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Failure characterization of laser welds under combined loading conditions

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ABSTRACT

This paper proposes a new failure criterion for laser-welded regions under combined normal and shear loading conditions for the crash analysis of an auto-body. The failure criterion had been deduced from experimental results with nine different loading conditions including the normal loading and the pure-shear loading condition. The fixture jig set to mount a specimen was designed to obtain failure loads of laser welds under combined loading conditions with a constant shear to normal load ratio. To evaluate the pure-shear strength of laser welds fabricated using the same welding condition with a two-layered lap joint, a testing fixture and a specimen were designed with the aid of information from finite element analysis results. Using the testing fixtures proposed in this paper, failure tests of laser welds of CR340 1.2t steel sheet were carried out with the variation of nine different loading angles from 0° to 75° at the interval of 15° and from 75° to 90° at the interval of 5° to obtain failure loads and for identification of the failure characteristics at each loading angle. Based on the experimental data, a novel failure criterion was proposed for the description of failure behavior of laser welds. The failure criteria are divided into two regions of base metal failure and interfacial failure. The base metal failure region is expressed as a function of the normal and shear load, which is the so-called β-norm function, while the interfacial failure region is represented in a form of a modified power law function. The failure criterion proposed provides a fairly accurate description of the failure load obtained from the experiments under combined normal and shear loading conditions.

1. Introduction

The laser welding process is widely utilized in many industrial fields such as in space shuttles, aircrafts and automotive assembly procedures [1]. Spot welding processes are recently being replaced by laser welding processes in the auto-body assembly industry to improve productivity and to reduce costs. Laser welding processes have many advantages: for example, they are a low heat input; have a high welding speed; are easy to automate; and have high accuracy. It is, therefore, important to understand the failure characteristics of laser welds of an auto-body component when a large load is applied to evaluate the crashworthiness of the structure. Failure of the laser-welded region is likely to be observed prior to failure of the base metal when a large load is applied to the structure because extremely high stress is concentrated at the end of a weld bead. As the load that is transferred from one part to a joining part is abruptly changed after the laser-welded region fails, the behavior of the structure usually reveals large discrepancies between the experiment and the numerical simulation. Despite the importance of understanding the failure characteristics, most research investigating laser welding has concentrated on forming a healthy laser-welded region by controlling the welding parameters such as the laser beam power, the laser beam focus, the welding speed, and so on [2–6].

The failure of laser welds recently has gained the focus of extensive studies both experimentally and theoretically. To evaluate the durability and the crashworthiness of an auto-body, researches into the mechanical strength of laser welds can be classified into two categories: the first category estimates the fatigue strength of laser welding; and the second category estimates the strength of the laser-welded region and provides related failure criteria for a finite element modeling method of laser welds. Invaluable researches have been focused on estimating the fatigue life of laser welds [7–12]. In these researches, high-cycle/low-stress fatigue tests were initially conducted using lap-shear and butt-welded specimens. Researchers then calculated the parameters related to the fracture mechanics, such as the linear elastic stress intensity factor or the elasto-plastic fracture parameters of the specimens, to estimate the fatigue crack growth in the specimen both analytically and using finite element analysis. Additionally, it is necessary to estimate the strength of laser welds when a large load is applied to the structure to understand the failure characteristics and propose an appropriate failure criterion providing finite element model for laser welds

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used in structure analyses or a crashworthiness assessment of auto-body components. For these purposes, lap-shear tests and cross-tension tests have been performed to estimate the failure loads of laser-welded regions [13–16]. Kuppuswamy et al. [13] carried out various types of failure tests such as lap-shear tests, tensile/shear tests and coach-peel tests to apply various loading angles to laser welds under quasi-static loading conditions. Based on an empirical consideration of material and sheet thickness combinations, a substitute finite element model was developed for modeling C-shaped laser welds for crash simulations. Kavamura and Batalha [14] estimated the mechanical strength of spot welds and laser welds using experimental and numerical methods under combined loading conditions using the Arcan jig. Lee et al. [15] carried out failure tests using lap-shear specimens under quasi-static loading conditions and performed two-dimensional plane strain finite element analyses to understand the failure mode of laser welds in lap-shear specimens. Based on these investigations, they proposed a failure or separation methodology of laser welds in lap-shear specimens using finite element analyses by adopting the Gurson yield function. Kang et al. [16] examined laser weldability for hot-press-forming steels with and without Al – Si coating. Butt and lap joint welding characteristics of hot-press-forming steels were investigated, and trials were carried out to improve weld strength in lap joint welding.

These researches still need to understand the failure characteristics or to provide the failure criterion of laser welds compared with a spot weld. To investigate the failure characteristics and criterion of spot welds under combined loading conditions, previous researchers adopted various types of testing fixtures to establish combined loading conditions including normal, mixed normal/shear, or shear loads, that act on a spot-welded specimen by changing the position of the fixtures [17–31]. Lee et al. [18] proposed a failure model in the shape of an ellipse that was based on the failure test results under quasi-static loading conditions with mixed normal/shear loads. Wung et al. [31] suggested an empirical failure model to describe shear, in-plane rotation, peel, and normal separation modes of spot welds. Lin et al. [29,30] obtained an approximated limit load solution for a spot weld based on the assumption of a simplified stress field around the spot weld under combined normal/shear loading conditions. They developed a simplified force-based failure criterion. Langrand and Combescure [25] developed a failure criterion to express most of the failure modes of spot welds. Song and Huh [17] carried out failure tests of spot welds under seven different combined loading conditions with a constant ratio of the shear load to the normal load using specially designed testing fixtures to prevent rotation of specimens. Based on the experimental results, they proposed a failure criterion that takes the β-norm shaped function to describe the quasi-static failure loads of spot welds. Recently, several researches have been reported to study the effect of strain rate on the strength of a spot weld [27,28,32–38]. Lin et al. [33] conducted dynamic failure tests of a spot weld in mild steel under normal and combined normal/shear loading conditions using a gas-driven impact machine. Sun and Khaleel [34] employed servo-hydraulic testing machines to conduct dynamic failure test of a spot weld. Song et al. [32] also conducted dynamic failure tests of spot welds in CR340R using a high speed material test machine and lap-shear specimens. They introduced a dynamic failure model of a spot weld to describe the strain-rate dependent failure contours under combined normal/shear loading conditions based on experimental results. Wood et al. [35,36] described a strain rate dependent spot weld failure

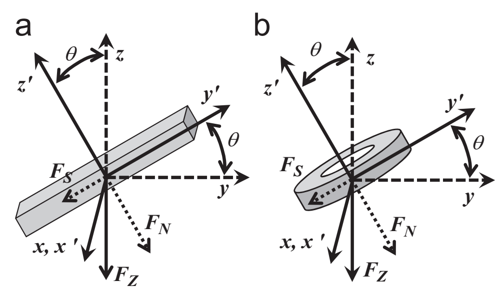

Fig. 2. Decomposition of the applied loads on a laser weld into a normal and a shear component at a loading angle of θ : (a) stitch-type laser laser welds; (b) O-type laser welds.

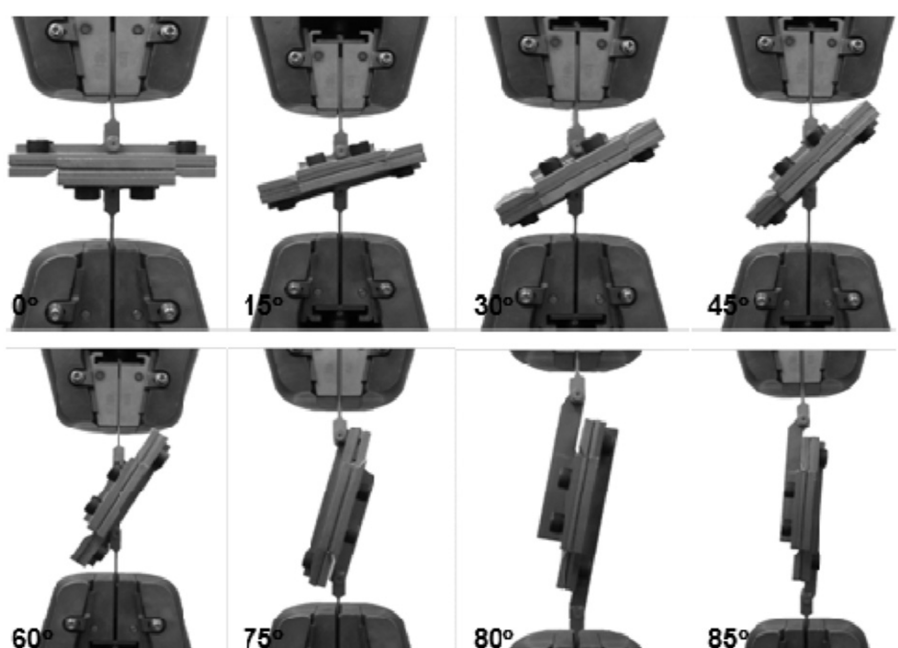

Fig. 1. Fixture set for failure tests of laser welded specimen under combined loading conditions.