Engineering Failure Analysis 93 (2018) 340–355

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Fracture mechanics based estimation of fatigue lives of laser welded joints

Rakesh Goyal[a,*], Sergey Bogdanov[b], Mohamad El-zein[c], Grzegorz Glinka[b]

[a] *John Deere Asia Technology Innovation Center, Pune, MH 411013, India*
[b] *Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada*
[c] *Deere & Company, MTIC, One John Deere Place, Moline, IL 61265, United States*

ARTICLE INFO

Keywords:
Laser welds
Stress analysis
Fracture mechanics
High strength steels
Fatigue life

ABSTRACT

The conventional joining methods like resistance spot welding and arc welding have several challenges during joining of thin sheets of high strength steel materials. One of the main challenges is that application of these joining methods may result in a severe distortion of welded structure. Therefore, laser welding process has emerged as an alternative joining process which can help mitigate some of these challenges. Lower heat input from laser during the welding process results in a smaller size weld heat affected zone and also in lower overall distortion of the structure. The laser welding process presents an exciting opportunity in designing lighter weight structures. However, the major roadblock to application of laser welding method for large structural parts is that fatigue behavior of laser welded joints is not yet well understood. In order to study the fatigue performance of laser welded joints, detailed experimental and numerical investigations have been carried out and the results are presented in this work. The scope of experimental studies included a large set of coupons with different thicknesses and material combinations. Experimental fatigue test data has been generated for the laser welded joints produced using thin sheets of three grades of high strength steel materials (HSLA and UHSS grades) of several thicknesses (1 mm, 1.6 mm, 2 mm and 3 mm). The fatigue test data sets were obtained at R-ratios of $R = 0.1$, $R = 0.2$ and $R = 0.3$. Another variable introduced into experimental studies was an orientation of laser weld joint with respect to applied loading direction. After fatigue tests were completed, detailed metallurgical investigations have been carried out to understand the failure mechanism and the crack growth behavior in laser welded joints. Based on the observed experimental and numerical studies it was concluded that the strain life based fatigue analysis method which has been successfully applied to study weld toe failures for the arc weld joints is not sufficient for the evaluation of laser welded joints. This is due to the reason that laser welded joints have unique challenges due to weld root crack failures and extremely high stress concentration at the location of crack initiation in the root of laser welded joints between the plates. The fracture mechanics based method has been developed for the fatigue life assessment of laser welded joints. In order to apply this method comprehensive three-dimensional finite element studies were performed. Numerical studies show good correlation of the estimated fatigue lives obtained using proposed fracture mechanics method with the experimental data.

---

[*] Corresponding author.
E-mail address: GoyalRakesh@JohnDeere.Com (R. Goyal).

https://doi.org/10.1016/j.engfailanal.2018.07.017
Received 28 January 2018; Received in revised form 23 June 2018; Accepted 20 July 2018

1. Introduction

The need for light weighting of structural parts in the automotive and other ground vehicles machinery is increasing than ever mainly due to emission control regulations and fuel efficiency requirements. The use of high strength steel materials along with thinner gauge sections is one of the ways to save weight and increase fuel efficiency. It is also well known that various types of joints are integral to any structure. Conventional joining methods such as gas metal arc welding and resistance spot welding are widely used across the industry for joining structural members. In addition to good understanding of the manufacturing process variables, significant amount of design data and level of confidence exist with the design and analysis methods of joints produced using these contemporary conventional processes. Laser welding on the other hand is an emerging technology which has been utilized for few years by the automotive industry but the widespread usage of it is still limited especially in the case of manufacturing of heavily loaded structural components. The laser welding process has shown great potential for the improved manufacturability of such assemblies especially when joining thin sheets of high strength steel grades. Due to much lower heat input of the laser welding process, it results into minimal distortion of large welded assemblies, which can greatly help to achieve and maintain tighter dimensional tolerances.

Laser welding enables to easily join two plates of sheet metal; however, such a joint introduces, between the two welded plates, a crack-like stress concentration region which can significantly influence the fatigue life of the joint. Unfortunately, the understanding of fatigue performance of laser welded structural joints is rather limited. Therefore, the failure mechanism of laser welded joints under cyclic loading conditions needs to be better understood [1–3]. A significant gap exists in terms of the design and analysis methods when using laser welded joints in cyclically loaded structural components [4–5]. Strain life based fatigue analysis method commonly used for analyzing arc welded joints are not suitable for the design of laser welded joints. Therefore, the finite element stress analysis (FEA) and fatigue analysis methods for evaluating laser welded joints need to be developed to help accelerate the product design cycle and improve the level of confidence while designing with these joints.

In order to address the above gaps, the present research is focused on the development of a methodology to predict fatigue life of laser welded joints. Various aspects of the methodology are discussed in the paper. Detailed description of the experimental work along with summary of experimental findings has been discussed in the paper. The challenges related to applicability of strain life method for the analysis of laser welded joints have been highlighted. The details of numerical analysis including 3D fine mesh FE modeling of laser welded joint have been presented as well. The fracture mechanics based method has been applied to estimate fatigue life of laser welded joints and the results have been compared against the experimentally obtained data. Conclusions and recommendations based on the results presented earlier are discussed at the end of the paper.

2. Materials

Three different grades of high strength steel material have been used in the investigation presented below. High strength low alloy steel grades (HSLA-50 and HSLA-80) and ultra-high strength steel grade (UHSS-100) have been utilized during this work. The chemical composition and mechanical properties of these high strength steel materials are shown in Tables 1 and 2 respectively. For each of these 3 material grades, cyclic stress-strain curves and Manson-Coffin curves were obtained experimentally as per the standard strain controlled fatigue test procedure described in ASTM E606. Drawing of the round test sample geometry with diameter (d) of 6 mm is shown in Fig. 1. The samples were CNC machined to rough shape and ground in the loading direction to a surface finish of 0.2 RMS (microns). All fatigue specimens were carried out at room temperature (23 °C) using a closed loop servo-hydraulic two post 100kN load frame. The tests were run in strain controlled manner and the stress strain response was recorded at cyclic intervals. The failure criteria used was a drop in peak stress of 30% of from the first cycle. The frequency of the tests was run at 3 Hz.

Stabilized stress data obtained from strain-life fatigue tests were used to construct the cyclic stress strain curve shown in Fig. 2. The cyclic stress-strain curve is described by the Ramberg-Osgood relationship which is shown below:

$$\varepsilon = \sigma/E + (\sigma/K')^{1/n'} \tag{1}$$

where ε is the total strain amplitude, σ is the cyclically stable stress amplitude, *E* is the cyclic modulus of elasticity obtained from the best fit of the above equation to the test data, K′ is the cyclic strength coefficient, and n′ is the cyclic strain hardening exponent.

Constant amplitude fatigue test data is further used to obtain the strain life fatigue curve. The stress amplitude corresponding to the peak strain amplitude was calculated from the peak load amplitude at one half of the specimen's life. Constant amplitude fatigue curves for 3 grades of high strength steel are given in Fig. 2 and are described by the following equations:

$$\Delta\varepsilon_e/2 = \sigma_f'/E\ (2N)^b \tag{2}$$

Table 1
Typical chemical composition high strength steel grades (wt%) per ASTM A1011.

Material	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V	Nb
HSLA-50	0.15	1.65	–	0.020	0.025	0.15	0.20	0.06	0.20	0.005	0.005
HSLA-80	0.15	1.65	–	0.020	0.025	0.15	0.20	0.16	0.20	0.005	0.005
UHSS-100	0.15	2.00	–	0.020	0.025	0.15	0.20	0.40	0.20	0.005	0.005