in this case gaseous N₂. The main heat transfer mechanisms were, therefore, conduction through the contact points and the interstitial fluid.

The thermal diffusivity measurements were conducted at temperatures of 25, 100, 200, 300 and 400 °C. The given result for each sample are the averages of three individual shots of irradiation that were directed on to the sample surface from below, and the three temperature increments detected from above. The shot parameters for each sample were iterated using the equipment software. The detector signal was recorded as a function of the time and the half time \( t_{1/2} \) in eq. 4 of the total temperature increment calculated from these results. In the measuring device utilized “the calculation range should be approximately 10–12 x half times and optimal duration of measurement 100–30,000 milliseconds”. These requirements were all met in our experiments.

The thermal diffusivities of the measured samples are shown in Figure 4. The samples are denoted as follows: Steel (pressure vessel steel A387), PC (Pyroceram 9606), Steel/PC (Steel A387 and Pyroceram 9606 freestanding stacked combination), Steel 450 C/PC (Steel A387 and Pyroceram 9606 freestanding stacked combination with prior oxidation of steel for 50 h at 450 °C) and Steel 650 C/PC (Steel A387 and Pyroceram 9606 freestanding stacked combination with prior oxidation of steel for 50 h at 650 °C).

The thermal diffusivities of the stacked samples fell as the thickness of the oxide layer increased. When the steel was oxidized at 450 °C, the oxide layer was only 2 µm thick. However, the oxide layer had a rough surface which seemed to decrease the true contact area between the surfaces and ‘pushed’ the PC and steel surfaces further apart. As for the sample which was oxidized at 650 °C, this
contained internal porosity and lamellas (Figure 3(b)) which lowered the thermal diffusivity even further because of the amount of air in the pores and between the lamellas. In our experiments, the contact pressure between the surfaces was exerted by gravity compression, which was only 155 Pa. A higher contact pressure would probably have increased the true contact area by flattening some of the oxide peaks, particularly in the samples with the thicker oxide layer. This could increase the thermal diffusivity of stacked samples with oxide intermediates.

For stacked samples with the same diameter, the density and specific heat capacity were determined by calculating the average value, as follows:

\[
x = \frac{y_{pc}d_{pc} + y_{st}d_{st}}{d_{pc} + d_{st}}
\]

(Equation 5)

Where \( y_{pc} \) and \( y_{st} \) are the specific heat capacity and density of Pyroceram 9606 and steel respectively, and \( d_{pc} \) and \( d_{st} \) are the samples’ respective thicknesses. The subscripts \( pc \) and \( st \) refer to Pyroceram and steel A387 gr 11, respectively. In this approach, the density and specific heat capacity of the thin oxide layer on the steel were neglected.

The thermal conductivities of the samples are shown in Figure 5. In the stacked samples, the thermal conductivity at room temperature in the non-oxidized sample was 10 W/mK. This value fell to 5.7 W/mK and 2 W/mK when the steel was oxidized at 450 °C and 650 °C for 50 h, respectively. This decrease is due to the higher thermal contact resistance between steel and PC when there is an oxide layer between the samples.

Once the thermal conductivities of the individual and stacked samples had been calculated, it was possible to evaluate their thermal resistances, from which the thermal contact resistance of the samples could be derived.

The median thermal contact resistances with error bars are shown in Figure 6. As a point of comparison, the thermal resistance for a 25mm thick refractory lining, having a thermal conductivity of 10 W/mK, is \( 2.5 \times 10^{-3} \text{ m}^2\text{K/W} \). The median thermal contact resistances calculated for the oxidized steel/PC interfaces in our experiments varied between 0.1 and \( 2.3 \times 10^{-3} \text{ m}^2\text{K/W} \). The highest measured contact resistance, \( 4 \times 10^{-3} \text{ m}^2\text{K/W} \), was in a steel/PC sample where the steel sample had been oxidized at 650 °C for 50 h. This sample also displayed the greatest deviation in results. When the measuring temperature was increased to 400 °C, the median thermal contact resistance in this sample fell to \( 0.8 \times 10^{-3} \text{ m}^2\text{K/W} \), which is roughly one third of the thermal resistance of the refractory lining referenced above. On the other hand, in the stacked sample where the steel counterpart was oxidized at 450 °C, the thermal contact resistance decreased to \( 0.132 \times 10^{-3} \text{ m}^2\text{K/W} \), which is still ~5 % of the thermal resistance of our reference refractory lining.
Although there were large deviations in our results, particularly notable for the steel/PC 650 C sample, there were no clear overlaps. This perhaps accentuates the unique nature of each contact situation for different surfaces. However, our results suggest that thermal contact resistance can play an important role in the design of refractory linings for high temperature applications.

The thermal contact resistance (Figure 6) of polished metal in contact with PC was negligible, and even slightly negative values were calculated. These could be due to inaccurate specific heat evaluation for the stacked free-standing sample according to Equation 6. However, the trend with oxidized interfaces was clear. As the oxide layer got thicker, the thermal contact resistance increased. Although the thermal contact resistance of the oxidized interfaces decreased at higher temperatures, this is probably due to increased heat transfer by irradiation.

The bearing ratio (Htp) provided some information about the compatibility of the contacting surfaces. When the sample was in a free-standing installation, the only compression on the joint came from gravity. Some of the highest peaks of the oxidized samples may have been smoothed out due to even this slight compression, and therefore the true surface patterning of oxidized metal in a contact situation is still somewhat unclear. The surface parameters of the samples are shown in Table 2.

The variation of the surface plane was highest in the Steel Oxidized 650 °C sample, due to the thickness of the partly-detached oxide layer, which increased the surface roughness.

The roughness average (Ra) value for PC was 0.283 µm, and for Steel 0.123 µm. The Ra value for Steel, Steel Oxidized 450 °C and PC were quite uniform and low but for Steel Oxidized 650 °C it was nearly two orders of a magnitude greater, once again due to the thick (50 µm) rough oxide layer on the surface of the sample, (Table 2).

The same was true of the maximum profile height, which was two orders of magnitude larger in the steel sample oxidized at 650 °C than it was in the other samples. This resulted in higher

![Figure 6. Thermal contact resistance (m²K/W) of steel/PC interfaces at 25, 100, 200, 300 and 400 °C.](image)

| Table 2. Surface parameters of the studied samples |
|---------------------------------|----------------|----------------|----------------|----------------|
|                                 | Ra (µm)      | Rq (µm)      | Rt (µm)       | Htp (µm)      |
| Steel                           | 0.123        | 0.157        | 1.43          | 0.558         |
| PC                              | 0.283        | 0.370        | 4.96          | 1.22          |
| Steel Oxidized 450 °C           | 0.334        | 0.436        | 12.46         | 1.26          |
| Steel Oxidized 650 °C           | 16.20        | 20.57        | 280.8         | 65.94         |
thermal resistance values in the free-standing stacked Steel/PC 650 C sample. Additionally, it was noticeable that the oxide layer on the steel was at least partly detached from the substrate, which also caused higher thermal contact resistance. The surface roughness of the contacting planes increased the interfacial porosity and thus decreased the number of heat-conducting routes.

The surface 3D plot of studied samples is shown in Figure 7. The surface roughness difference is clear between sample oxidized in 450 °C and 650 °C, Figure 7(a,b) respectively. The size of studied surface area was 1.86 × 2.44 mm. This area represents only small fraction of the total contact surface area (506.7 mm²) in round sample with diameter of 25.4 mm. The 3D plot suggests that the true gap between ceramic and metal surfaces is larger compared to the thickness of oxide layer only. The true gap between surfaces is difficult to evaluate since the number, and strength of the oxide peaks supporting the metal sample is obscure.

In practice, our measuring installation with freestanding contact and pre-oxidized metal surfaces seldom occurs. The refractory linings in most incineration processes are typically supported by metal anchoring, and the lining is cast or sprayed on top of the metal tubing. In such cases, the contact between the refractory lining and the metal is assumed to be initially quite good. Nevertheless, if oxidation of the steel surfaces occurs during a plant’s operation it could, over time, impair the contact and significantly increase the thermal contact resistance.

4. Conclusions
Thermal diffusivity measurements were conducted on common pressure-vessel steel with different oxidation treatments, a reference ceramic material, and their freestanding stacked combinations. These measurements were taken at temperatures of 25, 100, 200, 300 and 400 °C using light flash equipment. The thermal diffusivity values were then used to calculate the thermal conductivities, thermal resistances and finally the thermal contact resistances of the samples.

The thermal contact resistances of the oxidized samples varied from 0.1 to 0.4 × 10⁻³ m²K/W, depending on the thickness of the oxide, the quality of the contact, and the temperature. The radical increase in the thermal contact resistance of the stacked sample with the steel counterpart oxidized at 650 °C was due to the build-up of a porous oxide layer on the surface of the sample steel disc. The oxide layer was 50 µm thick, partly detached and lamellar. It seems clear that the detachment of the layer and its lamellar structure with gaps between can produce extra thermal resistance in a heat flux pathway.

The surface of the oxidized steel in the stacked samples was roughened, which reduced the number of thermal contact points between the surfaces. In addition to the innate porosity of the oxide layer itself, the increased roughness of the surface made the contact even more porous. According to our experiments, when operating in an oxidizing atmosphere, it is recommended to keep the temperature at a ceramic/steel interface lower than 450 °C in order to minimize the thermal losses resulting from the increased thermal contact resistance. It is also important to ensure proper contact between the ceramic lining and the metal structures in order to maintain the heat flux required in the process. If this is not sustained, problems can occur during high temperature processes because the right amount of heat may not be available for each step in the process.

Our experiments also reinforced support for a light flash apparatus as a reliable research tool that can be used to evaluate the thermal contact resistance of steel/ceramic interfaces.
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