Hot Cracking Phenomena in Welds III

John Lippold · Thomas Böllinghaus · Carl E. Cross
Editors

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Springer

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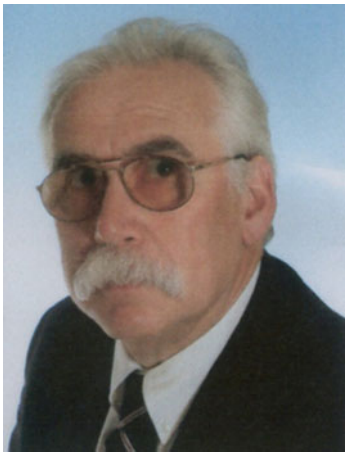

This conference and the proceedings are dedicated in memory of Prof. Dr.-Ing. habil. Dr. E. h. Horst Herold, formerly of Magdeburg University in Germany. He was the "founding father" of the inaugural Hot Cracking Workshop and a co-editor of the first two proceedings.

Prof. Herold was born in Leipzig in 1945. He graduated from Rostock University in 1969 as a Shipbuilding Engineer and in 1976 earned his Dr.-Ing. degree. From 1988 until his death in 2008, he was on the faculty of the University of Magdeburg in Germany. From 1988 to 2005 he served as the Director of the Institute of Joining and Beam Technology, and from 2006 to 2007 the Director of the Institute of Materials Joining Technology.

Prof. Herold will be remembered as a kind and gentle person who had a passion for his profession. He has touched the lives of many and left us all the better for it. We will miss him as a friend and colleague.

Preface

The term "hot cracking" is generally used to describe cracking that occurs at elevated temperature and, in the context of materials joining, generally constitutes weld solidification cracking, and weld metal and heat-affected zone (HAZ) liquation cracking. Ductility-dip cracking can also be considered a "hot cracking" phenomenon, even though DDC occurs in the solid-state but only slightly below the solidus temperature of the material. Hot cracking is a major weldability issue with many structural materials including aluminum alloys, steels, stainless steels and nickel-base alloys.

This conference was the third in a series of workshops that started in 2004. The first workshop was organized by Prof. Horst Herold and Prof. Thomas Böllinghaus and held in Berlin in March 2004. The proceedings from that workshop, entitled *Hot Cracking Phenomena in Welds* (ISBN 3-540-22332-0) were published in January 2005. The second workshop in March 2007 was organized by Prof. Böllinghaus, Prof. Herold, Prof. Carl Cross, and Prof. John Lippold and also held in Berlin. The proceedings from that workshop, *Hot Cracking Phenomena in Welds II* (ISBN 978-3-540-78627-6), were published in May 2008. These first two proceedings constitute 42 papers with contributions from over 10 countries.

The third workshop was held in Columbus, Ohio in March 2010 and hosted by The Ohio State University and Edison Welding Institute. There were over 80 participants and 22 presentations from 8 countries (USA, Germany, France, United Kingdom, Finland, Japan, Sweden, and Brazil). Paper topics included weld solidification cracking, liquation cracking, ductility dip cracking, weldability testing, and modeling. The conference was organized into three major sessions based on material type: aluminum and magnesium alloys, steels and stainless steels, and nickel-base alloys. Each of these sessions was started with a keynote presentation. Keynote speakers at this workshop were Prof. Sindo Kou (Univ. of Wisconsin – USA), Prof. Thomas Böllinghaus (BAM – Germany), and Prof. John DuPont (Lehigh University – USA).

The papers collected here together with the 42 papers from the previous workshops represent the best compilation of information on the topic of hot cracking of welds that has ever been collected. Among these papers, readers can find information on hot cracking mechanisms, characterization, weldability testing approaches,

and modeling techniques. The authors are among the leading experts in the field and have been provided the opportunity (without page limitations) to present their results and express their opinions.

The editors wish to thanks all the authors for their excellent contributions and for keeping to a schedule that allowed publication of these proceedings in a timely manner. We would also like to thank the Edison Welding Institute for providing the venue for this workshop and, in particular, to Mr. Nate Ames and Mr. Brad Hudson for assisting with the organization and advertising of the workshop.

Columbus, OH — John Lippold
Berlin, Germany — Thomas Böllinghaus
Berlin, Germany — Carl E. Cross
January 2011

Photo of Presenters

Front row (from left): C. Cross, S. Kou, J. DuPont, T. Böllinghaus, J. Lippold
Back row (from left): A. Ramirez, K. Nishimoto, Y-P. Yang, E. Giraud, D. Keil, M. Karhu, M. Gittos, M. Gallagher, J. Andersson, V. Karkhin, J. Sowards, B. Alexandrov, S. McCracken, A. Niel

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Part I
Aluminum and Magnesium Alloys

Hot Cracking in Welds of Aluminum and Magnesium Alloys

S. Kou, V. Firouzdor, and I.W. Haygood

Introduction

Aluminum (Al) alloys are known to be susceptible to hot cracking during fusion welding, including solidification cracking and liquation cracking. Figure 1 shows these two types of hot cracking in a bead-on-plate weld made by gas-metal arc welding of a 6.4 mm-thick 6,061 Al plate with a 4,043 Al filler metal (Fig. 1a). Both types of hot cracking are intergranular. Solidification cracking occurs in the fusion zone during solidification of the weld pool and is thus characterized by a dendritic fracture surface (Fig. 1b). Liquation cracking, on the other hand, occurs in the partially melted zone during solidification of the grain-boundary liquid and is thus characterized by an essentially smooth fracture surface (Fig. 1c). More details about hot cracking can be found elsewhere [1].

Magnesium (Mg) alloys, similar to Al alloys in having a relatively wide freezing temperature range as compared to the melting point, are also susceptible to hot cracking especially liquation cracking. In view of the growing interest in using Mg alloys to reduce the vehicle weight and energy consumption in the automotive industry [2], the hot cracking of Mg as well as Al welds will be discussed.

Liquation and solidification cracking in fusion welding of Al and Mg alloys, including arc and resistance spot welding, will be discussed in the present study. Liquation cracking in friction stir welding, which is considered as a solid-state welding process, will also be discussed.

Liquation Cracking

Liquation Cracking in Arc Welding

Liquation and liquation cracking in Al arc welding have been studied extensively, e.g., by Kou and coworkers [3–14] and Rao et al. [15–17]. Figure 2 shows

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