International Journal of Mechanical Sciences 78 (2014) 154–166

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Failure analysis for resistance spot welding in lap-shear specimens

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ARTICLE INFO

Article history:
Received 4 April 2012
Received in revised form
14 October 2013
Accepted 15 November 2013
Available online 21 November 2013

Keywords:
Spot welds
Airy stress function
Finite element analysis
Advanced high strength steel (AHSS)
Plastic deformation
Failure mechanism

ABSTRACT

Based on the elasticity theory and finite element method, this paper aims to explore the failure incidence of resistance spot welding in dual-phase lap-shear specimens. The stress function approach is adopted to derive an analytical solution to a lap-shear specimen containing a spot weld nugget subjected to the uniformly distributed loading condition, which provides a means to exploring the stress distributions near the spot weld nugget. The normalized effective stress obtained indicates that the initial yielding failures likely occur at four specific angles of 38.02°, 141.98°, 218.02°, and 321.98° along the spot weld nugget in the lap-shear plate. In addition, the contours of normalized stress are also plotted in the polar system to understand the surrounding stress distributions, which reveals that the locations of the maximum and minimum values of normalized radial, hoop, and shear stresses are located at angles 0°/180° and 90°/270°, 90°/270° and 0°/180°, 135°/315° and 45°/225°, respectively, as the normalized radial distance r/a goes to infinity. The elasto-plastic finite element analysis (FEA) is also conducted to analyze the initial necking or thinning phenomenon. It is found that the angular locations of the maximum equivalent plastic strain or initial necking failure points are located at four angular intervals for the advanced high strength steel (AHSS) plate with a spot weld nugget. The derived stress distributions allow predicting failure behavior and evaluating damage evolution on many engineering structures jointed with spot welds.

1. Introduction

Resistance spot welding is considered one of main joint techniques that have been extensively used in the automotive industry with typically each vehicle containing several thousand spot welds. With rapidly increased requirements in lightweight, many automotive companies have widely been utilizing various advanced materials, such as aluminum alloy and advanced high strength steel (AHSS), to stamp into final products such as automotive body panels and other major structural frames. AHSSs, as one class of promising engineering materials used in car body structures, have drawn increasing attention recently, which allow reducing structural weight but enhancing the performance under operational and crashing conditions. Nevertheless, challenge remains in integration of AHSS into automotive structure through quality welds. Indeed, the weldability of AHSS signifies a critical issue in vehicle production. To make better use of such advanced materials as dual-phase steels for welding process, it is important to characterize and quantify their spot welding behaviors properly [1]. In practical automobile applications, the nugget pullout is a preferable failure test approach because the load-carrying capacity is higher, and the interfacial failure usually carries lower mechanical loading and absorbs less energy than the nugget pullout failure [2]. Since the spot weld may generate an inherent crack along the weld nugget, it is of a critical importance to the study on failure modes.

There have been some studies on the stress distributions around a spot weld recently [3–6]. However, reliable evaluation of fatigue life remains challenging mainly because the stress field close to the spot region is rather complex due to the notch effect along with the edge of the spot weld [7]. In addition, these spot welds are often subjected to multiaxial loading. As a result, various types of specimens such as *U*-tensile specimens, cross-tension specimens, lap shear specimens and coach peel specimens have been used to determine the strengths and fatigue lives of spot welds under different loading conditions [8–10]. As one of most typical joint structures the lap-shear specimens have been commonly used to examine the fatigue life, failure mechanism, impact and static strengths of spot welds [5,11–20]. In this joint scenario the tension and shear represent the critical loading conditions. The fatigue strength of such joints has been analyzed and measured on a basis of peak stresses at the weld root of the joint [21–23].

Note that stress distribution near the spot welds is crucial to evaluate the fatigue strength of such joints. Note that although the plastic stress/strain around the nugget plays a more direct role on the failure model and mechanism of spot welds, it is very difficult

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0020-7403/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmecsci.2013.11.011

to derive the analytical elasto-plastic solutions to the stresses and strains in the lap-shear specimens based on the elasto-plasticity theory [6,24,25]. On contrast, elasticity-based analytical solution is still deemed fairly effective to gain preliminary insights into the stress and strain distributions near the spot weld. For example, Zhang [9,26] obtained the approximate elastic solutions to the nominal stress fields near the weld nuggets that were considered as the rigid inclusions in the infinite plates under general loading conditions. The analytical solutions of stress with rigid inclusions in the plates under shear, bending and opening loading conditions were also derived by Muskhelishvili and Radok [27] and Timoshenko et al. [28]. In addition, a number of researchers also examined the stresses and strains near the nugget and their relations to failure modes based on the elasticity theory. For example, Kan [12] showed that initial yielding occurs on in the middle of the nugget circumference around the spot weld in a lap-shear specimen by simplifying the problem to a 2D sheet subjected to a uniformly distributed shear force. However, the obtained results were mainly based on the assumption of the uniform shear stress distributions along with the weld nugget. Salvini et al. [7,24] proposed a simplified spot weld model and obtained an analytical solution based on the elasticity theory, in which the weld nugget was also considered as a rigid inclusion in a finite plate subjected to shear, bending and orthogonal loading conditions. They attempted to evaluate the local stiffness and stress of spot joints by introducing the new criteria for predicting fatigue behavior and damage evolution in some special mechanical structures joined in different spot welds [29].

In addition to the analytical solution, some other approaches have also been adopted to the understanding of mechanical behaviors of spot welds. Some researchers investigated the failure mechanism under shear-tension condition by using experimental methods [30–35]. Besides, the numerical methods were also widely adopted to study the plastic strains/stresses or failure of the weld joints under shear-tension or impact conditions [36,37]. A simplified model of a lap-shear specimen was presented and a 2D elasto-plastic finite element (FE) analysis based on the cyclic stress–strain curves was used to obtain the local strain distribution for characterizing the fatigue failure mode [12]. Satoh et al. [38] and Deng et al. [39] developed the 3D elastic and elasto-plastic FE solution to the stress and strain near spot welds in the lap-shear specimens, thereby exploring the mechanical behavior of spot welds, in which the former [38] indentified the fatigue crack initiation sites under high-cyclic and low-cyclic fatigue loading conditions, while the latter [39] understood the effects of the nugget size and sheet thickness on the interfacial and pull out failure modes. Lin et al. [11] not only obtained the analytical stress solutions for an infinite plate containing a rigid inclusion, but also suggested that the location of the initial necking failure should occur near the middle of the nugget circumference in the sheet based on the elasto-plastic finite element analysis. And the failure of the sheet was determined by the forming limit diagram (FLD) which has been widely adopted in the sheet metal forming engineering. Recently, Asim et al. [40] conducted an experimental study on the failure mechanism and strength of laser welds in lap-shear specimens of high strength alloy steel. They pointed out that the laser welds failed in a ductile necking/shearing mode that was initiated at a distance away from the crack tip near the boundary of the base metal and heat affected zone.

In this paper, an analytical solution will be derived to explore the stress distributions near the spot weld nugget in a lap-shear specimen subjected to a uniformly distributed load. Based on the analytical solutions from the stress function approach in the elasticity theory, the locations of the initial yielding are estimated from the angular and radial distributions of the normalized effective stress near the nugget in the lap-shear specimen. Furthermore, the obtained stress contours are plotted in the polar coordinate system to understand the locations of the maximum and minimum values of the normalized radial, hoop and shear stress. Nevertheless, these elastic analytical solutions only provide some preliminary understanding of the stress and strain status near the spot weld. In order to explore the failure mechanism due to the resistance spot welds, an elasto-plastic finite element analysis is also conducted here for the spot weld nugget welded by two different advanced high strength steels (AHSSs) (DP600 and DP980). In the elasto-plastic FEA, the lap-shear specimen is subjected to uniformly distributed loading. The angular locations of the maximum equivalent plastic strain or initial necking failure points are determined to understand the development of plastic flow. Thus, the derived equivalent von Mises stress and plastic strain solutions allow us to predict failure behavior and damage evolution in some AHSS structures jointed by spot welds.

2. Analytical solutions

2.1. Two dimensional analytical model

To derive an analytical solution, a simplified two dimensional (2D) model with a spot weld joint subjected to a uniformly distributed load is presented in Fig. 1. Similar configuration of the lap-shear specimen has also been adopted by other researchers [5,11,41]. In the figure, the doublers that play a role on supporting pieces are used to align the applied load, thereby avoiding the initial realignment of the specimen under lap-shear loading conditions. The shaded cylinder represents a rigid inclusion of diameter $2a$ that can be considered as an approximation to the spot weld in a lap-shear specimen. According to the superposition principle in elastic theory, the load applied to the lap-shear specimen can be decomposed into four loading components, namely counter bending, central bending, shear, and tension, respectively. As a primary load in the lap-shear specimens, the shear tension is considered in this study and the 2D analytical model is illustrated in Fig. 2.

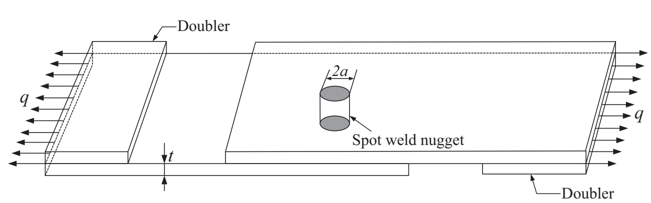

Fig. 1. A schematic plot of a lap-shear specimen subjected to a uniformly distributed load q and the spot weld nugget is idealized as a circular cylindrical weld nugget.

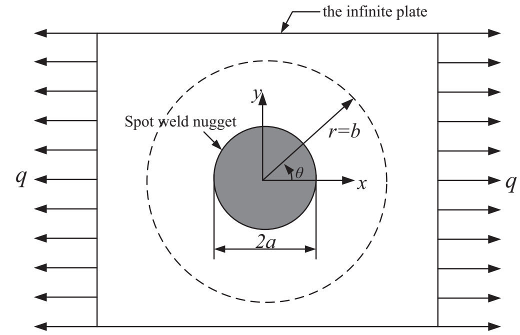

Fig. 2. A 2D analytical model of a rigid inclusion of radius a in an infinite plate subjected to a uniformly distributed load q.