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STUDY OF THERMAL CONDUCTIVITY OF THE POROUS OXIDE LAYER

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Abstract: *Steel production and processing are connected with high temperatures. Due to a reaction between hot surface of the steel and oxygen contained in surrounding atmosphere, oxides are formed on the surface of the steel. Created layer of oxides is called scales and has influence on cooling and quality of steel. Thickness and structure of scale layer are influenced by chemical composition of the steel, temperature and atmosphere during oxidation. Scale layer can be considerably porous which has a significant influence on thermal conductivity of this layer, because air pores have much lower thermal conductivity compared to scales. Steel samples were prepared and porosity of scale layer was studied. Further, the average thermal conductivity of porous scale layer was determined for different regimes of oxidation by FEM modelling. It was found that the average thermal conductivity of porous scale layer is influenced not only by porosity of scale layer, but also by distribution of air pores, which can has a significant effect.*

Keywords: Oxides, scales, porosity, thermal conductivity

1. Introduction

A reaction between hot surface of the steel and oxygen contained in surrounding atmosphere during steel processing forms oxides on the surface of the steel. These oxides are called scales. Scale layer consists of various oxides including three ferrite oxides: wüstite (FeO), magnetite (Fe_3O_4) and hematite (Fe_2O_3). Scales on the alloy steel with alloying elements like silicon, chrome or nickel include another oxides (Fe_2SiO_4, $FeCr_2O_4$, $NiFe_2O_4$, ...). Thickness and structure of scale layer are influenced by chemical composition of steel, temperature and atmosphere during oxidation.

Scale layer influences the quality and cooling of steel (Wendelstorf et al., 2008), (Chabičovský et al., 2015). Porous scale layer has much lower thermal conductivity compared to steel and that is why this layer acts like insulant. The thick scale layer can strongly affect the cooling, but even the thin scale layer can affect cooling intensity. The surface roughness after oxidation is different from the surface roughness before oxidation (Sun et al., 2004) and this change also influences the cooling (Fukuda et al., 2016).

It is necessary to know the thermophysical properties of the scale layer for the numerical simulation of the spray cooling. The thickness and the thermal conductivity of the scale layer are the main parameters which influence heat transfer through the scale layer. Thermal conductivity of the scale layer depends on type of oxides in scale layer and also on the porosity of the scale layer, because air pores have much lower thermal conductivity compared to scales. Thermal conductivity of wüstite, magnetite or hematite can be found in (Colás, 1995) and (Genève, 2010) as temperature independent values or in (Takeda et al., 2009) as a function of the temperature. Unfortunately, the porosity is not considered. Thermal conductivity of the scale layer created by oxidation on low carbon steel can be found in (Endo et al., 2014). The value of thermal conductivity was $k = 3,8\ \mathrm{Wm^{-1}K^{-1}}$ for room temperature. The porosity is not mentioned. Porosity is considered in (Pohanka et al., 2016). The value of thermal conductivity was $k = 1,2\ \mathrm{Wm^{-1}K^{-1}}$ for temperature $T = 800\,°\mathrm{C}$ and the porosity was $37\,\%$. Samples from steel 54SiCr6 with scales were used.

In this paper the porosity of the scale layer on the steel grade 54SiCr6 is studied and also the average thermal conductivity of the porous scale layer for different regimes of oxidation is determined by FEM modelling.

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2. Measurement and evaluation

2.1. Samples

Samples of dimensions $20 \times 20 \times 25$ mm from steel 54SiCr6 were used for oxidation in furnace. The temperature of oxidation was $900\,°C$ and the time of oxidation was 15, 30 and 60 minutes. Regimes of oxidation are labelled as 'C1' (oxidation time 15 min), 'C2' (oxidation time 30 min) and 'C3' (oxidation time 60 min). Two samples were used for oxidation in each regime. After oxidation 5-8 mm thin piece from each sample was cut off (see Fig. 1a) and then this piece was cut to five parts (see Fig. 1b). The grey represents scales and dash-dotted lines represent cuts in the Fig. 1. Parts number two and four were chosen for observation on a microscope.

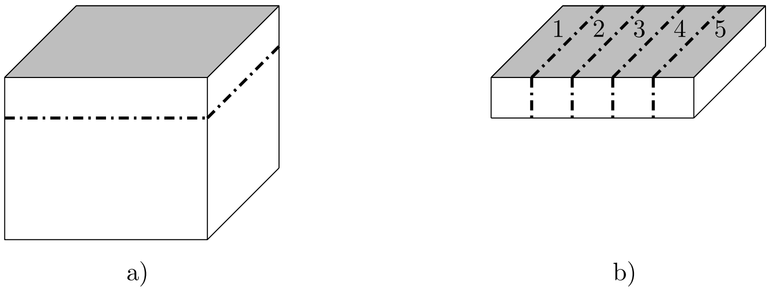


Fig. 1: Cutting of samples

2.2. Porosity of scale layer

The porosity of scale layer was determined by using pictures from microscope. Typical picture of scale layer is in Fig. 2a. The light layer at the bottom represents steel, the dark layer at the top is a fixing glue and in the middle are scales with air pores (dark areas). Pictures of scale layer have a bimodal histogram. Using this fact, the layer of scales without air pores was segmented (see Fig. 2b) by thresholding. The segmentation was done in MATLAB. Further, the picture of scales without air pores was converted to black and white picture (see Fig. 2c). The Fig. 2d represent the layer of scales with filled air pores. From pair of black and white pictures the porosity of scale layer was calculated.

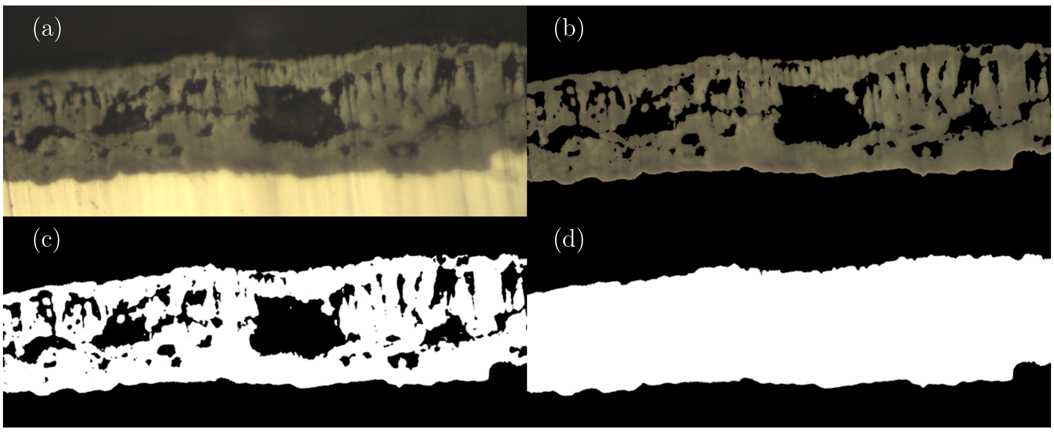


Fig. 2: Determination of porosity of scale layer

2.3. Thermal conductivity of porous scale layer

ANSYS Workbench was used for the determination of the average thermal conductivity of porous scale layer. The representative part of sample was chosen based on analysis of scale layer porosity for each regime of oxidation (C1, C2, C3). Pictures of selected parts from microscope was redrawn in AutoCAD and used as a 2D input geometry for calculation of the average thermal conductivity of porous scale layer. The temperatures T_p and T_s were used as boundary conditions (see Fig. 3). The value of temperature T_p was always five degrees lower than the temperature for which the average thermal conductivity was determined and the value of temperature T_s was five degrees higher. The result of steady-state thermal analysis was position-dependent heat flux on the boundary with temperature T_s. This heat flux was integrated and divided by the length of the boundary with temperature T_s. Further, from equation (which comes from the Fourier law)

$$\bar{k} = \frac{q''\delta}{(T_s - T_p)}, \tag{1}$$

where q'' is the heat flux and δ is the thickness of the scale layer, the value of the average thermal conductivity of the porous scale layer $\bar{k}$ was calculated. The thickness of scale layer δ was determined from pictures from microscope and oxide FeO was considered for all regimes.

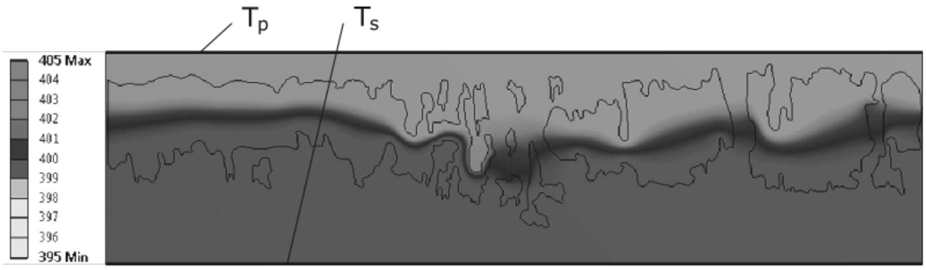


Fig. 3: Temperature distribution of porous scale layer

3. Results

3.1. Porosity of scale layer

The values of the average porosity of the scale layer for each regime of oxidation and their standard deviations are written in Tab. 1. (Four parts of samples were used to determine the average porosity in each regime of oxidation). It can be seen that porosity increase with time of oxidation.

Tab. 1: Porosity of the scale layer for different regimes of oxidation

Regime of oxidation	C1	C2	C3
Porosity [%]	19,3	24,1	44,6
Standart deviation [%]	6,2	11,5	13,7

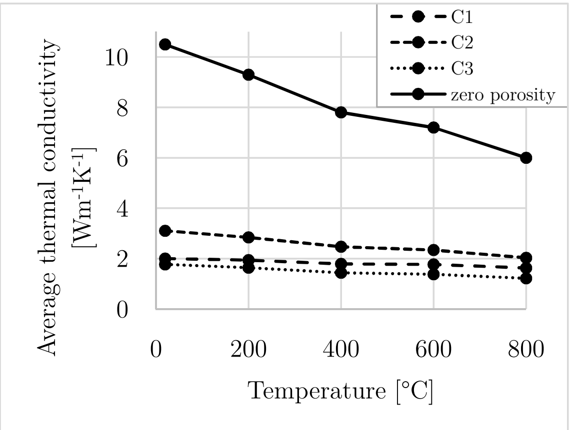
3.2. Thermal conductivity of porous scale layer

The average thermal conductivity of the porous scale layer dependent on the temperature is for different oxidation regime in Fig. 4a. The solid line represent scale layer without air pores (layer with zero porosity). The porosity of chosen parts of samples was $21,7\,\%$ for oxidation regime C1, $27,6\,\%$ for C2 and $45\,\%$ for C3. Significant influence of the porosity on the average thermal conductivity can be seen in Fig. 4a. Opposed to results from (Pohanka et al., 2016), where the thermal conductivity for temperature $T = 800\,°\mathrm{C}$ and porosity $37\,\%$ was $k = 1,2$ $\mathrm{Wm^{-1}K^{-1}}$, higher values were observed.

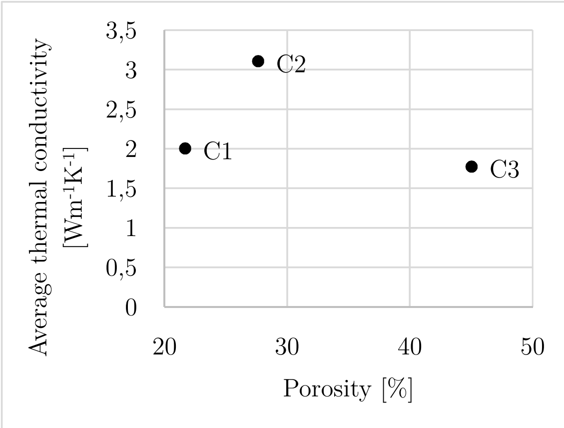
Dependence of the average thermal conductivity on the porosity of the scale layer is in Fig. 4b. It is seen that with the growing porosity the average thermal conductivity does not have to decrease. If we compare samples oxidized in C1 (porosity $21,7\,\%$) and C2 (porosity $27,6\,\%$), we can see that the average thermal conductivity has higher value for scale layer with greater porosity. It is caused by distribution of air pores. In case of the sample oxidized in regime C1, air pores formed continuous thin layer across almost whole picture (see Fig. 5a). This phenomenon was not observed for sample oxidized in regime C2 (see Fig. 5b).

4. Conclusions

The porosity of the scale layer was experimentally investigated. It was shown that the porosity increases with time of the oxidation. The average thermal conductivity of porous scale layer was determined for

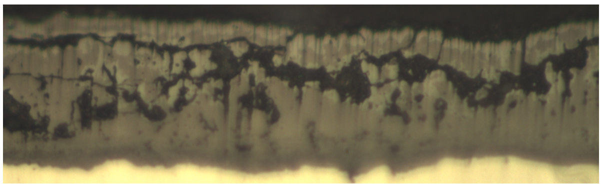


(a)

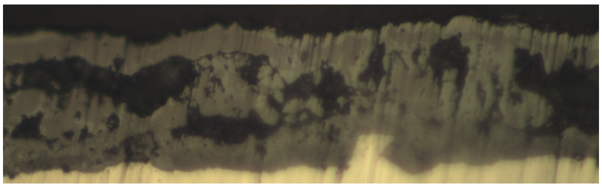


(b)

Fig. 4: The average thermal conductivity dependent on the temperature (a) and porosity (b)



(a)



(b)

Fig. 5: Distribution of air pores, regime of oxidation C1 (a) and C2 (b)

different regimes of oxidation. It was found that the average thermal conductivity of the porous scale layer is significantly influenced by porosity of the scale layer, but the distribution of air pores also plays important role. If air pores form continuous layer across almost the whole sample, the value of the average thermal conductivity of this scale layer can be lower than the value of the average thermal conductivity of scale layer with higher porosity, where air pores do not form continuous layer.

Acknowledgments

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