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Fatigue properties of cut and welded high strength steels – Quality aspects in design and production

Zuheir Barsoum[a,b*], Thomas Stenberg[a,b], Eric Lindgren[b]

[a]KTH Royal Institute of Technology, Teknikringen 8, Stockholm 100 44, Sweden
[b]Nordic Welding Engineering AB, Nansta 208, Forsa 820 65, Sweden

Abstract

In this study, several aspects regarding effect of quality on the fatigue strength in welded cut HSS have been investigated and are discussed. A novel numerical algorithm has been developed which assesses the welded surface and calculates and quantifies weld quality parameters and the presence of defects which are critical in fatigue applications. The algorithm is designed for implementation in serial production. It will provide robust and reliable feedback on the quality being produced, which is essential if high strength steels are utilized and high quality welds are necessary for the structural integrity of the welded component. Two welding procedures which can increase the weld quality in as welded conditions have been assessed. It was found that by using these methods, the fatigue strength can be increased with 20% compared to normal weld quality. Furthermore, two fatigue assessment methods ability to account for increased weld quality in low cycle and high cycle fatigue applications has been studied. One of these methods showed sufficient accuracy in predicting the fatigue strength with small scatter and also account for increased weld quality. The influence of surface quality on cut edges was studied and the fatigue strength was estimated using international standards and a fatigue strength model for cut edges. It was found that the fatigue strength in testing was 15-70% higher compared to the estimation, thus proving a weak link between the international standard and fatigue strength.

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Keywords: Fatigue; welded joints; quality; high strength steel

1. Introduction

Design and manufacturing of welded structures is an important task which requires accuracy, especially for robotic welding in serial production. For lightweight welded structures however, where thinner and high strength steels are utilized, the increased nominal stress levels require consideration of other design aspects such as buckling, plastic collapse and fatigue strength. High strength steels suffer from an increased sensitivity to notches and defects

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compared to mild steels. For welded components, the fatigue strength will be the same for high strength steel and mild steel if no improved weld quality is achieved [1]. Thus, improving the design of the welded structure by using high strength steel requires improved weld quality, which in turn demand an improved quality assurance. Today, most of the quality assurance for welded components is carried out by the audit process, separate to the production line, using standard gauges. Hammersberg and Olsson [2] concluded that basic standard gauges and methods for weld quality assurance are out-dated if care is not taken to investigate and improve the used measurement systems relative to the actual variations occurring in production. Thus, to fully achieve lightweight design in welded structures, manufacturing companies which utilize serial production will face challenges in quality assurance when introducing high strength steel in their products.

2. Weld quality

The weld quality quantifies the welded joints ability to perform the functional requirements of the weld during the service life of the structure. Which could be either durability in static and/or dynamic loading, corrosion resistance, appearance or any other mechanical function. Insufficient quality must be avoided due to serious consequences in safety and cost, i.e. failure occur at an early stage. Excessive quality on the other hand may result in increased fabrication cost which does not add more customer value to the product. It is also necessary as a design engineer to specify the sufficient quality in the relevant locations of the structure, as various locations in the structure may experience increased loading due to local stress raisers such as stiffeners, holes and notches [3]. The ISO 5817 [4] standard was designed in the 1960´s using a German design code DIN 5863, by welding workshops which were following the principle of "good workmanship". However, later studies [5] show that the acceptance limits for different imperfections within ISO 5817 does not correlates with the resulting fatigue life. Fig. 1 illustrates examples of imperfections in ISO 5817. Jonson et al [6] developed a new weld quality system which has become a Volvo Group corporate standard [7] which have the distinct characteristic of relation between each weld quality level should correspond to a 25% increase in fatigue strength, which is approximately a factor 2 increase in fatigue life. In order to account some of the drawbacks ISO 5817 was revised in 2014 in order to incorporate some of the findings in the Volvo standards.

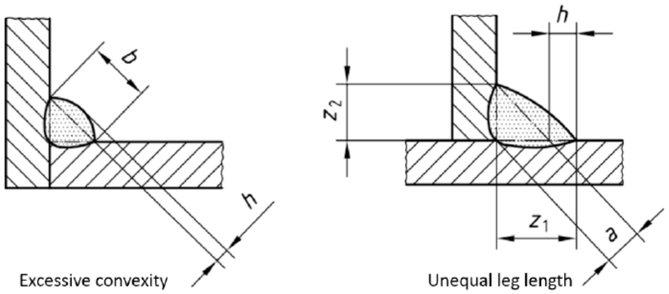

Fig 1. Examples of imperfections in ISO 5817 [4].

3. Measurement systems for quality assurance

Today, numerous handheld manual gauges are available to assess the weld quality in production and inspection. To decide whether a gauge is appropriate for quality assurance or not depends on (i) what feature the system is supposed to measure, (ii) the specified tolerance width of that feature on the part, and (iii) if the gauge's contribution to the variation is significantly lower than the tolerance width of the part. Hammersberg and Olsson [2] conducted a measurement system analysis on the gauge when measuring the weld throat thickness, see Fig. 2. It was concluded that the gauge had a contribution of almost 60% of the total variation, which is too large for Go/No Go decisions (>9%) and process development (>4%). Other tools available for measuring the local weld geometry are vision systems, where the welded surface is scanned and the evaluation is performed in a computerized environment. A newly developed weld quality control and assurance with concept of a total digitalization and automation of the quality measuring process. This system, *WeldAssist*™ [8], consists of an automated method, a new laser scanning technology, algorithms and software. It is verified that the system can successfully be used as modern tool for automated unbiased geometrical weld quality assurance and implemented in weld production environment [9]. Fig 3 shows a schematic overview of how the system works.

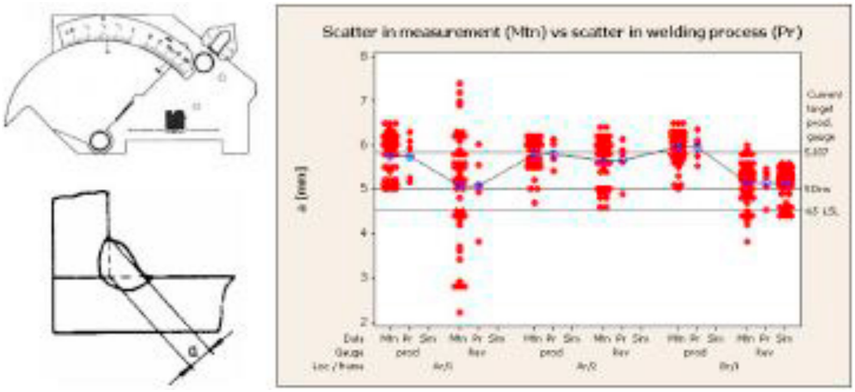

Fig 2. Measurement system analysis of gauge for measuring the throat thickness.

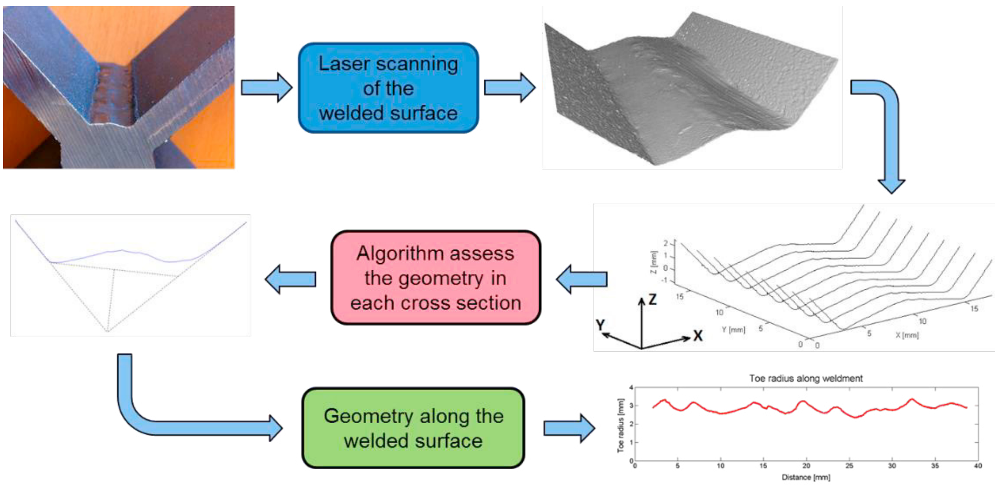

Fig 3. Schematic overview of quality measurement system *WeldAssist*™.

4. Improved fatigue strength using alternative methods

The welding process itself induces several types of material flaws and imperfections into the welded joint. Material flaws are for example softening in the heat affected zone and tensile residual stresses. Weld imperfections such as undercuts and small weld toe radii increases the stress concentration in the weld toe, which decrease the fatigue life of the welded joint and the presence of cold laps decrease the fatigue life even further [10]. The available methods to increase the fatigue life of a welded joint can be divided into two main groups; methods for reducing tensile residual stresses and methods for weld geometry improvement. Methods for improving the residual stress state are mainly post-weld treatment methods, such as High Frequency Mechanical Impact methods (HFMI) [11]. However, such methods will increase the cost of manufacturing in terms of excessive work efforts and also prolonged lead time in production. Thus, if the fatigue strength can be improved using an improved welding process, additional costs for post treatment can be avoided. Optimizing the welding process includes selecting appropriate welding process parameters, positioning and also choice of filler material and shielding gas [12, 13]. Fig 4 shows the fatigue life increase with a reference to as-welded condition for different alternative welding techniques, with a potential of up to 270 % increase in fatigue life with e.g. smooth undercut.

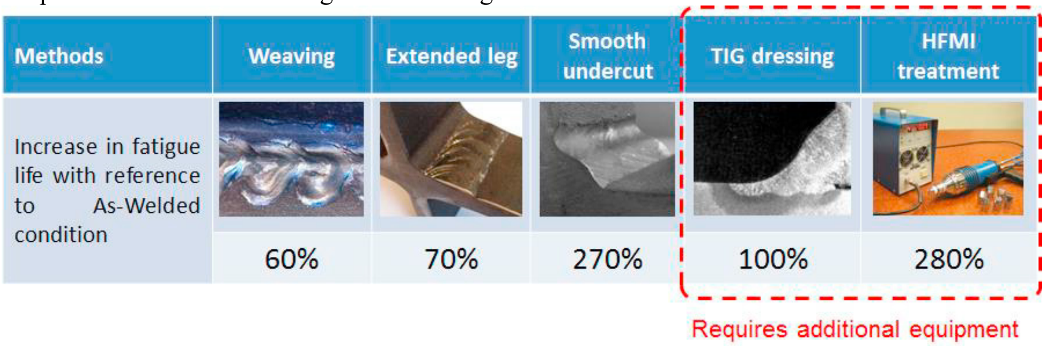

Fig 4. Improving the fatigue life with alternative methods.

5. Fatigue design for improved weld quality

Since fatigue failure of a welded joint is mainly governed by the local stress conditions, it is necessary to use local design approaches. The choice of fatigue design method is based not only on the work effort and accuracy of the approach, but also on the load level, failure location and the complexity of the structure. Depending on the load level, i.e. the amount of plasticity in the joint, different methods are suitable for fatigue assessment since different failure mechanisms occur depending on the loading. Strain based approaches have proven to be more accurate compared to stress based methods when there is a high level of plasticity in the joint, this is denoted as low cycle fatigue. Lower load levels which give less plasticity in the welded joint and its notches are denoted as high cycle fatigue, for which stress based methods for fatigue assessment are more adequate. There is a transition between low cycle fatigue and high cycle fatigue behavior which is dependent on a number of factors, primarily on what local load the critical crack tip is subjected to. For welded joints with improved quality – either high quality as welded or post weld improved joints – the local stress concentration is reduced and thereby also the local loading on the fatigue crack tip. From a lightweight design perspective – which incorporates producing high quality welds – it is necessary to know how to account for increased weld quality at the design stage. It is therefore essential to choose a design method which can account for improved weld quality. In the study by Stenberg et al [14] two stress based methods, the effective notch stress method and the structural stress approach, to estimate the fatigue life in the low cycle and the high cycle fatigue regime, considering the weld quality. The study shows that both methods are capable to estimate the fatigue life with good accuracy within the low cycle and the high cycle regime. The effective notch stress generally shows a smaller scatter, it also considers increased weld quality with good accuracy, in contrast to the structural stress approach. Fig 5 show the predicted fatigue strength along with fatigue test data.

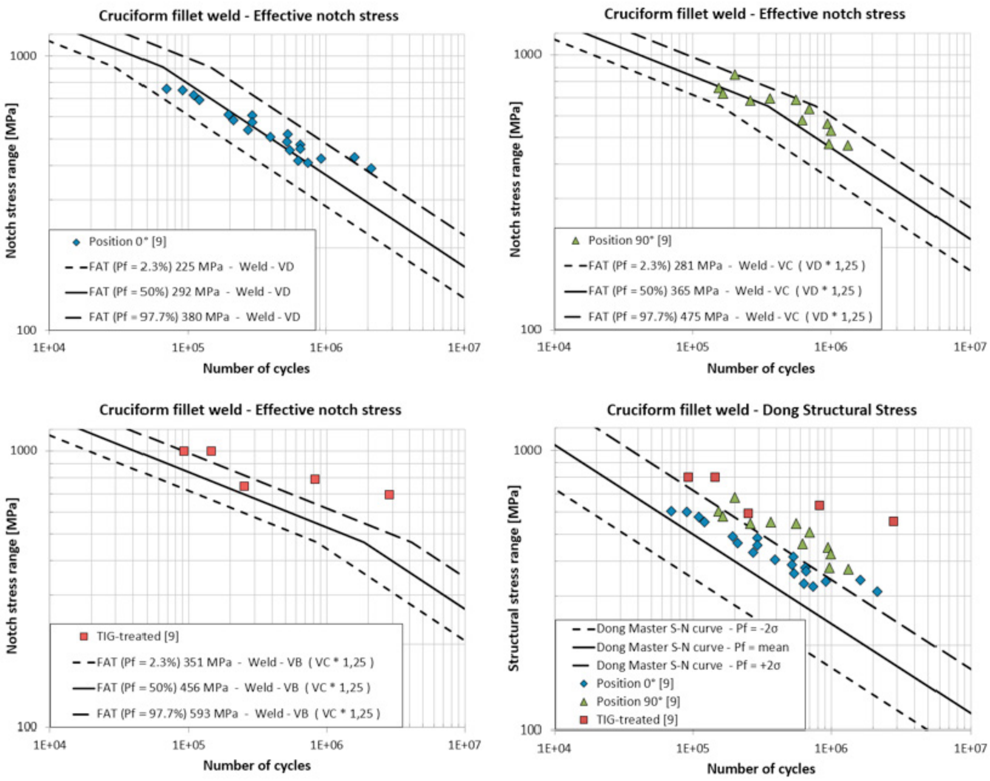

Fig 5. Fatigue strength prediction using the two concepts on cruciform joints welded with different weld quality.

6. Fatigue and quality aspects of cut edges

In fatigue loaded applications it is important that the introduction of high strength steels goes hand in hand with the improvement of production quality. Since defects are commonly induced from the manufacturing processes such as welding and cutting, these will eventually delimit the service life of the structure if steels with increased strength are used. The main governing factors of the fatigue strength in cut edges are the surface quality (surface roughness, hardness etc.), yield and ultimate strength of the material and residual stresses induced during the manufacturing, which has to be taken into consideration in the fatigue design phase. Stenberg et al [15] conducted a study on the influence of surface roughness on the fatigue strength in high strength steels and different cutting processes; oxygen, plasma, laser and waterjet cutting. Estimations of the fatigue strength are made based on the measured surface roughness and the ISO 9013:2002 standard for thermal cutting quality tolerances, along with the fatigue strength model developed by Sperle [16], see Fig 6. The ranges 1-4 corresponds to quality ranges according to ISO 9013:2002.

The testing shows a 15– 70% increase in the fatigue strength compared to the estimation, proving a weak connection between the surface quality levels in ISO 9013:2002 and the fatigue test results, see Fig 7. Different codes and design recommendations (IIW, EC3 and EN 13001) for fatigue strength of cut surfaces are compared with the fatigue test results which clearly shows an increased fatigue strength with enhanced quality and steel grades. However, the codes and design recommendations do not allow for any fatigue strength improvement with improved quality and increased yield strength.

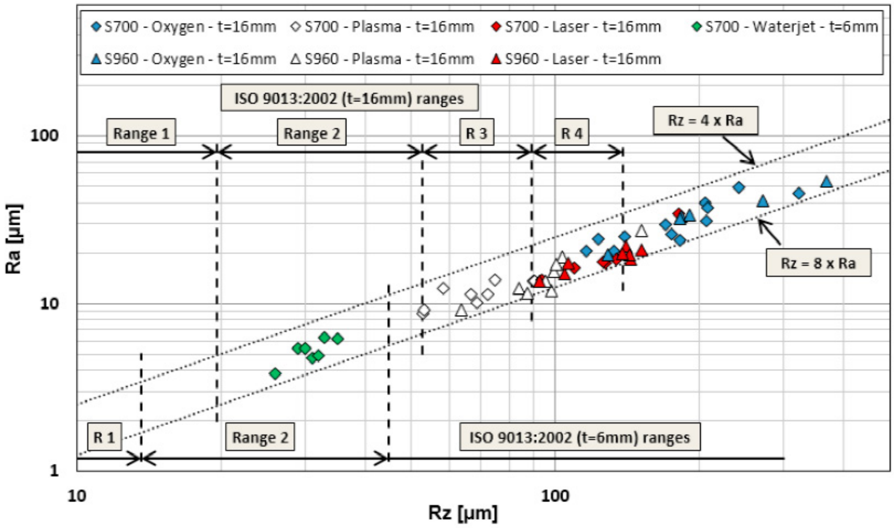

Fig 6. Surface roughness measurement on cut edges.

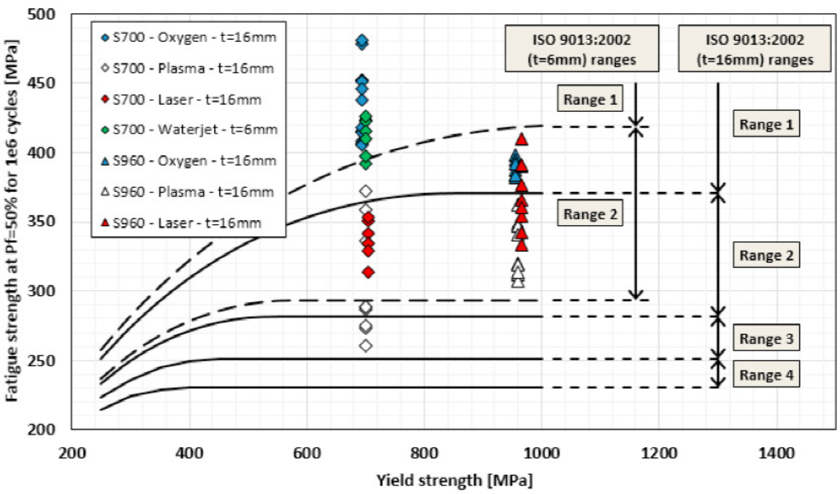

Fig 7. Median fatigue strength and model by Sperle [16] and surface roughness acceptance limits in ISO 9013:2002.

Conclusions

- Novel weld quality assurance methods will enable design and manufacturing of lightweight welded structures
- High quality welded joints can be produced in as welded conditions using optimized welding procedures
- Welded joints should be designed and manufactured in accordance to the purpose of the weld, not to fit general requirements
- Only local fatigue assessment methods are capable to account for high quality welds in design of welded structures
- Current design guidelines and codes prove to be conservative and ambiguous in terms of production quality
- There is an urgent need to develop design guidelines and recommendations which allow designers to account for increased quality of welded joints and cut surfaces

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