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Dependence of fracture strain on flaw size in rail switches—Experiments and theoretical modelling

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A R T I C L E I N F O

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A B S T R A C T

With increasing requirements regarding wear resistance of rails especially in switch components, high strength materials have entered also this field of application. This poses new challenges for the manufacturing process, especially in bending the curvature radius. During the bending process of switch components a high strain is applied to the outer fiber of the rail foot, about ten times larger than in normal operation when a train passes through the rail. The current paper presents an investigation, whether and to which extent rails made of high strength materials have to be treated differently during the bending process if one takes into account potential flaws on the bending behaviour of rails.

In the present contribution static tests on three-point bending specimens with surface cracks of varying lengths are performed for four materials with different microstructures from medium to high strength rail grades. For the prediction of static failure the failure assessment diagram (FAD) is widely used where the normalized crack tip loading is plotted against the degree of plastification. To provide a diagram more readily applicable to design purposes, the nominal strain of the outer fiber at failure—obtained by finite element (FE) simulations of each individual experiment—is plotted against the crack size. This diagram for the dependence of the static failure strain on the flaw size can be seen as the static equivalent to the Kitagawa-Takahashi diagram for fatigue.

1. Introduction

High strength materials are being increasingly considered for improving the wear resistance of rail infrastructure, especially in switch components. In order to assess the usage of these rails also for switch manufacturing with very special production processes like factory-bending, bending related questions were dealt with during this investigation. The applied load during bending—as a central element of the manufacturing process for switches—is about ten times higher than the typical load observed during a train passage. As a characteristic quantity for the bending process one can take the strain at the outer fiber of the component. It is understood that the standards prescribe a minimum rupture strain of 8–9% in the tensile test. However, the standard specimens have a ground and polished surface, whereas the finishing of the rail surface is much coarser; due to the surface roughness and flaws generated during processing—which acts much the same as small surface flaws—the actual rupture strain for the rail will be lower than for the standard specimen.

In order to analyze the fracture behaviour and to design a failure curve of the nominal strain in the outer fiber depending on the size of such surface flaws, three-point bending specimens with surface cracks of varying lengths have been manufactured from four

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Nomenclature

a	initial crack length [mm]
$a^{(e)}$	size of the finite element [mm]
a_{pl}	transition point between LEFM and EPFM [mm]
α	material constant of the Ramberg-Osgood hardening equation [–]
β	material constant to calculate the dependency of the Q-stress [–]
B	thickness of the specimen [mm]
D	material constant to calculate the Q-stress depending on the crack length [–]
D_r	parameter in the failure assessment diagram [–]
E	Young's modulus [MPa]
ε	total strain [–]
ε_0	strain at the yield stress in the Ramberg-Osgood hardening equation [–]
ε_{el}	elastic strain until yield point [–]
ε_f	failure strain [–]
$\varepsilon_{f\text{-}EPFM}$	failure strain in elastic-plastic fracture mechanics [–]
$\varepsilon_{f\text{-}LEFM}$	nominal failure strain in linear-elastic fracture mechanics [–]
ε_{pl}	plastic strain beyond yield point [–]
ε_{ref}	nominal applied strain at rupture [–]
ε_v	equivalent strain [MPa]
F	applied force [N]
$f(a/W)$	geometry function [–]
$f(L_r)$	function to describe K_r in the FAD [–]
$f(n)$	plastic correction function of the J-Integral beyond the yield strength [–]
F_{max}	maximum applied force at rupture [N]
H	height of the specimen [mm]
I_n	material constant of the HRR field [–]
η	material constant to calculate the critical J-Integral depending on the Q-stress [–]
J	J-integral [kN/m]
J_c	critical J-Integral [kN/m]
J_{el}	elastic part of the J-integral [kN/m]
J_{mat}	material dependent J-Integral [kN/m]
J_{pl}	plastic part of the J-integral [kN/m]
k	material constant to calculate the Q-stress depending on the crack length [–]
K	(mode I) stress intensity factor [MPa√m]
K_{Ic}	fracture toughness [MPa√m]
K_{mat}	material dependent fracture toughness [MPa√m]
K_r	parameter in the failure assessment diagram [–]
L_r	parameter in the failure assessment diagram [–]
n	hardening exponent of the Ramberg-Osgood hardening equation [–]
ν	Poisson ratio [–]
p	material constant to calculate the critical J-Integral depending on the Q-stress [–]
R	stress ratio [–]
r	distance from the crack tip in the HRR-field [mm]
s	distance between the load line and the support [mm]
σ	total stress [MPa]
σ_{el}	nominal elastic stress until yielding point [MPa]
σ_0	yield stress in the Ramberg-Osgood hardening equation [MPa]
σ_{ij}	stress tensor of the HRR field [MPa]
$\tilde{\sigma}_{ij}$	tabulated material parameter for calculation of the HRR field [–]
σ_b	nominal stress in the outer fiber due to bending [MPa]
σ_{ref}	nominal applied stress at rupture [MPa]
$\sigma_{\theta\theta}$	stress in tangential direction [MPa]
$\sigma_{\theta\theta,FEM}$	stress in tangential direction obtained from the numerical simulation [MPa]
$\sigma_{\theta\theta,HRR}$	stress in tangential direction obtained from the HRR field [MPa]
σ_{UTS}	ultimate tensile strength [MPa]
σ_v	equivalent stress [MPa]
σ_y	yield stress [MPa]
θ	angle for the position of the stress element in the HRR field [°]
v	deflection [mm]
w	strain energy density [MPa]
w_{el}	elastic part of the strain energy density [MPa]
$w_{el}(\varepsilon_0)$	elastic part of the strain energy density at yield point [MPa]
w_{pl}	plastic part of the strain energy density [MPa]
$Y(a/W)$	geometry function [–]

typical rail materials with different microstructures and have then been tested until fracture. A comparison of fracture mechanism estimation with experimental results will be performed in order to deliver simple failure criterion for the bending process.

2. Materials

The different material hardening behaviours are specified by the Ramberg-Osgood material law.

Table 1
Ramberg-Osgood parameters.

Material	n [–]	α [–]	σ_0 [MPa]	ε_0 [–]
Pearlite	4.56	0.1329	316	0.001497
Fine-pearlite	3.82	0.1872	302	0.001465
Bainite	9.18	0.1207	685	0.003567
Ferrite-martensite	12.55	0.0321	944	0.004796