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Proceedings of the 4th Symposium on Structural Durability in Darmstadt SoSDiD

May 14th - 15th, 2014,
Darmstadt, Germany
MARITIM Konferenzhotel

FRAUNHOFER VERLAG

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Editors:
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FOREWORD

For more than a century, Darmstadt has been a centre of essential expertise in structural durability. Test and measurement equipment, computational methods and design philosophies have been developed here, over the past decades. To illustrate the continuity of activities in this field several institutes and companies have grouped together to present the Symposium on Structural Durability in Darmstadt. The symposium is organised by

Fraunhofer Institute for Structural Durability and System Reliability (Fraunhofer LBF) / System Reliability and Machine Acoustics (SzM)

Zentrum für Konstruktionswerkstoffe State Materials Testing Institute / Chair and Institute for Materials Technology (MPA/IfW)

Institute of Steel Construction and Materials Mechanics (IFSW)

Instron® Structural Testing Systems GmbH (INSTRON)

Hottinger Baldwin Messtechnik GmbH (HBM)

The objective of the Symposium on Structural Durability in Darmstadt (SoSDiD) is to present the current state of the art to the national and international fatigue community. Contributions have been gathered from German and international experts as well as from Darmstadt research work in structural durability. The symposium is intended to supply a lively forum for discussing basic questions and current trends, bringing together scientists and engineers working in this field.

In the area of structural durability the main subjects in 2014 will be welded and bolted joints, effects of corrosion, thermo-mechanical and low cycle fatigue, lightweight design as well as fatigue testing.

J. Baumgartner T. Melz

SoSDiD 2014 May 14th - 15th Darmstadt, Germany

HBM AWARD

Prize awarded to

Dr.-Ing. Halvar Schmidt

for his work at the
Fraunhofer Institute for Structural Durability and System Reliability LBF
with the title

"Fatigue Analysis of Structural Adhesive Joints under Variable Amplitude Loading"

The objective of this work was an application related durability analysis of adhesively bonded structures under cyclic loading with constant and variable amplitudes and establishing of a suitable design methodology. The use of such bonded structures is steadily increasing for example in the modern automotive industry.

Car body design is today more than ever at the focus of efforts to cost and weight reduction. The curb weight concerns a wide range of aspects such as reduction of CO_2 emissions or range extension for electric-powered vehicles. A joining technology steadily gaining significance in this context is adhesive bonding. Components benefit from increased stiffness, improved crash performance or the ability to join non-metallic materials like FRP. For providing reliability the fatigue design of bonded structures is of major importance. Furthermore, potential weight reduction is possible if spectrum (variable amplitude) loading is considered additionally.

For determining reliable characteristic values for fatigue strength, prerequisites for fatigue tests had to be defined at first (failure criteria, methods for crack detection) and a suitable component-like specimen was developed. Constant amplitude tests revealed that fatigue strength decreases continuously also in the high-cycle regime. The behavior of structural adhesive joints of steel sheets under spectrum loading was investigated with consideration of sequence effects, too. Thereby, it was verified that also for bonded structures a mixed load spectrum renders the highest damage compared to a less mixed one. The obtained Gassner-lines show in stress amplitude an exceedence by about factor 1.8 of the Woehler-lines revealing a significant lightweight potential of adhesively bonded structures. A numerical fatigue analysis was conducted according to a structural stress concept. This is based on linear-elastic effective stresses computed by the finite element method and reference SN-curves resulting from constant amplitude fatigue tests. The real spectrum damage was calculated by the linear damage accumulation law according to Palmgren-Miner without knee point of the SN-line. Damage sums close to $D_{exp} \approx 0.1$ were determined, depending both on stress distribution (specimen geometry), loading mode (type of load spectrum) and failure criterion (crack initiation, rupture). Alternatively, the fatigue behavior was also investigated by fracture-mechanics based on the method of energy release rate. However, this method revealed no advantages compared to the applied structural stress concept.

The research work was performed by Halvar Schmidt in a project of the Research Associations of Automotive Technology (FAT), Berlin, supported by the Foundation for Applied Steel Research via the AVIF, Düsseldorf, and in a project of the Research Association for Steel Application (FOSTA), Düsseldorf, supported by the German Federal Ministry of Economics and Technology, Berlin, via the AiF.

Hottinger Baldwin Messtechnik GmbH
Im Tiefen See 45
64293 Darmstadt, Germany

Darmstadt, May 2014

INSTRON AWARD

Prize awarded to

Dr.-Ing. Matthias Kaffenberger
M.Sc. Ehan Shams
Dipl.-Ing. Ina Platte
M.Sc. Franziska Strobel

for their work at the
Technische Universität Darmstadt, Germany, Fachgebiet Werkstoffmechanik
in the area of

"Fatigue Assessment of Weld Ends"

Manufacturing modern welded structures often leads to weld start and end points. In particular, in automotive structures, intermittent welding is often more the rule than the exception. The weld start and stop points are – from a mechanical point of view – severe notches with high stress con-centration factors. Under cyclic loading, crack initiation occurs at the weld ends. The research started when only minor knowledge on the fatigue strength of such structures was available in the literature. Research has been performed by the honoured team thus extending knowledge and skills in this field of application considerably. A fatigue strength assessment procedure for weld ends, especially in thin sheet structures was developed based the notch stress approach.

Dr.-Ing. Matthias Kaffenberger started with measuring the real geometry of weld ends. He used a high resolution three-dimensional scanner. Such information including the important data on the notch curvature and angle are unique. Based on this data he created finite element meshes which modelled the real geometry and all geometrical imperfections. The thereby calculated notch stresses enabled him to design an applicable modelling procedure for weld ends. The consideration of geometrical and statistical size effects ensures transferability for a variety of weld configurations in thin sheet as well as in thick sheet structures.

Mr. Ehsan Shams, M.Sc., extended the assessment procedure for cases where the fatigue crack initiates from the weld root rather than from the weld toe. Such failure situations predominantly occur for nominal cyclic shear loading of seam welds. He measured the geometrical particularities of a weld root migrating to a toe at the weld end. A cleavage fracture was produced for getting optical access to root details. He virtually merged the fragments in the computer and determined notch stresses for this configuration. He also designed a modelling procedure for practical application and provides the associated fatigue strength.

Dipl.-Ing. Ina Platte applied the approach for ensuring transferability to the root failure situations. She was able to demonstrate that the fatigue life for all load configurations – normal or shear stresses carried by the weld – can be described by a unified approach based on notch stresses and taking size effects into account as proposed by Dr. Kaffenberger.

Mrs. Franziska Strobel, M.Sc., investigated the path along which a fatigue crack grows after it has been initiated at the root of a weld end. She applied the tools of linear elastic fracture mechanics. She created three-dimensional models of cracked weld end situations, determined the stress intensity factors and performed fatigue crack growth analyses.

Instron Structural Testing Systems
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Darmstadt, May 2014

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SIMULATION OF FATIGUE CRACK GROWTH IN WELDED JOINTS

H. Th. Beier[1)], B. Schork[2)], J. Bernhard[3)], D. Tchoffo Ngoula[1)],
T. Melz[3)], M. Oechsner[2)], M. Vormwald[1)]
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ABSTRACT

This paper gives an overview on recent research results of the Darmstadt group inside a project called IBESS. Purpose of this project is the fracture mechanics based simulation of Wöhler-curves (S-N-curves) of welded joints. Part of this project is the investigation of initial defects and imperfections of welded joints. Metallographic and fractographic investigations have been done to derive a definition of an initial crack situation. Also investigations of the crack growth of multiple short cracks were performed on the basis of thermographic and fractographic studies. Another part of IBESS gives attention to the stability of the residual stress field in a welded joint due to the transient plastic deformation behaviour under cyclic loading. Numerical simulations using Döring's material model have been done to investigate the effect of a cyclic loading on a residual stress field in an uncracked and a cracked situation.

KEYWORDS

Fracture mechanics, welded joints, initial defects, residual stress field

INTRODUCTION

A research project named IBESS has been established in 2012. IBESS is a German acronym for „**I**ntegrale **B**ruchmechanische **E**rmittlung der **S**chwingfestigkeit von **S**chweißverbindungen", which means "integral fracture mechanics based determination of the fatigue strength of weldments". Aim of this three years project is the development of a procedure for an improved assessment of fatigue life of welded components which are subjected to cyclic loading. In fact, a lot of boundary conditions affect the fatigue strength of a welded joint, i.e. weld geometry, initial defects, welding residual stresses, material inhomogeneity, strength mismatch, misalignment, elastic-plastic deformation behaviour, development of crack geometry (a/c-ratio). To consider these influences IBESS has been divided into 8 sub-projects:

- BAM - Federal Institute for Materials Research and Testing, Berlin, Department for Component Safety: *Analytical fracture mechanics determination of the fatigue strength.*
- RWTH Aachen University, Department and Chair of Ferrous Metallurgy (IEHK), Aachen: *Quantification of the local strain hardening behavior in cyclic loaded welded joints.*
- Technische Universität Braunschweig, Institute of Joining and Welding (IFS), Braunschweig: *Residual stress fields in multi-layer welds.*
- Fraunhofer Institute for Mechanics of Materials IWM, Freiburg: *Microstructure-based description of the formation of cracks at defects in welds.*
- Hamburg University of Technology, Institute for Ship Structural Design and Analysis, Hamburg: *Crack propagation tests on longitudinal stiffeners for validation of IBESS procedure.*
- Technische Universität Darmstadt, Institute for Materials Technology (MPA/IfW), Darmstadt: *Investigation of initial defects and imperfections and their significance to damage of welded joints under cyclic loading.*
- Technische Universität Darmstadt, Institute of System Reliability and Machine Acoustics (SzM), Darmstadt: *Analysis and fracture mechanics description of the growth of short multiple cracks in the weld toe notch.*
- Technische Universität Darmstadt, Institute of Steel Construction and Materials Mechanics (IFSW), Darmstadt: *Modeling of fatigue crack growth in welded joints under consideration of the transient plastic deformation behavior.*

For validation of the theoretical results a lot of Wöhler-tests on welded cruciform joints and butt welded joints made from steel S355 and S960 are in work.

The following will present and discuss the basic idea of the fracture mechanics approach, the current results of the initial defects investigations, the studies of crack growth of multiple short cracks in the weld toe notch and the influence of a cyclic loading on a welding residual stress field.

FRACTURE MECHANICS-BASED DETERMINATION OF FATIGUE STRENGTH

The fatigue damage process of cyclically loaded structures may be described by 3 stages, (1) crack initiation, (2) crack propagation and (3) unstable crack growth.

(1) The crack initiation phase starts with dislocation movements inside grains and yields in micro-structural short cracks, which might be arrested at grain boundaries. In the case of defects inside the material (i.e. pores, inclusions) these defects can be seen as initial cracks without a crack initiation phase.

(2) If the cyclic loading is larger than the fatigue limit these cracks will propagate to technically short cracks, which can be then described by fracture mechanics methods. Crack propagation can be divided into a short crack and a long crack part. Short crack propagation is defined (a) by the influence of the cyclic plastic zone on the crack tip load, which does not allow the pure use of linear elastic

fracture mechanics (LEFM) and (b) by the fact, that – caused by plasticity - crack closure effects built up with raising crack size from 0% to 100%. From this point on cracks can be defined as long cracks. If these cracks develop in a highly loaded notch field and the cyclic plastic zone is larger than about 1/10 of the crack length, elastic plastic fracture mechanics (EPFM) concepts must be used instead of LEFM.

(3) At the end of fatigue life unstable crack growth occurs either in the case of brittle or of ductile damage of the structure. Different damage criteria can be defined like loss of stiffness, leakage, defined crack length and so on.

The crack initiation phase is short in comparison to the crack propagation part (e.g. about 15% of cycles up to a short crack for polished, unnotched specimen [1]). This means, that the portion of crack initiation time might be neglected for calculation of fatigue strength. Nevertheless, the question of crack initiation is part of the IBESS research.

Crack closure effect means, that just the opened crack contributes to the cyclic damage accumulation and en effective crack tip parameter can be calculated based on this information.

As a standard the fatigue strength is given by Wöhler-curves. For a certain detail the number of cycles up to failure for different stress ranges can be calculated and printed in an S-N-diagram (Fig. 1).

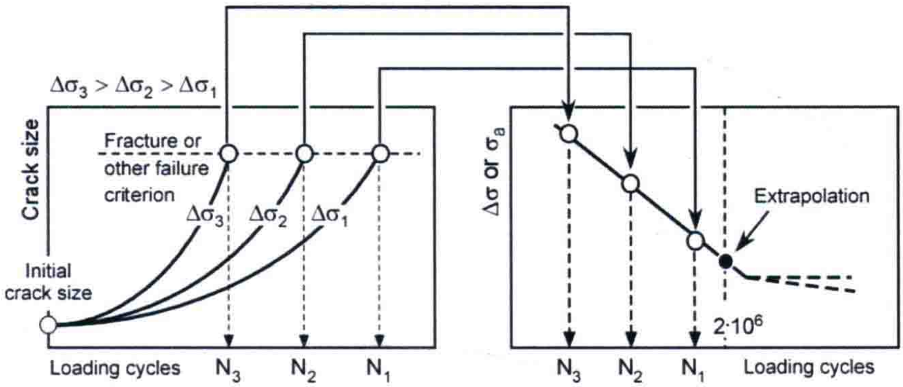

Fig. 1: Determination of a Wöhler-curve by fracture mechanics approach

Starting with stage (2) for welded joints an appropriate initial crack state must be defined. This might be a single dominating crack or a multiple crack situation. It depends mainly on the local weld geometry and therefore on the welding technique, on the initial defects distribution and on the load level. Then short cracks start growing and for a multiple crack-state crack coalescence will occur. To obtain reasonable results this mechanism must be modelled.

Short crack propagation should be calculated using EPFM, if not, non conservative results may be obtained because of the neglect of the crack growth accelerating plastic part of the crack tip loading and the described development of the crack closure effect. In spite of this today often LEFM is recommended [2], the error caused by neglecting the multiple crack situation and the plasticity effects for short cracks is corrected by use of a scaled initial crack size. Because the initial crack situation depends on more than one parameter, this approach is basically limited to these special welded joints which are used to derive the scaled initial crack size. The EPFM-approach used for short cracks can then be taken over to calculate the long crack propagation.

Another important factor which influences the fatigue strength of welded joints is the welding residual stress field. Due to the thermo cycle resulting from welding process together with temperature dependent yield stresses and heat expansion of the material, tensile residual stresses are built up in the interesting area of weld notches. Martensite formation caused by high cooling rates in ferrite steels yields to an increase of volume and therefore to compressive stresses. Both mechanisms must be added together. Note that the fatigue strength is not dependent on the resulting residual stress field after welding (!) but on the remaining stress field after cyclic loading. The residual stresses, either compressive or tensile, are acting as mean stresses and contribute to the crack closure effect.

Additionally misalignments resulting from assembly and welding process must be kept in mind to. For this, a link should be made to manufacturing codes in order to detect the influences of misalignments to fatigue strength.

After reaching a defined fracture criterion - stage (3) –a pair of data stress range versus number of cycles as one point in the Wöhler-curve has been calculated.

The calculations are based on material properties coming from experimental investigations of welded joints. This is for base material, weld material and heat affected zone: monotonic and cyclic stress-strain-curve, transient cyclic deformation behaviour, fracture mechanics parameter for describing crack propagation and crack arrest. Just a few data can be taken from literature, but it is expected that for standard situations many of this basic data is sufficient.

For a more detailed description of the fracture mechanics based IBESS approach see reference [9].

INVESTIGATION OF INITIAL DEFECTS AND IMPERFECTIONS

As described the fracture mechanics based calculation of fatigue strength starts with an appropriate initial crack state. For welded joints there are many sites like pores, material inhomogeneity, undercuts etc. which can be interpreted as initial cracks (see Fig. 2).

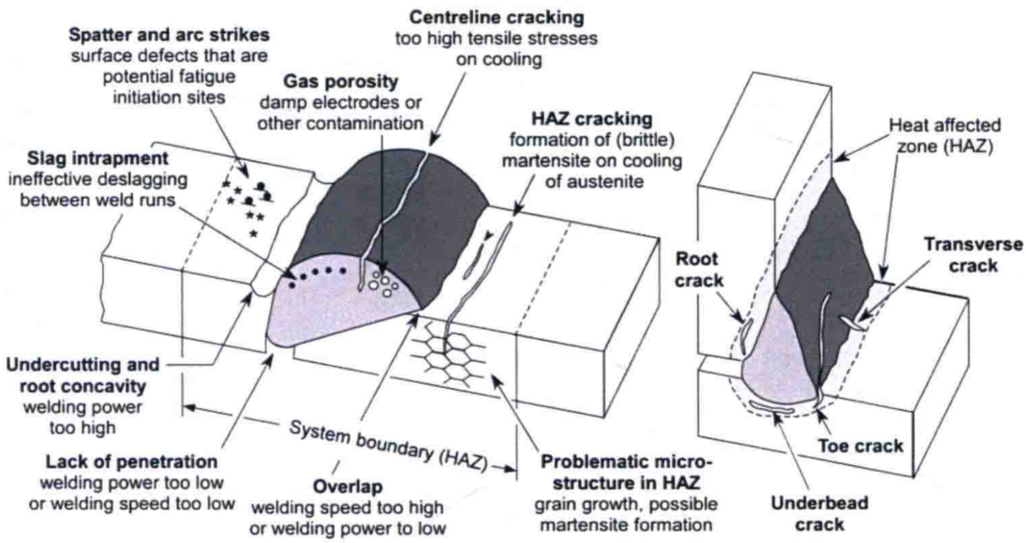

Fig. 2: Possible discontinuities for formation of initial cracks [9]

Part of IBESS-research is therefore the investigation of initial defects and imperfections and their significance to damage of welded joints under cyclic loading. Research partner for this task is Institute for Materials Technology (MPA/IfW) of Technische Universität Darmstadt.

Specimens for validation of the IBESS-procedure are butt welded joints and cruciform joints (test section 50mm x 10mm) made from steel S355 and S960 and longitudinal stiffeners made from S355 as component similar demonstrators (Fig. 3). The specimens are welded using gas metal arc welding in an automatic process.

The weld geometry is taken from 3D-scans with a resolution of about 30 µm for a reduced number of specimens. Undercuts and root concavity (Fig. 2) can be read out from this scans directly.

Basic characterization of inner defects or imperfections is done by investigation of metallographic sections for non cycled specimen. The investigation is focused on high loaded regions, for which crack formation is expected, e.g. the small area of the weld toe. Samples are cut out of the welded joints and the skin is polished. The critical area is scanned by optical microscopy and visible imperfections are measured and counted. For all specimens studied so far no major imperfections or defects could be found (Fig. 4).

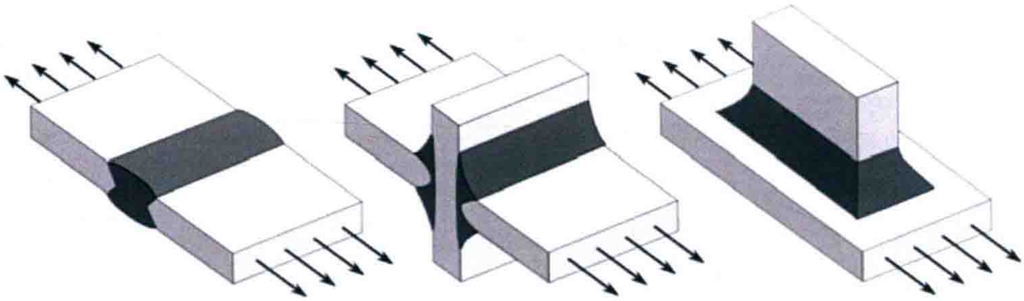

Fig. 3: Specimen: butt welded joints, cruciform joints and longitudinal stiffeners (principle).

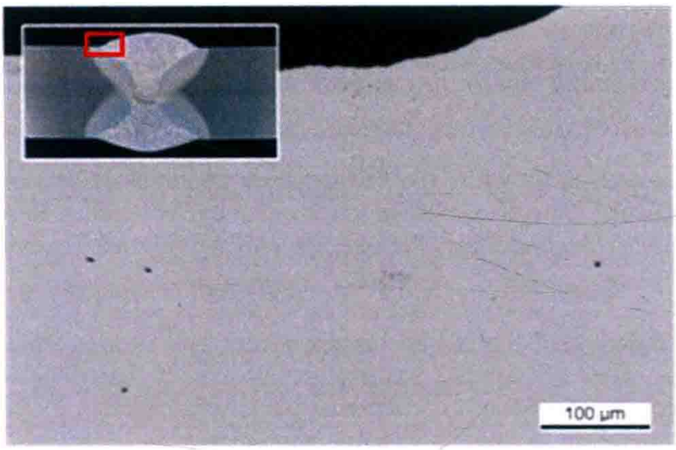

Fig. 4: Metallographic section: critical area at weld toe with small inclusions.

An area equivalent diameter is calculated for each imperfection. Only the maximum imperfection per critical area is taken into account and the size distribution of mayor imperfections can be drawn as the relative occurrence probability in dependence of its diameter (Fig. 5).

Most imperfections have an equivalent diameter of about 5 to 15 µm, the largest discovered imperfections are in the order of 25 µm. These values are in the dimension of the grain size of the base metal and smaller than the grain size in the heat affected zone. Thus it can be expected that these imperfections are not necessarily origins for initial crack formation. However, it gives an idea of a smallest initial crack dimension for fracture mechanics based calculations.