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Fatigue strength analysis of laser-hybrid welds in thin plate considering weld geometry in microscale

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ABSTRACT

Utilization of thin plates together with laser-based welding processes allows manufacturing of large weight efficient steel structures. However, the fatigue strength of welds in thin-plate structures with plate thicknesses below 5 mm is observed to have large variation, which brings challenges to fatigue strength assessment. One possible reason for this variation is the increased influence of actual weld geometry that is neglected in common fatigue strength assessment approaches utilizing geometry idealization. To reveal this influence the fatigue strength of 3 mm thick laser-hybrid welded butt joints were studied using the measured microscale weld geometry and the notch stress approach. Notch stresses were defined using Neuber's stress averaging approach which allows the determination of the fatigue-effective stress without fictitious geometric modifications. For the studied specimens the large scatter of fatigue strength in the high-cycle region could be explained using this approach with high-resolution weld profile measurements combined with thorough finite-element analysis. It was observed that axial misalignment in narrow laser-hybrid welds causes a significant notch stress increase on the root side reducing the fatigue strength dramatically in terms of structural and nominal stress. In order to capture the increased notch stress it is crucial to use a significantly smaller stress averaging length than commonly assumed for welded joints.

1. Introduction

Utilization of high-strength steels and thinner plates can provide weight savings for large welded steel structures such as ships. For joining of the thin plates laser-hybrid welding has received special interest due to its lower heat input and distortions, and also due to possible cost savings, compared to traditional arc welding [1–3]. Several studies have shown that significant improvement of fatigue strength can be obtained by utilizing high-strength steels and advanced welding processes compared to traditional materials and welding processes [4–6]. However, the challenge with welded joints in thin plates is the large variation observed in fatigue strength even with detailed local stress approaches [7,8], which has led to unaltered fatigue strength irrespective of the steel strength and weld quality in design codes and recommendations (e.g. [9,10]). In order to exploit the full potential of lightweight thin-plate structures and welding processes capable of producing high-performance welds, the accuracy of the stress-based fatigue strength assessment must be improved. This requires further understanding about the factors affecting fatigue strength, such as the influence of weld geometry.

Weld geometry has a large influence on the fatigue strength of welded joints and it is considered to be one of the main measures of weld quality regarding fatigue strength [11–13]. The existence of geometric imperfections, such as undercuts, are observed to be one of the reasons for large fatigue strength scatter especially for joints in thin plates [7]. However, while the influence of weld notch geometry on the fatigue strength is recognized, it is traditionally excluded from the analysis by geometry idealization due to uncertainties regarding the actual shape of the notch and lack of knowledge about the relation between the fatigue strength and the geometry. Modern geometry measurement technology is able to measure the geometry of the weld notch at the scale of micrometers, but the challenge of assessing fatigue strength based on this data remains. One main difficulties is the interaction of material microstructure and notch geometry at this scale – the phenomenon known as notch sensitivity [14,15].

In fatigue strength assessment of welds the geometry variation and notch sensitivity is commonly dealt with by the utilization of the effective notch stress approach by Radaj [16]. In this approach the weld geometry is idealized by a certain flank angle and

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Nomenclature

α	angular misalignment	σ_y	yield strength
Δ	range, e.g. $\Delta\sigma$ for stress range	θ	weld flank angle
ρ	radius of actual notch	e	axial misalignment
ρ^*	microstructural length, stress averaging length	k_m	stress magnification factor
ρ_F	radius of fictitious notch rounding	K_w	notch factor
σ	stress	N or N_f	load cycles until failure
σ_{eff}	effective notch stress	R	fatigue test load ratio
σ_{nom}	nominal stress	s	notch support factor
σ_{ρ^*}	average stress over ρ^*	t	plate thickness
σ_s	structural stress	T_σ	fatigue strength scatter index

fictitious weld radius. For normal quality welds in steels a fictitious notch radius $\rho_F = 1$ mm is commonly used [10]. This fictitious notch rounding is based on the theory of microstructural support introduced by Neuber [15]. He showed that the effective stress in a notch can be calculated using a fictitious notch having a radius given by the equation

$$\rho_F = \rho + s\rho^*, \tag{1}$$

where ρ is the actual radius of the notch, ρ^* is a material dependent microstructural length, and s is the support factor dependent on geometry of the specimen and notch. Value $\rho_F = 1$ mm is derived by assuming sharp weld notches ($\rho = 0$), a notch in a flat plate ($s = 2.5$) and mild cast steel properties ($\rho^* = 0.4$ mm, according to [15]).

Fictitious radius $\rho_F = 1$ mm combined with FAT225 class has shown to be in good agreement with the fatigue test results when a large amount of different weld geometries are analyzed together [17]. However, this fictitious notch rounding approach is currently limited to plate thicknesses above $t = 5$ mm [10]. For welds in thinner plates different fictitious notch radii have been proposed [18], but no consensus about the matter has yet been found due to lack of physical justification. Also, the value $\rho_F = 1$ mm has poor foundation for analysis of laser-hybrid welds. Due to different weld geometry compared to traditional welds [19] the assumptions for the sharp notch and the support factor value, varying with the notch geometry [20], can be questioned. In addition, the high hardness of laser-hybrid welds [21–23] indicates significantly smaller microstructural length than $\rho^* = 0.4$ mm according to the studies by Neuber [15], where values $\rho^* < 0.1$ mm are suggested for ferritic steel with yield strength above 300 MPa.

One reason for the challenges in fatigue strength assessment of joints in thin plates might relate to the increased influence of the actual weld notch geometry, making the geometry idealization methods inaccurate. The actual weld notch geometry is usually far from the idealized models when measured at the scale of micrometers; see Fig. 1. It is also expected that in laser welded steels with high hardness the influence of the weld notch geometry is even greater due to increasing notch sensitivity of the higher strength material. However, the influence of microgeometry, or topography, on weld fatigue has not yet been extensively studied and only few publications exist. Alam et al. [24] studied the fatigue behaviour of an eccentric laser hybrid fillet weld in four-point bending and came to the conclusion that weld toe radius is not always the dominating factor in fatigue performance as surface ripples may cause significant local stresses. The effect of the weld ripples on fatigue was also observed by Otegui et al. [25] for traditional welds. Neither of these studies, nor that of Hou [26] utilizing measured 3D geometry of the weld, examined the relation between fatigue strength and microgeometry by taking into account the notch sensitivity effect.

For finding explanation to the large scatter observed in fatigue strength of joints in thin plates the notch geometry effects should be examined together with the notch sensitivity theory. Thus, in this study the influence of measured weld notch geometry on the fatigue strength of laser-hybrid welds in thin plates is studied by utilizing micrometre-scale geometry measurement technology, extensive finite element analysis (FEA) and notch stress approach with notch sensitivity consideration. The aim of the study is to reveal the need for geometry measurements in the fatigue strength characterization of welded joints in thin plates. Applicability of the stress averaging approach by Neuber [15] on the analysis of measured weld geometry is also tested as current approaches are developed for the analysis of idealized weld geometries.

2. Fatigue strength assessment of welded joint based on measured notch geometry

The original theory of microstructural support by Neuber [15] is utilized in this study; see Fig. 2. In brief, Neuber suggested that instead of assessing the fatigue strength of the structural member based on the linear elastic maximum stress at the notch, the stress should be averaged over a thin surface layer. This stress-averaging effect is related to the heterogeneous microstructure of the material, which causes the load on critical microstructural elements (e.g. grains) to be distributed to surrounding elements and thus reducing the effective stress at the notch. The averaging depth is referred to as the microstructural length, or stress averaging length, and it is denoted by ρ^*. The fatigue-effective stress can then be expressed as

$$\sigma_{eff} = \frac{1}{\rho^*}\int_0^{\rho^*} \sigma(y)dy \tag{2}$$

where $\sigma(y)$ is the linear-elastic stress as a function of depth y. The stress averaging length ρ^* is a material parameter and by experimental methods Neuber derived values of ρ^* for different materials (e.g. structural steel); see e.g. [15]. In these studies limited to parent materials the stress averaging length was observed to be related to material strength. However, this relation is usually neglected in the analysis of welded joints and a fixed value of ρ^*, e.g. 0.4 mm, is used. Use of a material dependent value for ρ^* has, however, been shown to explain special fatigue characteristics of laser-hybrid welds in strain-based crack initiation and crack growth simulations including increased short-crack propagation time due to small grain size [27]. This suggests that a material dependency of ρ^* should also exist in simpler notch stress analysis methods.