Residual Stresses in Welded Steels with Longitudinal Stiffeners Determined by Neutron and X-Ray Diffraction

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The presented residual stresses were determined from a mild steel S355NL and a quenched and tempered high-strength steel S960QL by means of X-ray and neutron diffraction. The residual stresses were measured from welded steel plates with longitudinal stiffeners attached to both sides in as-welded condition after post weld treatment and mechanical loading. The objective of this paper is to present welding-induced residual stresses in longitudinal stiffeners in order to have a reliable reference for the evaluation of residual stress effects on fatigue strength. Furthermore, the results obtained are compared to residual stress measurements from earlier investigations.

INTRODUCTION

Residual stresses affect fatigue strength and must be considered in the evaluation of the behavior of welded components under fatigue loading. It is generally assumed that tensile residual stresses in welded joints reduce fatigue strength, whereas compressive residual stresses are beneficial. For component design, the actual residual stresses from welding are often unknown, so that conservatively high tensile residual stresses of the order of the yield strength ($R_y$ or $R_{pl}$) are assumed. For the evaluation of the fatigue strength, it is common to test small-scale specimens for reasons of simplicity and to transfer results to large-scale components. This method is generally used to establish a data basis for nominal stress design by means of S-N design curves according to several design codes (Hobbacher, 2009; Eurocode 3, 2010; JSSC, 1995; DNV, 2010). A major problem of small-scale specimens is that residual stresses at the location of crack initiation are often assumed to be much smaller than in full-scale components due to the lack of geometrical constraints. For example, longitudinal-shaped welds as butt welds or transverse stiffeners show smaller residual stresses without axial constraints (but not with high shrinkage constraints) during welding (Nitschke-Pagel et al., 2014). Low constraints are usually to be expected in laboratory-scale components, whereas large-sized components have higher stiffness. Furthermore, equilibrium for residual stresses in small-scale samples is only possible over sheet thickness or in plane. Large welded components allow equilibrium over the entire cross-section, which might allow higher stiffness and thus higher tensile residual stresses. Design codes treat this problem by providing design S-N curves for stress ratios with high tensile mean stresses, for instance, $R = a_{min}/a_{max} = 0.5$ (Hobbacher, 2009; Eurocode 3, 2010). High tensile mean stresses are used in fatigue testing for compensation of missing tensile residual stresses. The problem is that welded structures do not necessarily contain high tensile residual stresses, and thus residual stress effects might be overestimated conservatively. Effects from phase transformation have the ability to reduce tensile residual stresses by volume expansion during $\gamma$-$\alpha$ transformation (Wohlfahrt, 1986).

One small-scale sample type that is suitable for the determination of residual stress effects in small scale is the longitudinal stiffener. The axial shrinkage constraint of this sample type is high, and thus it can also be called a small-scale component. This sample type shows mean stress independency in as-welded condition during fatigue testing from $R = -3$ to $R = 0.5$, which is explained by high tensile residual stresses (Rürup, 2003). Hence, steel plates with longitudinally attached stiffeners are supposed to be similar in terms of residual stresses in small and large scale. It is generally assumed that high tensile residual stresses are present at the edge faces of the stiffeners where the fatigue crack starts. This weld detail was investigated earlier in terms of the relation between welding-induced residual stresses and fatigue strength (Buxbaum et al., 1987; Bogren and Lopez Martinez, 1993; Lopez Martinez et al., 1997; Berge and Eide, 1982; Stoschka et al., 2010; Nitschke-Pagel and Dilger, 2011; Varfolomeev et al., 2012; Weich, 2009). Although residual stresses were determined at the specimen surface and over thickness with reliable methods, the interpretation of the results may have been misleading. The cited measurements are very well-documented regarding the magnitude of the residual stresses, the location of measurements, and the condition of the sample. But for reasons of simplicity, it may happen that misleading conclusions regarding the influence of the residual stresses on the fatigue strength are drawn. In some cases, for several reasons, the residual stresses were not explicitly determined at the location of crack initiation but rather some millimeters away from the weld toe. The measured residual stress profiles were then extrapolated into the weld toe (Buxbaum et al., 1987; Lopez Martinez et al., 1997). One reason for this was that the weld toe could not be reached by the X-ray beam due to overlapping weld material (Buxbaum et al., 1987). In other investigations some mechanical treatment, for instance, grinding or cutting, was performed at