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Abstract
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about 200 words

Keywords
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maximum of 10 keywords
your suggestion will be the basis for subject and materials indexes
avoid single generic terms such as "fatigue"

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Units
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numerical references in square brackets, e.g. [1] and [2-3]
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EXAMPLE

MULTIAXIAL FATIGUE BEHAVIOUR OF LASER BEAM WELDED THIN STEEL SHEETS FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

The multiaxial fatigue behaviour of thin laser beam welded tube-tube specimens of the structural steel St35 was assessed according to the methodology of the fictitious weld root radius of $r_f = 0.05$ mm and the application of the Effective Equivalent Stress Hypothesis (EESH), especially considering the fatigue life reducing influence of out-of-phase loading in comparison to in-phase loading. The results are applicable for the fatigue design of laser beam welded car body and chassis structures of thin steel sheets ($t \leq 3$ mm).

KEYWORDS

Multiaxial fatigue, laser beam welds, structural steel, combined loading, axial, torsion, finite element modelling, fictitious notch radius, local stress concept

INTRODUCTION

Laser beam welding is a joining technology, which is applied more and more in the manufacture of car bodies and chassis structures, Fig. 1, in order to realize lightweight structures with sufficient stiffness.

Fig. 1: Car structure in white

Thus, the realization of lightweight structures from thin sheets ($t \leq 3$ mm) is not only a manufacturing issue; also in the design stage appropriate assessment methodologies are required. In the past four years a local stress concept based on the method of the fictitious radius of $r_f = 0.05$ mm with its corresponding Woehler curve was developed and successfully applied for the fatigue strength estimation of laser beam welded steel as well as aluminium structures [1-5]. However, these investigations were carried out only under pure axial or pure torsion loading. The influence of a combined multiaxial loading on fatigue life, which occurs on car bodies, frame and chassis structures has not yet been investigated.

The present paper specifically addresses the influence of changing principal stress directions on fatigue life induced by out-of-phase axial and torsion loading of laser beam welded, overlapped tube-tube steel specimens. The paper will discuss whether conventional strength hypotheses, such as von Mises, are able to convert the investigated complex multiaxial stress states into the state obtained under uniaxial loading. If not, the applicability of a more appropriate hypothesis for considering out-of-phase loading, such as the Effective Equivalent Stress Hypothesis (EESH) for ductile steels [6, 7], will be investigated. This hypothesis was already successfully applied for the assessment of multiaxial loaded steel seam welds [6].

SPECIMEN, MATERIAL AND TESTING

Material

Since thin sheets for car bodies do not allow the fabrication of the tube-tube-specimens, Fig. 2, necessary for the combined multi-axial loading, the tube halves were manufactured from seamless tubes of the structural steel St35 corresponding to mild steel sheet qualities used in the automotive industry. Table 1 contains the chemical composition and Table 2 the conventional mechanical properties of the ferritic steel St35.

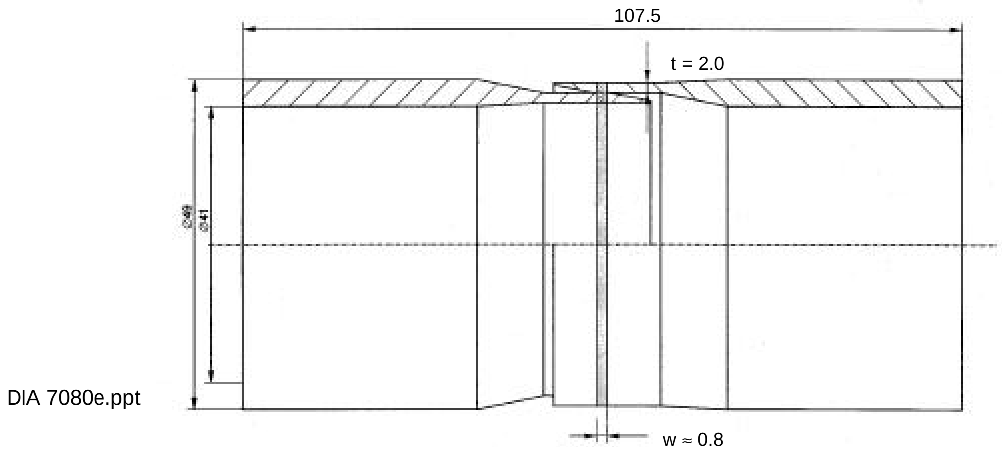


Fig. 2: Laser beam welded, overlapped tube-tube specimen

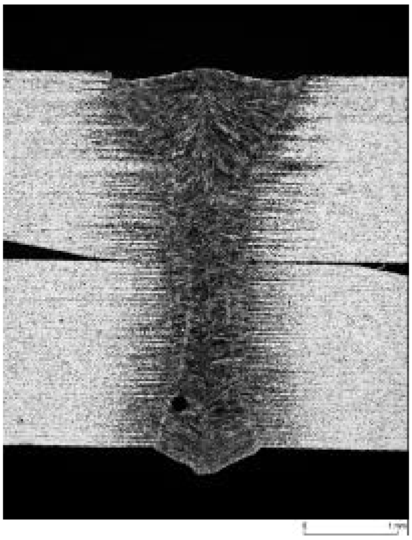
C	Si	Mn	P	S	Cr	Ni	Mo	Ti
0.11	0.26	0.43	0.004	0.007	0.056	0.090	0.055	<0.001

Table1: Chemical composition of St35 (in weight %)

$R_{p0.2}$ in MPa	R_m in MPa	E in GPa	e in %	HV0.2
235	405	206	26	140

Table 2: Conventional mechanical properties of St35

The tubes were welded by a 3 kW solid-state laser, with a welding velocity of 1.85 m/min under an atmosphere of Ar with a flow of 15 l/min. The microstructure of a welded joint is shown in Fig. 3. The average width of the laser welds between the weld roots was around w = 0.8 mm.



Hardness:

$HV1_{Base}$ = 123

$HV1_{HAZ}$ = 174

$HV1_{Weld}$ = 242

Outer tube

t = 2 mm

w = 0.8 mm

Inner tube

t = 2 mm

DIA 7106e

Fig. 3: Microstructure of a laser beam welded joint

Testing

The tube-tube specimens were tested in a servo-hydraulic biaxial test rig with a 100 kN axial and 2.5 kNm torsion actuator under load control. The testing frequency was between 5 to 10 s^{-1} depending on the load level and the load ratio was R = -1.

Four different test series were carried out: pure axial loading, pure torsion, combined in-phase ($\delta = 0°$) and out-of-phase ($\delta = 90°$) loading. The selected ratio of the nominal shear to the nominal normal stress amplitudes of the combined loading was $\tau_{na} / \sigma_{na} = 0.58$.

The failure criterion was the total failure of the specimens. During the tests the stiffness change (load versus deformation) was continuously registered. The period between significant change of stiffness (10 % stiffness drop) and total failure, caused by macroscopic crack propagation, was too short and therefore not separately considered for the fatigue life assessment, i.e. the results were all presented for the number of cycles to total rupture.

EXPERIMENTAL RESULTS

Fig. 4 and Fig. 5 display the experimental results in terms of load amplitudes versus cycles to failure and in terms of nominal normal and shear stress amplitudes, respectively.

E X A M P L E

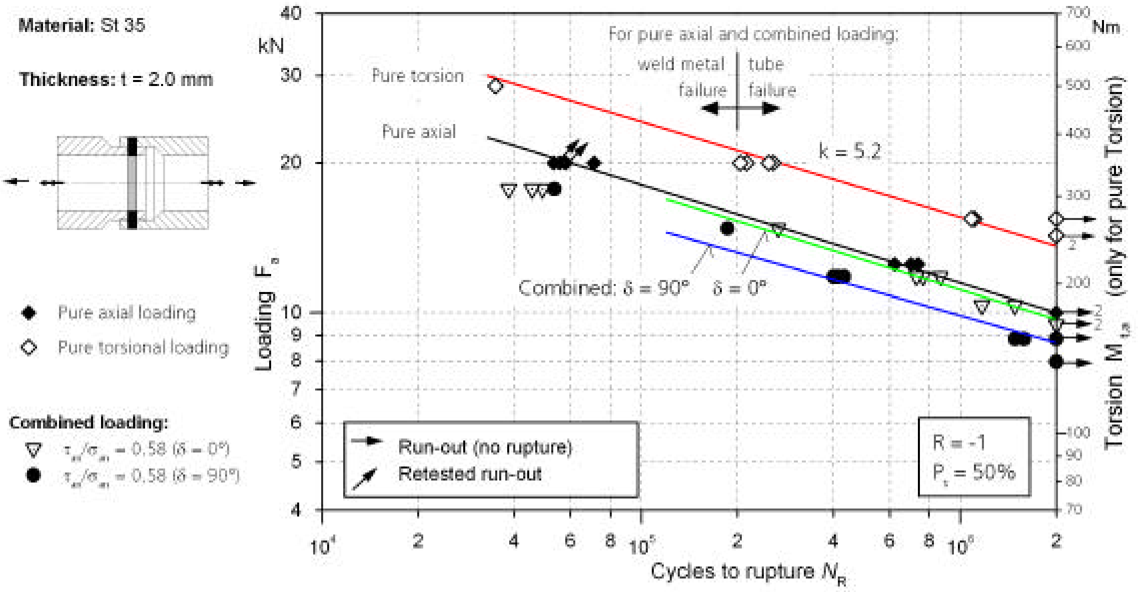


Fig. 4: Experimental results in terms of load amplitudes versus cycles to failure

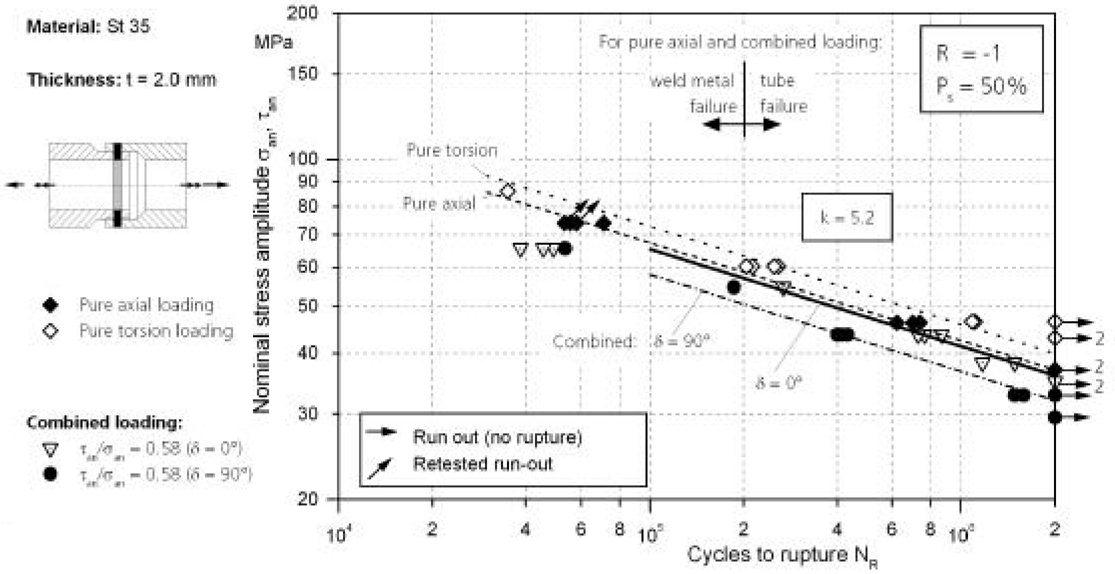
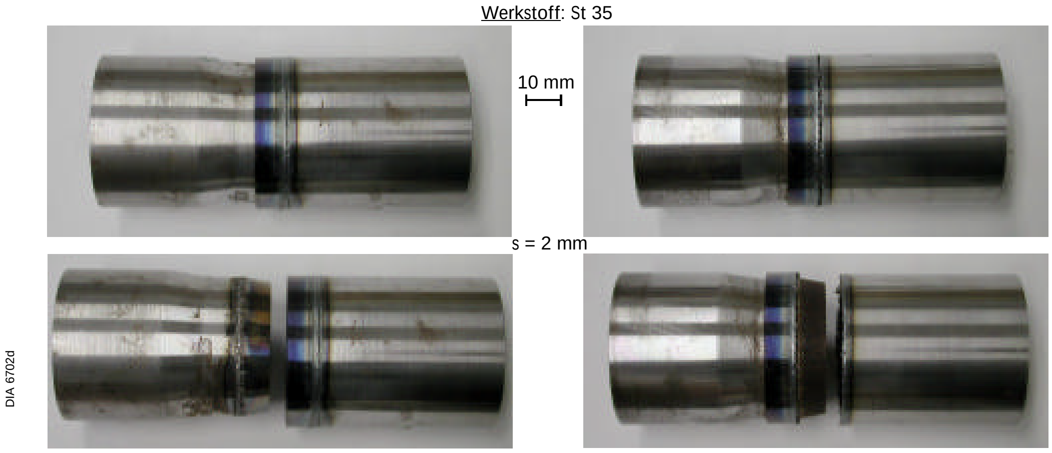


Fig. 5: Woehler curves in terms of nominal normal and nominal shear stress amplitudes

For pure axial loading and combined axial and torsion loading two types of failures were observed, Fig. 6. At high load levels the cracks propagated through the weld metal between the tube halves, on low load levels through the heat affected zone of the tube wall. This separation of the results with regard to the described two failure modes is also indicated in all figures with the SN-curves. Weld metal failures on all levels were observed only for pure torsion.



a. High load-level,
failure of the weld-seam

b. Low load-level,
failure through the tube

$\sigma_{an}=40$ MPa, $\tau_{an}=40$ MPa, R = -1, $\delta=0°$, $N_A=3{,}51\cdot10^5$

$\sigma_{an}=32$ MPa, $\tau_{an}=32$ MPa, R = -1, $\delta=0°$, $N=1{,}8\cdot10^6$

Fig. 6: Failure modes of laser beam welded tube-tube specimens

The most important result is that under combined axial loading and torsion, in case of tube failures the out-of-phase loading significantly reduces the fatigue life compared to in-phase loading. This fact proves that conventional hypotheses such as von Mises are not applicable for laser beam welded structures of ductile steels, because they render a higher fatigue life under out-of-phase loading than under in-phase loading [6]. The next sections will discuss the appropriateness of the Effective Equivalent Stress Hypothesis (EESH) to treat the obtained results.

In the case of weld metal failures at higher levels, out-of phase loading renders a higher fatigue life. Since this result has been obtained only with one specimen, further investigations are necessary for a sustainable assessment. Thus, this result in connection with the changing failure mode may also indicate a failure mechanism based on semi-ductile behaviour of the weld metal, compared to the tube failures based on ductile material behaviour of the tube [6, 7].

EVALUATION OF THE RESULTS

Since crack initiation and propagation is a local event, it is necessary to apply local concepts for their assessment [8]. In past years, the local stress concept using the fictitious radius of r_f = 0.05 mm has been introduced for the assessment of welded structures from thin sheets with sharp weld roots, especially for spot and laser beam welds [4, 5]. This concept was also successfully adapted to uniaxial loaded laser beam welded joints. By modelling the notches with a fictitious radius of r_f = 0.05 mm and calculating local linear-elastic stresses, a uniform master Woehler curve for steels and another one for aluminium was derived compiling all results within a very tight scatter-band [1-5]. This concept, having its background on linear-elastic fracture mechanics [5], will be used here for the assessment of the multiaxial fatigue behaviour of the investigated tube-tube specimens.

Finite-element modelling

The weld roots are modelled by a keyhole notch with a fictitious radius of r_f = 0.05. Fig. 7 displays the FE-model and the details.

necessary to consider the two different failure modes, failure of weld metal or failure through tube wall.

This investigation shows that complex multiaxial stress states occurring on laser beam welded thin steel sheets of car bodies and chassis structures can be satisfactorily assessed. However, since present investigations were carried out only with one thickness under constant amplitude loading, it is necessary to verify the application of the described methodology – the combination of the fictitious radius with the EESH – for different thickness combinations also when variable amplitude loading is present.

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