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Fatigue analysis of multipass welded joints considering residual stresses

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ABSTRACT

Gas metal arc welding (GMAW) is one of the most used joining method in the industry. However, one of the main problems of this process is the generation of residual stresses (RS). There are different approaches to predict the fatigue life of welded joints, but in general, these approaches do not consider the real value of RS. Therefore, the current approaches to estimate fatigue life of welded components are conservatives.

This paper describes an alternative method to asses high cycle fatigue (HCF) life prediction based on numerically estimated RS values. Results have shown good correspondence for the HCF range, with a maximum average error of 15% in stress for the studied configurations. The proposed method can be used as a valid tool to optimise the geometry of the component and thus decrease the economic cost.

1. Introduction

Welding is the most widespread joining technique for metallic structures due to its applicability to many geometric configurations [1]. The main failure mode of welded joints is the fracture due to fatigue [1–3]. Usually, the fatigue strength of welded joints is much lower than the base material strength [4], since there are other variables, such as RS, stress concentration effects, areas with different mechanical properties or inhomogeneous geometry of the weld joint.

As mentioned in the preceding paragraph, RS have direct impact on the high cycle fatigue life behaviour of welded components [4,5]. However, the estimation of RS pattern in welded structures is very complex since multi-physics phenomena as heat, electricity, or mechanical work take part in them [6,7]. In addition, the accurate measurement of RS nowadays presents some limitation as experimental methods are not fully reliable [8–10]. Consequently, most of the currently used fatigue life estimation approaches do not consider RS real value.

Among the different approaches to predict the fatigue life of welded joints that do not consider the real value of RS the following methods can be remarked: (i) the nominal stress method, widely used and included in the majority of standard codes [11–18]); (ii) the structural stress methods, such as hot spot stress [11,17–19], thickness stress linearisation method developed by Dong et al. [17,19,20] or the method for welding toe structural stress determination developed by Xiao and Yamada [17,19,21]; and (iii) local methods such as notch stress approach [11,16–18]. The main drawback of these methods is the lack of accuracy, because they do not consider the real value of RS. Thus, nominal stress and structural stress approaches are very conservative in the High Cycle Fatigue (HCF) regime [22]. On the other hand, notch stress approach [18,23,24], estimates the endurance limit with higher accuracy. However, provides optimistic results for loads higher than the fatigue limit for the HCF regime. In addition, in order to obtain consistent results for structural steels, it has been shown that the effective notch radius must have the value of 1 mm [11,25,26]. Consequently, the main limitation of this method is the computational cost due to the element size in the rounded region.

Still nowadays, the analysis of the fatigue behaviour of welded joints subjected to multiaxial stresses is not fully resolved [27,28]. There are different approaches to deal the previous problem, which are based on obtaining an equivalent uniaxial stress. Between the different approaches, the following methods can be remarked: (i) the recommendations suggested by the standard codes [11,12,14,29], (ii) the effective equivalent stress hypothesis proposed by Sonsino [30,31], for ductile steels welds under multiaxial non-proportional loadings, (iii) the methods based on critical plane approach [2,32,33]. The main drawback of the previous methods is that they do not consider the real value of RS.

Other methods are based on the crack propagation approach proposed by Paris and Erdogan [34]. Some of them include RS such as the work developed by Barsoun et al. [35], based on the Linear Elastic Fracture Mechanics (LEFM). Recently, Zamiri et al. [36] include RS to estimate fatigue life of welded joints based on crack propagation using X-FEM. However, the main drawbacks of these

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Table 1
Chemical composition of the S275JR structural steel.

Material	% C max.	% Mn max.	% P max.	% S max.	% N max.	% Cu max.
S275JR	0.21	1.5	0.035	0.035	0.012	0.55

methods are the high computation cost, as well as the difficulties in the correct RS estimation. Furthermore, crack propagation methods require an initial crack size and location, which can be hardly defined in a design stage.

A promising approach has been developed by Bae et al. [37] where the fatigue life prediction is conducted considering the RS value for spot welds. In this approach, the value of the stress amplitude is defined employing the well-known equation of Goodman and the value of maximum principal stress at the nugget edge. Bae et al. [37] analysed different spot-welded joints, with various dimensions and shapes, and they showed that the developed method can provide accurate evaluation of the fatigue strength. However, the main drawback of this method is that it is developed for spot-welded joints and it cannot be directly applied for multipass spray transfer welds.

This paper is aimed at developing a procedure to estimate accurately the HCF life of different geometries of multipass spray transfer welded joints considering initial RS. For that purpose, initial RS are calculated following the recently developed modelling procedure to predict RS pattern in multipass welding [38]. Three geometries of welded joints have been analysed in detail: (i) 0° butt weld, (ii) 45° butt weld and (iii) T-joint welding. Furthermore, the developed fatigue life prediction procedure has taken into account the multiaxial stress state by using the critical plane approach based on Papadopoulos [39]. The developed procedure has been experimentally verified for different multiaxial stress states.

2. Theoretical procedure

The proposed theoretical procedure to predict fatigue life of multipass welded joints in the high cycle regime considering RS consists of two steps. First, RS pattern of the welded samples is estimated based on the numerical procedure presented recently by the authors [38]. Then, life estimation for HCF is conducted by considering the influence of the RS in the critical zone. In order to consider multiaxial stress state, the critical plane approach proposed by Papadopoulos [39] and extended to welded structures by

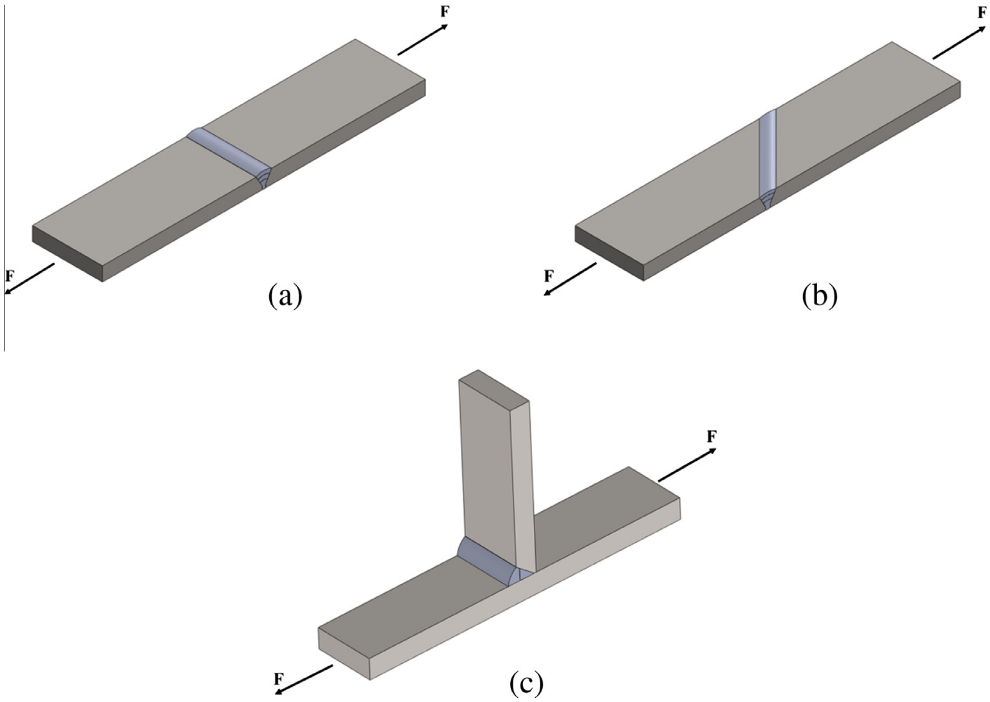

Fig. 1. Analysed welded joints and applied load for (a) butt weld at 0°, (b) butt weld at 45° and (c) T-joint.

Table 2
Theoretical welding process parameters and FEM input parameters.

Case study	Pass	Process parameters		FEM input parameters		
		Welding power (W)	Welding speed (mm/min)	Body heat flux (W/mm^3)	Discretisation length (mm)	Kill-rebirth rate (s^{-1})
0° butt weld	1	7090.9	550	74.3	5	1.8
	2	8225.4	500	76.3	5	1.7
	3	9686.9	400	68.5	5	1.4
45° butt weld	1	7090.9	550	73.6	5.1	1.8
	2	8225.4	500	75.6	5.1	1.6
	3	9686.9	400	67.8	5.1	1.3
T-joint weld	1	8258.9	500	79.4	5	1.7
	2	10267.9	350	62.9	5	1.2