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and Didier C.J. Farrugia

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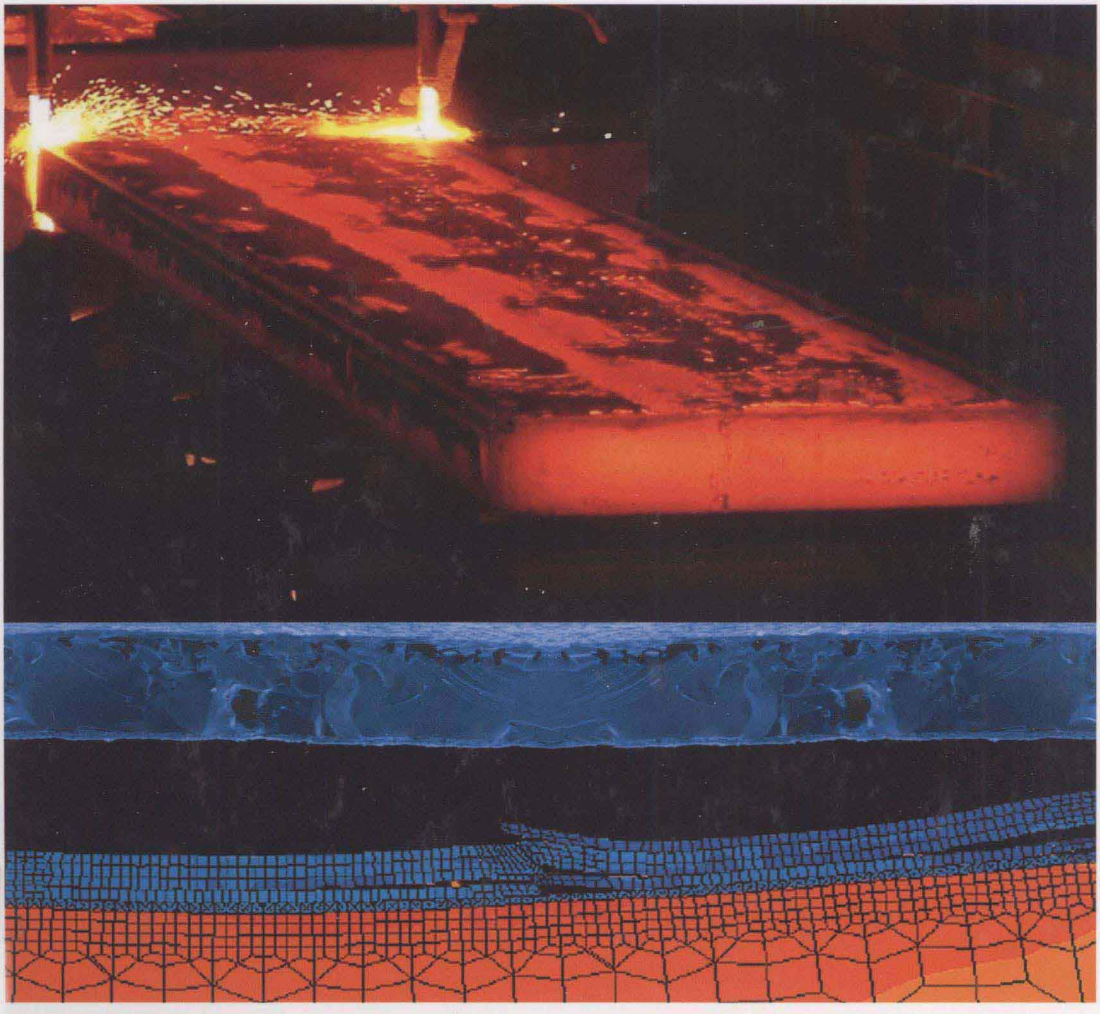

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Further Reading

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Preface

The authors' interest in oxide scale behavior during high-temperature metal processing began with a desire to have more accurate descriptions of friction and heat transfer during thermomechanical processing. This was needed for their modeling work on both microstructure evolution and shape changes, particularly for hot metal rolling operations. The evolution of microstructure is a major component of the research of the Institute for Microstructural and Mechanical Process Engineering: The University of Sheffield (IMMPETUS) in the UK, where Michael Krzyzanowski and John Beynon worked closely together. The research within IMMPETUS spans ferrous and nonferrous metals, particularly the important structural alloys of aluminum, iron (stainless and carbon steels), magnesium, nickel, and titanium. The boundary conditions describing the effects of thermal and mechanical loads on the metal are crucial for accurate prediction of the details of metal flow and the operating temperature fields. However, the research into these boundary conditions quickly revealed that the oxide scale on the hot metal would need to be treated as a detailed material in its own right, and not just a homogenous layer with nominal properties, traditionally described as a single friction or heat transfer coefficient. Thus began a major research effort to understand how oxide scale performs under the severe operating conditions that are typical of industrial metal forming at elevated temperatures, with their combination of large plastic deformations, often at high speeds, with sharp temperature gradients, all changing quickly with time.

At the same time, Didier Farrugia, based at Corus' Swinden Technology Centre nearby, was leading modeling activity into both microstructure evolution and shape changes. He became interested in extracting practical and simple algorithms for friction and heat transfer from the detailed research being undertaken in the university. He and his Marie Curie Fellows, Christian Onisa whose contribution to Chapter 9 has been invaluable and Quiang Liu, concentrated on friction in the hot rolling of long steel products and aligned their research with IMMPETUS. A long partnership with the University of Sheffield resulted, whereby the detailed research has been guided by the needs of industry, and the industry models have benefited from the insights gleaned during the research.

Collaboration with other companies, particularly in steel and aluminum, also helped accelerate the progress of the research. These productive relationships were

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aided by a seamless combination of techniques to tackle the various problems, bringing together computer-based models, laboratory experiments, and industrial trials and data.

It is striking that work that began with a focus on being able to quantify friction and heat transfer more accurately, quickly evolved into a much richer field of investigation into surface quality. The greater understanding of how oxide scale performs under these severe operating conditions has allowed the evolution of surface quality to be much better understood, including the important issue of how to control the surface quality, not just predict it.

This book is underpinned by the essential output from this work, enhanced by extensive reference to the excellent work of others in this field. It is the authors' desire that this book will inspire yet more people to take up this vital field of research for both its inherent intrigue and industrial importance.

The authors are indebted to colleagues from the Institute for Microstructural and Mechanical Process Engineering: The University of Sheffield (IMMPETUS), UK, where the main research results presented in this publication were obtained and to Corus Research, Swinden Technology Centre, in UK. They would also like to acknowledge the outstanding role of regular meetings and invaluable discussions with industrial partners; it was the guidance that effectively led this research over many years. Finally, the authors would like to express their appreciation to their various employers who allowed them some of the time needed to write this book. For the rest of the time we thank our partners.

January 2010

Michal Krzyzanowski, Sheffield, UK
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1 Introduction

Since all practical metal-working operations are conducted using equipment that is open to the atmosphere, oxidation of the metal surface is inevitable and, for high-temperature operations, of major significance. This oxidation is unwelcome since it represents a loss of metal and usually has to be removed at the end of the operation. Less obvious is the influence that the oxide scale has on the metal-working operation, in terms of forces and temperature, surface quality of the finished product once the scale has been removed and on the degradation mechanisms acting on the tools. These effects are fully appreciated by the metals industry, which has achieved a great deal to develop operations that cope with the oxidation problem by making their processes consistent, so that scale removal and surface quality are reasonably reproducible from piece to piece. However, such consistency is difficult to achieve with new operations, where the alloy or forming operation has not been trialed. It remains the case that the influence of oxide scale on processing conditions and product quality are variable, even under the best of conditions. If this situation is to improve, then the understanding and quantification of oxide scale behavior has to improve significantly. This can be achieved through a combination of detailed physical observation and computer-based modeling of both laboratory tests and factory operations. This book summarizes current work dealing with oxide scale behavior during high-temperature metal processing. Two main structural metals are considered, aluminum and steel, the latter easily dominating in terms of tonnages worldwide. The main industrial operation considered is rolling, which itself dominates forming operations. Although these are the main examples in the book, there is much of generic importance that can be applied to other forming operations, notably forging.

The oxidation of metals has been investigated over many years, with the complexity of different types and structure of oxide, different degrees of adherence to the metals, and variable integrity of the oxide scale according to the alloy, atmosphere, and heating conditions that are employed. Less well understood is the way deformation alters the oxide scale and how that altered scale itself affects the deformation process. This is a complicated topic because of the inaccessibility of the interface between hot metal and the forming tool, which greatly restricts the ability to measure directly what is happening, particularly under industrial conditions. As a result, deduction based on partial evidence has

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become the main method for understanding the behavior of oxide scale under hot working conditions. More recently, this has been supplemented by computer-based modeling to help interpret the observations and to predict behavior in other circumstances.

Even the basic properties of the oxide scale are poorly defined under high-temperature industrial processing conditions because the circumstances are usually far removed from laboratory conditions where relatively well-controlled experiments can be conducted. More realistic laboratory testing has its own problems of measurement access, so computer-based models are needed to analyze the test results so that "pure" material properties can be extracted for later application to industrial processes. This industrial application in turn requires a computer-based model so that the material properties can be inserted into a realistic description of the details of the stock-oxide-tool system. Even this chain of events is complicated by the need for several different types of laboratory test, each one contributing an element of the behavior that can be built up into a full description of the detailed complexity of the industrial operation.

There are two main domains where understanding oxide scale behavior matters. First, the operating conditions of friction and heat transfer, particularly at the interface between stock and tool, need to have the oxide scale included in the modeling if accurate predictions of these important boundary conditions are to be achieved. This has profound implication in changing the tribological conditions in the contact area between the product and the tool as well as initiating degradation mechanisms such as wear and thermal fatigue on the tool. Accuracy in these boundary conditions is a requirement of most metal-forming modeling, where operating forces and temperatures are being calculated. Traditionally, single and approximate coefficients are used for friction and heat transfer. In many circumstances this can be accurate enough, but there are many other situations where more accuracy is needed, particularly in operations involving large areas of contact and long contact times with the tool, where friction and heat transfer will inevitably play a larger role. It is important to assess the need for detailed modeling before embarking on the assembly of such detailed information: both analytical and computer-based models can assist this preliminary assessment.

The second main domain, where detailed knowledge of the oxide scale matters, is in the surface quality of the formed product. This applies particularly for metal rolling, where a high-quality surface finish is normally required, such as sheet metal for white goods (e.g., refrigerator cases) and plate for yellow goods (e.g., earth-moving equipment). At high temperatures, the oxide scale may be sufficiently ductile to deform along with the underlying hot metal. In this case, the surface of the metal is as smooth as the surface of the roll or die. However, in many cases the oxide is not hot enough to flow plastically, fracturing instead, such as steel at less high temperatures and aluminum throughout the hot working temperature range. In this case, the underlying hot metal can extrude up through the cracks to make contact with the tool. As well as sharply changing the local friction and heat transfer conditions, once the metal has been "descaled," these extrusions become protrusions, or bumps, on the metal surface, degrading the metal's smooth appearance. A more subtle effect concerns the ease of descaling, which may be affected by the thermomechanical processing conditions, which can make the oxide difficult to remove. Given that the metal-forming operation is run to optimize the shape change and microstructural refinement in the metal, changing the operating conditions to facilitate better control of the oxide scale is still rare. It is hoped that as understanding of oxide scale behavior improves, enabling good predictions of behavior during hot forming operations, an element of process control for surface quality will be introduced as standard.

For the researcher, there remains a wealth of issues to be investigated into the behavior of oxide scale in high-temperature metal processing. Although this book lays down much guidance and presents many data, it is very clear to the authors that much needs to be done before an acceptable level of insight has been achieved across the range of commonly formed alloys. This is largely because the chemical composition of the alloy plays a major role in the behavior of the oxide scale. In addition to the major differences between alloy groups (aluminum alloys, carbon steels, and stainless steels) within these groups, particularly in carbon steels, small compositional changes have a large influence on oxide scale behavior, as will be discussed in this text. Although some inroads have been made to analyze and quantify the effect of composition, many more measurements need to be made.

For the industrialist, the approach presented in this book opens the door to much more quantified insight into the complicated world of oxide scale, which for many years has relied on observations with too little underpinning theory. There is much to be gained from embracing the computer-based modeling approach, informed by measurements in the laboratory and factory, in achieving better quality products more reliably. Applications for this approach abound, across ferrous and nonferrous alloys, flat and long product rolling, and open- and closed-die forging. Although most of the book is devoted to the underpinning research, the metals and conditions reported are all industrially relevant and informed by current and anticipated practice. This makes the transfer of the research results to actual industrial practice relatively straightforward, as illustrated in the final chapter.

The technical content of this book begins in Chapter 2 where the crucial role of the secondary oxide scale for hot rolling and subsequent descaling operations is highlighted. This chapter gives an introduction to friction, heat transfer, and scale-related defects, thereby encompassing the main areas of influence of the oxide scale. As with the remainder of the book, friction and heat transfer information in the literature is presented in terms of relevance to industrial hot working operations.

The third chapter is devoted to high-temperature oxidation and the formation of subsurface layers. High-temperature oxidation has been studied extensively for some time, although mainly for applications where critical components are submitted to prolonged high temperature in service, which requires a protective oxide scale. This field of research and domain of application is only briefly described in this chapter. The main focus of the chapter is to describe the complexity of oxides forming on carbon steels and aluminum alloys under industrial conditions, including the constraint of short times and the effect of concurrent deformation. This results in more complicated oxide structures than are observed for metals simply oxidized in furnaces. The chapter closes with the particularly complicated case of subsurface layers formed in aluminum alloys, which can leave the metal prone to later filiform corrosion.

The methodology for quantitative characterization of oxide scale behavior in metal-forming operations is discussed in Chapter 4. This is illustrated by an important example, namely the prediction of oxide scale failure at entry into the roll gap. This is a crucial location for deformation of the scale, which can have considerable influence on its behavior in the roll gap and also on subsequent forming passes and descaling operations. The investigations that are reported illustrate how vital it is to make precise measurements of the most critical parameters of scale deformation and failure under hot working conditions for good accuracy in the subsequent modeling.

A range of recently developed laboratory-based experimental techniques, each providing a partial insight, is discussed in Chapter 5. The wide range of experimental methods presented in this chapter illustrates the complexity of the behavior of oxide scale in hot forming operations, including descaling, whereby so many tests are needed to build up sufficient evidence to understand the fine details of events under industrial conditions. Interpretation of such experimental results is often accompanied by serious difficulties due to inhomogeneities in the tests, very small measured loads and other various disturbances. Sometimes the measured data cannot be directly applied to mathematical modeling of the scale-related effects. For such cases, application of a physically based finite element model to provide numerical analysis of experimental results becomes a necessity. Several examples of such numerical interpretations are discussed in Chapter 6 for various laboratory techniques. It is worth highlighting the value of the finite element method in such modeling, with its capacity to encompass a wide range of phenomena and allow them to interact to provide realistic, coupled solutions to complicated problems.

The main assumptions, numerical techniques, and experimental verifications of the physically based model for oxide scale failure under hot rolling conditions are presented in Chapter 7. The chapter opens with the challenging issue of dealing with a wide range of length scales that are pertinent to these solutions. The analysis usually needs to go no finer a level than the microstructural scale of the order of microns, but this has to be tackled within a macroscale operation about five orders of magnitude larger, around a meter. To address this large range while continuing to encompass much of the details of the metal-oxide-tool interaction, as well as oxide microstructure, requires ingenuity if tolerable computation times for the modeling are to be maintained. Most of the modeling complexity is at the microscale, such as the range of failure modes for oxide scale, including brittle and ductile fracture. The finite element method can tackle these issues, as well as multiple sequences of deformation, common to industrial practice. The chapter closes with a new method which combines discrete and finite elements, which appears to be particularly well suited to complicated patterns of metal flow and oxide fracture without the need to guess beforehand where the fracture might occur.

Chapter 8 illustrates how advanced modeling can be used for prediction of micro events related to the oxide scale behavior on the surface of hot metal being rolled, including the formation of subsurface layers and how these events influence both the rolling process and the quality of the rolled product. This chapter discusses the important topic of the influence of minor changes in chemical composition on the behavior of oxide scale on carbon steels; an influence that is surprisingly large. Preliminary investigations attempting to provide a scientific rationale for the effect of chemical composition are presented based on simply binary alloys. Although well removed from the complicated industrial alloy compositions, there are clear indications how such compositions should be tackled in future research. Surface quality also features strongly in this chapter, beginning with the problematic issue of roll pick-up, whereby oxide scale detaches from the stock surface and is carried round by the roll to embed a surface defect in the following stock surface. Descaling is also discussed, particularly room temperature descaling by bending of the metal, and what can be done during the preceding hot rolling to make this process more efficient. The chapter closes with a discussion of the formation of subsurface layers in aluminum rolling during breakdown rolling, which appears to be the root cause of filiform corrosion.

As mentioned earlier, the whole book is approached from the viewpoint of industrial metal processing conditions. Thus the research reported is usually conducted under industrial or near-industrial conditions. Nevertheless, the laboratory investigations are just that, and there will always remain a need to translate that work into terms that relate directly to industrial practice. Chapter 9 provides this vital industrial input. After an introduction to industrial practice, particularly focused on long product rolling, the ways friction is normally characterized during industrial rolling are summarized. Chapter 9 then goes through a range of important industrial conditions, such as the influence of rolling geometries and descaling operations. Rolling geometry is particularly important for long product rolling, which is much more three-dimensional than flat rolling. The chapter then presents a new way of taking some of the fine details presented earlier in the book and creating a more representative and accurate friction law for use in industry. This is not a trivial exercise, but it is a pioneering development in the translation of the complexity observed into practical friction descriptions. It also includes anisotropic friction and the effect on roll wear. Creating such models is the first step, but knowing what to include and what to exclude requires a quantified appreciation of the sensitivity of the process to the detail. This is addressed next in Chapter 9, including the important addition of hot lubrication, which is used in long product rolling for complex sections and rails, though much less in flat rolling. As with so much modeling that feeds off practical measurements, the shortcomings of the modeling are revealed and the chapter includes further off-line measurements to provide greater insight into factors such as the effect of lubricant flow rate. It is important to validate such modeling with industrial measurements, and these are presented for both beam rolling and strip rolling with carbon steels, including mention of how inverse analysis can be used with industrial data. The chapter closes with a discussion of the lessons learnt from the work presented in this book for improving industrial practice and argues the need for yet more research.