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Haoyun Tu

Numerical Simulation and Experimental Investigation of the Fracture Behaviour of an Electron Beam Welded Steel Joint

Doctoral Thesis accepted by
the University of Stuttgart, Stuttgart, Germany

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Supervisor's Foreword

Welding techniques are widely used in many industry fields, e.g., manufacturing of cars, high-speed trains, and shipments. As the fracture behavior of weldments influences the serving life of the components, it is important and necessary to investigate its fracture behavior both in experimental and in numerical ways.

Dr. Tu has performed a lot of experimental and numerical works studying the fracture behavior of an electron beam welded joint obtained from steel S355 in his dissertation. In the first step, the 2D Rousselier, Gurson–Tvergaard–Needleman (GTN), and the cohesive zone (CZ) models were adopted to predict crack propagation of thick compact tension (CT) specimens obtained from weldments. The cohesive zone model is preferentially suggested as it is easy to use for scientists and engineers because the CZM has less model parameters and can be used to simulate arbitrary crack propagation. Based on his work, when the stress–strain curve and the volume fraction of nonmetallic inclusions are obtained from the literature or are introduced as design parameters, the fracture energy can be numerically derived. In the second step, the 3D optical deformation measurement system (ARAMIS) and the synchrotron radiation-computed laminography (SRCL) technique reveal for the first time the damage evolution on the surface of the sample and inside a thin sheet specimen obtained from steel S355. Damage evolution by void initiation, growth, and coalescence is visualized in 2D and 3D laminography images. Two fracture types, i.e., flat crack propagation originated from void initiation, growth, and coalescence and a shear coalescence mechanism, are visualized in 2D and 3D images of laminographic data, showing the complexity of real fracture. Finally, a 3D Rousselier model is applied for the first time successfully to predict different microcrack shapes before shear cracks arise by defining the finite elements in front of the initial notch with inhomogeneous f_0 values. The influence of the distribution of inclusions on the fracture shape is also discussed. According to his investigations on the fracture behavior of an electron beam welded steel joint, a homogeneous distribution of particles in the material provides the highest resistance to fracture. This is very valuable information for material designers and producers in the industry.

Overall, his work reveals the nature of the damage evolution of electron beam welded joints obtained from steel S355 and, moreover, shows how to apply the finite element method to predict the 3D fracture shape under flat crack propagation conditions.

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Prof. Siegfried Schmauder

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H. Y. Tu, U. Weber, S. Schmauder. Numerical investigation of the damage behavior of S355 EBW by cohesive zone modeling. Adv Mater Research 1102 (2015), 149–153.

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H. Tu, S. Schmauder, U. Weber. Numerical study of electron beam welded butt joints with the GTN model. Comput Mech 50 (2012), 245–255.

H. Y. Tu, S. Schmauder, U. Weber, Y. Rudnik, V. Ploshikhin. Numerical simulation and experimental investigation of the damage behavior on electron beam welded joints. Procedia Engng 10 (2011), 875–880.

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Contents

1 Introduction 1
1.1 Motivation 1
1.2 Outline 2

2 Scientific Background 5
2.1 Electron Beam Welding 5
2.2 Fracture Mechanics 6
2.2.1 The Fracture Mechanics Approach 6
2.2.2 The Brittle Fracture 8
2.2.3 The J-Integral 8
2.3 Constitutive Damage Models 10
2.3.1 The Rice and Tracey Model 10
2.3.2 The Rousselier Model 11
2.3.3 The Gurson-Tvergaard-Needleman (GTN) Model 13
2.4 Cohesive Zone Model (CZM) 15
2.5 ARAMIS System 19
2.6 Synchrotron Radiation-Computed Laminography (SRCL) 20
References 21

3 Characterization of Steel S355 Electron Beam Welded (EBW) Joints 27
3.1 Chemical Composition 28
3.2 Microstructures of Steel S355 EBW Joints 28
3.3 Mechanical Properties of S355 EBW 30
3.3.1 Hardness Measurement 30
3.3.2 Tensile Behaviour of Different Tensile Specimens 31
3.3.3 Fracture Surface of Notched Specimens 40

3.4 Fracture Behaviour of S355 EBW Joints 42
3.4.1 Fracture Toughness Tests 42
3.4.2 Fracture Surface Analysis of C(T)-Specimens 45
3.5 Summary and Conclusions 51
References 51

4 The Rousselier Model 53
4.1 Parameter Study Using the Rousselier Model 53
4.1.1 Influence of f_0 54
4.1.2 Influence of f_c 55
4.1.3 Influence of σ_k 57
4.1.4 Influence of l_c 58
4.2 Crack Propagation in the Homogeneous Base Material 61
4.3 Crack Propagation in an Inhomogeneous Region 64
4.4 Discussion and Conclusions 72
References 73

5 The Gurson-Tvergaard-Needleman (GTN) Model 75
5.1 Parameter Study Using the GTN Model 75
5.1.1 Influence of f_0 76
5.1.2 Influence of f_c 78
5.1.3 Influence of f_f 79
5.1.4 Influence of f_n 81
5.1.5 Influence of ε_n 82
5.2 Crack Propagation in the Homogeneous Base Material 85
5.3 Crack Propagation in an Inhomogeneous Material 88
5.4 Discussion and Conclusions 92
References 94

6 The Cohesive Zone Model 97
6.1 Parameter Study Using the Cohesive Model 97
6.1.1 Influence of Cohesive Strength T_0 and Cohesive Energy Γ_0 100
6.1.2 Influence of the Cohesive Element 100
6.1.3 Influence of the Shape of the TSL 104
6.2 Crack Propagation in S355 Base Material 105
6.2.1 Identification of the Cohesive Parameters 105
6.2.2 Identification of the Shape of the TSL 110
6.3 Crack Propagation in S355 Fusion Zone (FZ) 111
6.4 Crack Propagation at the Interface Between the FZ and the HAZ 112
6.5 Discussion and Conclusions 115
References 117

7 Optical Measurement of Crack Propagation with the ARAMIS System 119
7.1 Specimen Preparation 119
7.2 Experimental Results Obtained with ARAMIS 119
7.3 Comparison of Experiment with Simulation Results Obtained with the GTN Model 125
7.4 Discussion and Conclusions 129
References 131

8 In Situ Laminography Investigation of Damage Evolution in S355 Base Material 133
8.1 Laminography 133
8.2 In Situ Observation of Damage Evolution by Laminography Reconstruction 135
8.3 Discussion and Conclusions 160
References 162

9 Summary and Outlook 163
9.1 Summary 163
9.2 Outlook 167

Appendix 169

Notations and Symbols

Symbols

a	Half of the crack length (mm)
a_0	Initial crack length (of the specimen) (mm)
σ	Stress (MPa)
σ_c	Critical cleavage stress (MPa)
σ_{ij}	Stress tensor (MPa)
σ_{eq}	Von Mises equivalent stress (MPa)
σ_k	Material constant of the Rousselier model (MPa)
σ_m	Mean (hydrostatic) stress (MPa)
σ_0	Yield stress (MPa)
Δa	Crack extension (mm)
ΔD	Cross-sectional reduction (mm)
K_I	Stress intensity factor ($MPa\sqrt{m}$)
f	Void volume fraction
f_0	Initial void volume fraction
f_c	Critical void volume fraction in the Rousselier model
	Void volume fraction of void coalescence in the GTN model
f_f	Final void volume fraction (in the GTN model)
f_u^*	f^* in the GTN model ($f = f_f$)
l_c	Main distance between two neighboring voids (mm)
T_0	Cohesive strength (MPa)
r	Void radius (mm)
G	Energy release rate (J/m^2)
Π	Pi
q_1, q_2, q_3	Model parameters affecting the GTN yield surface
W	Strain energy density (Pa)
ε_n	Mean strain when void nucleation happens
s_n	Standard deviation

ε_{ij}	Strain tensor
η	Stress triaxiality ($\eta = \sigma_m/\sigma_{eq}$)
k	Damage acceleration factor in the GTN model
θ	Laminographic angle (degree)
v	Poisson's ratio
δ	Separation of the cohesive element (mm)
δ_0	Critical displacement at failure in the cohesive model (mm)
δ_{init}	Displacement when void initiation happens in the cohesive zone model (mm)

Capital symbols

A	Strain at rupture
A_g	Uniform strain
K_{nm}	Cohesive stiffness ($\delta = \delta_{init}$)(N/mm^3)
W	Width of fracture mechanics specimen (mm)
Γ_0	Cohesive energy (N/mm)
E	Young's modulus (MPa)
F	Force (N)
F*	Revised factor for initial void volume fraction
J	J-integral (N/mm)
$J_{0.1}$	J-value when $\Delta a = 0.1$ mm (N/mm)
J_i	J-value when the first finite element is damaged (N/mm)
J_R	Fracture resistance

Abbreviations

2D	Two dimensional
3D	Three dimensional
ASTM	American Society for Testing and Materials
B	Thickness of the specimen
Bcc	Body-centered cubic
BM	Base material
B_n	Net thickness of the specimen
C	Compliance of the C(T) specimen
C(T)	Compact tension
CCD	Charge-coupled device
CMOD	Crack mouth opening displacement
COD	Crack opening displacement
CTOD	Crack tip opening displacement
D	Damage variable in cohesive zone model
EBW	Electron beam welding
EDM	Electrical discharge machining
EDX	Energy-dispersive X-ray spectroscopy
FEM	Finite element method

FZ	Fusion zone
GTN	Gurson–Tvergaard–Needleman (model)
HAZ	Heat-affected zone
HEDB	High energy density beam
HV	Vickers hardness
M(T)	Middle-cracked tension (specimen)
SEM	Scanning electron microscope
SENB	Single-edge notched bend
SRCL	Synchrotron radiation-computed laminography
SRCT	Synchrotron radiation-computed tomography
TSL	Traction separation law