Growth and deformation behaviour of oxide scale on steel

Oxide scale is always formed on steel during the hot rolling process. The secondary scale formed after roughing is removed before the slab enters the finishing mill. The time that the slab runs between the descaler and the first rolling stand (5-10 s) is sufficient for a new tertiary scale to form. Its properties, depending on the steel chemistry and the process conditions, have an important impact on the final surface quality. Hot strip users’ requirements on scale properties are particularly strict to warrant good material response to subsequent processing steps like pickling, stamping or direct coating.

Three distinct types of iron oxide can be found in steel surface scales, with progressively decreasing oxygen - and increasing metal - contents from the free surface to the metal/oxide interface. These are: Fe$_2$O$_3$ (hematite), Fe$_3$O$_4$ (magnetite) and FeO (wustite), wustite having an extremely broad composition range, characterised by Fe$_{1-x}$O, with x comprised between 0.04 and 0.17. Furthermore, wustite is thermodynamically unstable below 570°C, which has direct consequences on low temperature oxide scale behaviour. At hot rolling temperatures, wustite exhibits a remarkably high plasticity.

Controlling the factors that affect the deformation behaviour and mechanical properties of the oxide scale is important when considering the heat-transfer behaviour at the strip-roll interface, its frictional conditions during processing and the surface quality of the product. The deformation behaviour and mechanical properties of the scale layer depend mainly on its temperature and thickness, which are the two major parameters to be considered when evaluating scale deformation.

High temperature deformation of the oxide layer is one of the most important phenomena in the hot rolling process. Several tertiary scale deformation behaviours could be expected. In principle, the oxide scale can either deform plastically or fracture, thus influencing the tool/work piece interaction and the surface finish of the formed product. Insufficiently documented as it remains today, the oxide plastic deformation is one of the most important events occurring during hot rolling.

Iron oxide is generally considered elastic and brittle. Nevertheless, several authors have shown that it can be deformed plastically. In view of the difficulties involved in controlling and measuring the scale temperature during rolling, direct
Summary

evaluation of its mechanical properties during hot rolling has been claimed to be impossible.

In this thesis, oxidation and high temperature plane strain compression (PSC) tests carried out under controlled atmosphere are used to simulate the oxidation and deformation behaviour during finish hot rolling. Results of studies on the plastic deformation of oxide scale at low strain rate can only be used in their limited experimental range, which is unfortunately far from current industrial conditions. In order to reproduce the chemical and thermomechanical conditions of an industrial finishing mill stand and to assess the possibility of plastic deformation of the scale, experiments at strain rates over 10 s\(^{-1}\) are necessary. PSC tests are considered to be the most valuable tool to reproduce these conditions at a laboratory level. The scientific objective is then to provide good experimental conditions to simulate and improve (at laboratory level) the oxide scale behaviour during hot working and to obtain specific conclusions confirming the plastic deformation of wustite at high temperature.

After the presentation of the general objectives and the context of this study (chapter I), chapter II gives a review of available data on scale properties, especially on tertiary scales, which remain on the steel surface until the end of the hot rolling. It has been observed that thickness, composition, morphology, adherence, alloying elements and surrounding oxidation atmosphere are relevant parameters that influence the tertiary scale. In accordance with literature, the steel properties, the events in the roll bite, and the hot rolling parameters as temperature, rolling velocity and reduction per pass must be taken in account to characterise the behaviour of the oxide scale during hot strip rolling. Special emphasis is paid on the fact that the oxide scale seems to be plastically deformed in the finishing mill temperature range (high temperature).

Chapter III gives an overview of the materials and equipments used for the study of the high temperature growth and deformation of the oxide scale layer. Controlled oxidation followed by plane strain deformation is the main experimental tool used. A detailed description is given of the oxidation device and of the peripheral equipments specially designed to develop the trials.

Chapter IV describes the oxidation experiments that were performed either under controlled atmosphere or in air in order to simulate the oxidation process during strip production. The oxidation kinetics of ultra-low carbon steel (ULC) in air, and its scale structure and composition over the temperature range of 750-
1250°C were investigated. An original laboratory oxidation device was designed and built in order to produce a single layer of essentially wustite.

In chapter V the behaviour of oxide scales under plane strain compression (PSC) is investigated at high temperature. Experimental conditions allow simulating the exact thermo chemical conditions prevailing between descaling and the first rolling pass in the finishing mill. The effect on the scale behaviour of parameters such as pass reduction and deformation temperature is assessed. Thus treated specimens were characterised by metallography and their scale thickness was measured under the optical microscope. Scale morphology was studied by SEM and OM.

Chapter VI concerns the high temperature deformation capacity of the oxide scales created under special controlled conditions and their relation with the actual scale deformation temperature during its contact with the tools. In this chapter, heating and high temperature PSC tests carried out under controlled atmosphere are used to study the temperature distribution within a plane strain compression test.

In chapter VII the EBSD technique is used to characterise the microstructures of oxide scales formed and deformed at high temperature. The technique can unambiguously differentiate between the candidate phases to provide the phase distribution within the scale.

The effect of alloying elements and of the surrounding atmosphere on scale growth has been extensively reported in literature. They usually retard the oxidation kinetics and promote void formation. Silicon is one of the most important alloying elements concerning the scale. In chapter VIII, special attention has been paid on the investigation of the effects of alloying Si on the high-temperature oxidation of steel, for a better understanding of the behaviour of modern steels during hot rolling.

Finally, chapter IX reviews and summarises the main results obtained. The advantages and disadvantages of the laboratory device especially designed in order to simulate the growth of tertiary scale oxide are analysed. The behaviour of oxide scales under plane strain compression (PSC) at high temperature is described. Based on the experimental conditions allowing a simulation close to the thermo chemical conditions prevailing between descaling and the first rolling pass in the finishing mill, relevant conclusions are given.