ABSTRACT OF THE DISSERTATION

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Fatigue Fracture Mechanism and Damage Evaluation of Friction Stir Spot Welded AISI 1012Cold Rolled-steel under Service Loading

（実働荷重下における AISI 1012冷間圧延鋼摩擦攪拌スポット継手の疲労破壊機構と損傷評価）

The successful application of friction stir spot welding (FSSW) technology has attracted considerable attention from the automotive industry with energy consumption and operational cost are significantly lower than other welding methods. Previous research of FSSW has focused on mechanical properties, microstructure analysis, and how to produce a joint that optimizes the corresponding parameter sets. However, some stress concentration parts remain at the area welded by FSSW: a hollow called a keyhole caused by the tool shape, a discontinuity in shape called a lip, and a slit between the upper and lower sheet. Furthermore, the area welded by FSSW has several microstructures: the heat-affected zone, thermo-mechanically affected zone, and stir zone. It is highly advantageous to identify the relationship between the shape of the welded area unique to FSSW, the microstructure, and the fatigue crack behavior; however, details are not definitively known. Moreover, automobile loads randomly vary in service and very little is known about fatigue properties under random force amplitude conditions, which are assumed to occur in actual force situations.

Herein, fatigue tests were performed under constant force amplitudes to investigate the fatigue properties and fracture mechanism of FSSW-joined AISI 1012 cold rolled-steel sheet. Welded components are often subjected to variable force amplitudes, which call for fatigue life prediction methods that consider fatigue damage accumulation. Therefore, this study proposes and demonstrates the effectiveness of a method for evaluating cumulative fatigue damage under variable force amplitude conditions which are including repeat two-step and random force amplitude.

Fatigue tests were performed under constant force amplitude condition to investigate the fundamental fatigue properties and elucidation of fatigue fracture mechanism. The specimen used for

this study had a fatigue limit of 0.1 kN. This value is very low compared with the maximum tensile force of the base metal and FSSW joint itself. The crack initiation occurred as a boundary between the welding interface zone and non-interface zone or slit tip regardless of amplitude level. In addition, the slit tip is located in the heat affected zones. The fatigue crack was found on the upper sheet at the distal slit through to the surface of sheet up to the concave zone. The fracture morphology is the mixed mode fracture. Therefore, fatigue fracture modes were independent on force amplitude level. Base on the 3-dimensional observation, the macroscopic fracture modes were independent on the force amplitude. The fatigue initiation life was dependent on the force amplitude. In other words, the fatigue crack initiation life under low force amplitude accounted for a comparatively large proportion of the entire fatigue life; whereas the fatigue cracks initiation life occurred in a relatively early stage under high force amplitude

An approach of fatigue damage evaluation method under repeated two-step force amplitudes was investigated based on the results under constant force amplitude. The FSSW joints used in this study show a deformation behavior specific to the thin plate structure. Therefore, the deformation behavior around the welded zone with the constant applied force amplitude was observed prior to the repeated two-step fatigue tests. The plastic deformation near the welded zone occurred under a force of 0.4–0.5 kN. Therefore, two cases were considered: in the first, macroscopic plastic deformation near the welded zone did not occur, and in the second, significant plastic deformation occurred. In fatigue tests with repeated two-step force amplitude, the fatigue limit of the welded joint disappeared. However, the fatigue damage evaluation using the modified Miner's rule erred too much on the side of safety, as the modified Miner's rule tends to overestimate the damage by applied forces below the fatigue limit. Thus, it was determined that, within the testing conditions used in this study, the fatigue damage evaluation using Haibach's method yielded an accurate evaluation. In the case where significant plastic deformation caused by the applied force occurred near the welded zone, the cumulative fatigue damage value based on Miner's rule was often larger than unity. Therefore, it is important to consider a cumulative damage estimation that takes into account the effect of pre-strain from the high force amplitude.

Also an approach of fatigue damage evaluation method under random force amplitudes was investigated based on the results under constant force amplitude**.** Two kinds of difference bandwidth force amplitude history generated using the stationary Gaussian random process, having narrow band and broad band frequency content. The various force ratios have no mean stress effect on the fatigue life of the welded joints. Therefore, it was possible to consider the cumulative damage by the rainflow counting method. The fatigue damage evaluation with the modified Miner's rule tends to underestimate the damage by applied random wave form which was include the force below fatigue limit, which yields an evaluation approaching on the dangerous side. However, the modification of fatigue damage using Corten-Dolan's method has been the results are satisfactory and the frequency ratio affects the evaluation of damage, and the frequency ratio to the suitable for consideration the fatigue damage is a few number of cycles below fatigue limit in a block of random force amplitude. By considering the cumulative fatigue damage evaluation base on Corten-Dolan's method, it was possible to evaluate the fatigue life of the FSSW joints under random force amplitude conditions, which appropriated the strength designed range to considerable attention in the automotive industry.