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Determination of CTOA in the molten material of spot welds using the Digital Image Correlation technique

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ABSTRACT

In order to compare the strength of the molten material of different spot welds bonding steel sheets, a specific wedge test has been developed. It produces stable crack growth at the interface of sectioned spot welds. The deformation of the molten material at the progressing crack tip is observed in situ during wedge insertion. The Crack Tip Opening Angle and the extend of the strain localization ahead of the crack tip are measured by Digital Image Correlation. It is shown that the rather simple measurement of the Crack Tip Opening Angle provides a good indication of the extend of the strain localization, which is believed to be related to the toughness of the molten material.

1. Introduction

Due to environmental issues and cost reduction, the today's challenge in the transport industry is weight reduction. Thin (about 2 mm thickness) steel sheets play a significant role in the automotive industry. These thin sheets are assembled by spot welding. But, High Strength Steel welds may exhibit full interfacial failure (i.e. crack propagation through the molten material at the interface between the welded sheets). Each vehicle contains several thousand welds. The safety analysis requires thus the application of crack initiation and crack propagation criteria to structures of thin sheets assembled by welding.

Several models for the analysis of crack propagation have been developed within the last three decades for homogeneous materials. The critical Crack Tip Opening Angle (CTOA) was shown to be the most suited for modeling stable crack growth and instability during the fracture process of homogeneous materials [1–6]. But, in thin sheet material, crack tunneling and slanting will lead to non constant values of the CTOA [7,8]. Newman et al. [9] showed that the critical CTOA values should be determined for various specimen configurations, crack lengths, and thicknesses. Unfortunately, spot welding of thin (about 2 mm thick) sheets leads to "small" volumes of the fusion zone, i.e. about $4 * 8 * 8$ mm. Determining the critical CTOA values for different specimen configurations and thicknesses is thus almost impossible.

Furthermore, the microstructure in the molten zone of a spot weld of steel is largely heterogeneous, as described by Zhang and Senkara [10]. Indeed, dendritic growth of austenite occurs during the fast cooling steps of the successive pulses of the spot welding process, finally resulting in micron-sized lenticular grains of martensite, along with a significant segregation of chemical elements between the periphery and the center of the molten zone. Using classical Linear Elastic Fracture Mechanics tools to characterize the toughness of such a heterogeneous material and such a non-standard geometry would raise concerns regarding the validity of the hypothesis associated with these approaches.

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Nomenclature

Variables

a	initial crack length
d_{low}	vertical displacement of the lower sheet measured at a distance l behind the current crack tip
d_{up}	displacement of the upper sheet measured at a distance l behind the current crack tip
F	load applied to the wedge
L	apparent length of the welded joint
l	distance behind the current crack tip at which the CTOD is measured
u	opening displacement
$\Delta\varepsilon_{yy}$	incremental vertical strain
ΔG	difference in grey level at each pixel between two successive frames
ΔU_y	incremental vertical displacement

Acronyms

CTOA	Crack Tip Opening Angle
CTOD	Crack Tip Opening Displacement

The present paper thus aims at highlighting the major interest of the CTOA in characterizing the fracture resistance of the molten zone of spot welds of thin sheets, with no particular hypothesis regarding their behavior. Although that methodology does not provide a straight-forward fracture parameter, the authors propose it as a robust basis for comparison between various steel grades, and for further investigations aiming at quantifying fracture parameters when coupled other measurements.

In this paper the relation between the strain localization and the CTOA during stable crack growth through the Fusion Zone material of spot welds is analyzed. In order to allow stable and reproducible crack propagation along the weld interface, a specific wedge test has been developed (Fig. 1, [11]). Appropriate interpretations of the wedge test output are thus investigated to identify a reliable characterization of the resistance of the molten material to crack growth. In that purpose, this paper intends to quantify the relevance of two measurements extracted from the in situ observation: the extent of the strain localization, and the CTOA. The variation of the CTOA with the cracked surface will be related to the extent strain localization at the crack front.

In a first part, the experimental set up of the wedge test is presented along with the procedure of sample preparation and an example of observation. The second part shows a brief summary of existing approaches characterizing the resistance to crack propagation from in situ observations. A third part is dedicated to the algorithm used to measure the in-plane displacements by Digital Image Correlation. The set up of the CTOA measurement is then detailed in the fourth part, while the fifth part presents the determination of the strain localization. A relation between the strain localization and the CTOA is finally highlighted in the sixth part, presenting two examples of measurements results. Finally, a discussion of the relevance of these measurements to characterize the resistance to crack growth is proposed.

2. The wedge test

Various wedge tests has been proposed in the literature to characterize the resistance to interfacial crack growth, for example in adhesives [12], or in steel brazed joints [13]. The load is applied by inserting a wedge at the interface of an assembly, implying an opening displacement where the wedge is in contact with the sample, eventually leading to a progressive failure of the interface. It stands out as a very stiff system, thus favoring stable rather than unstable regimes of crack growth. This part details the preparation of the samples from spot welded sheets, the experimental set up of the wedge test developed for this geometry of samples, and an example of observation.

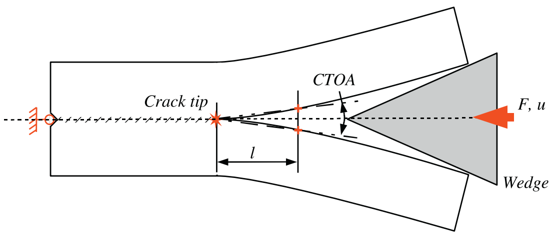

Fig. 1. Schematic set up of the wedge test and Crack Tip Opening Angle, defined as the opening angle required for crack growth, measured at a given distance l behind the current crack tip.