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Full Length Article

Numerical stress analysis in resistance spot-welded nugget due to post-weld shear loading

Rasoul Moharrami*, Behzad Hemmati

Mechanical Engineering Department, University of Zanjan, Iran

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ABSTRACT

The magnitude and state of residual stress has a great influence on the fatigue life of sheet metal joints used in the automobile and aircraft industries. The present study developed a parametric 3D finite element model for simulation of welding and post-weld loading on the specimen. Electro-thermo-mechanical analysis is utilized to estimate the residual stress distribution at the nuggets and their surroundings at different stages of welding and post-weld mechanical loading. The results show that at the end of post-weld loading, the maximum tensile residual stress location moves nearer to the edge of the weld nugget and the residual stress magnitude and distribution change. Also, residual stress have sufficiently effects on stress distribution at the weld joint due to mechanical loading. To accurately estimate the fatigue life of resistance spot-welded joints, moreover external stresses, residual stress and local strain hardening of the material near the edge must be considered.

1. Introduction

Resistance spot-welding was invented in 1877 and has been widely used since then in the automobile, aircraft and electronic industries because it is quick, produces good quality joints and is low cost [1]. During resistance spot-welding, a high electric current passes through the sheets and the temperature increases in the contact region until the metal fuses and a weld nugget is formed. The current is then switched off and weld nugget is allowed to cool down slowly to solidify under electrode force.

Residual stress is self-equilibrating stress existing in materials or components under uniform temperature conditions with no applied loads. Residual stress occurs in materials and mechanical components during manufacturing, such as in plastic deformation, heat-treating or thermo-chemical treatment. During resistance spot-welding, heterogeneous deformation is induced by temperature gradients, phase changes in the solidifying metal and electrode force, resulting in the development of internal residual stress. When the current is off, the weld zone begins to shrink upon cooling, but is restricted by the surrounding cooler base metal, which produces tensile stress in the joint.

During the welding and holding step, the electrode force causes the development of compressive stress in the weld nugget area. Residual stresses effects the mechanical properties of components such as tensile strength, fatigue strength and fracture toughness. Tensile residual stress is the opposite of compressive stress and is undesirable because it accelerates fatigue crack growth [2]. To study the effect of residual stress on fatigue behavior, stress intensity and residual stress ratio should be considered [3].

Long [4] simulated the residual stress generated in resistance spot-welding and compared the numerical results with residual stress measured using an optical technique of high sensitivity called moiré interferometry [5]. Cha [6] studied the effect of welding parameters and hardening of the tangent module on residual stress distribution. Nodeh [7] used a two-dimensional mathematical model to investigate the effect of applied voltage and welding time on the welding residual stress and compared the simulation results with experimental data from x-ray diffraction.

Fatigue is the most critical failure mode of spot-welded joints in automobiles [8]. The fatigue life of mechanically-fastened structures strongly depends on the local state of stress at the fastener and the surface condition of the sheets. After welding, a notch is formed at the periphery of the spot weld which concentrates the stress and produces excessive local deformation.

Fatigue crack propagation in highly-stressed regions depends on stress level. At a low stress level, the crack initiates some distance away from the nugget and then propagates around the nugget to a large width before propagating through the thickness. At high stress levels, the crack initiates closer to the nugget and propagates through the thickness without growing wider [9].

* Corresponding author.
E-mail address: r_moharami@znu.ac.ir (R. Moharrami).

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Nomenclature

Ø	Electric potential
ε	Electric conductance
k	Thermal conductivity
ρ	Density
c	Specific heat
$\dot{q}$	Internal heat generation rate per unit volume
$d\varepsilon_{ij}^{e}$	Elastic strain increment
$d\sigma_{ij}$	Stress increment
δ_{ij}	Kroenke delta
E	Young's modulus
υ	Poisson's ratio
μ	Shear modulus
$d\varepsilon_{ij}^{p}$	Plastic strain increment
Q	Plastic potential function
$d\lambda$	Proportionality constant term
α	Thermal expansion coefficient
$d\theta$	Temperature increment
U	Displacement

The grain structure of steel sheets alters due to rapid annealing from the electrodes. The grain structure in the nugget is considerably coarser than that of the parent metal. It can be observed that an increase in grain size generally results in a reduction in the fatigue endurance limit. On the other hand, a coarse grain structure can lead to a decrease in the rate of fatigue crack propagation [10].

The fatigue behavior of a spot weld has been investigated by many authors. Rathbun [11] examined the fatigue behavior of high-strength and low-strength steel under different loading conditions. Long [12] investigated the dislocation density and residual stress under low and high fatigue loading and their relationship with the fatigue behavior of spot-welded joints. Tanegashima [13] observed internal fatigue crack propagation around the spot-weld area in detail and studied the fracture type of the joint at different stress levels. Vural [14] experimentally analyzed the effect of the combination of materials and nugget diameter on fatigue life of a spot weld.

Rahman [15] studied the effect of spot diameter, sheet thickness and fatigue load on the fatigue life of spot-welded joints. Kang [16] investigated the effects of electrode tip geometry, surface indentation level and base metal strength on fatigue life under tensile shear loading. Radaj [17] used notch stress as an alternative to fatigue testing because the notch is often the location for crack development. Pan [18] studied the stress and strain in spot welds using a FE model and predicted the fatigue life using theh cyclic strain range method. Kang [19] used a mesh-insensitive structural stress parameter for determining the fatigue life of spot-welded joints under different loading conditions. Ertas [20] studied the effects of design variables such as spot-weld diameter and plate thickness on the fatigue life of spot welds using a 3D FE model. Wang [21] predicted the fatigue life of spot welds using elasto-plastic FE analysis and considering the effect of hardness distribution on cyclic material constants after welding.

Despite the effect of residual stress on fatigue life, only a few studies have investigated the fatigue life of spot-welded joints under residual stress. Bae [22] calculated the stress amplitude while considering welding residual stress at the edge of a spot weld. They found that the fatigue strength at a fatigue cycle limit for which welding residual stress was assumed was about 25% lower than that without of residual stress. Hassanifard [23] studied the effect of residual stress on fatigue life for different electrode forces using the modified Morrow damage equation. Mirsalehi [24] employed a crack propagation-based fatigue life estimation approach that considered residual stress at the nugget edge of the spot weld. Triyono [25] predicted the S-N curve for spot-welded joints under residual stress at the edge of spot weld and found it resulted in the reduction of fatigue strength.

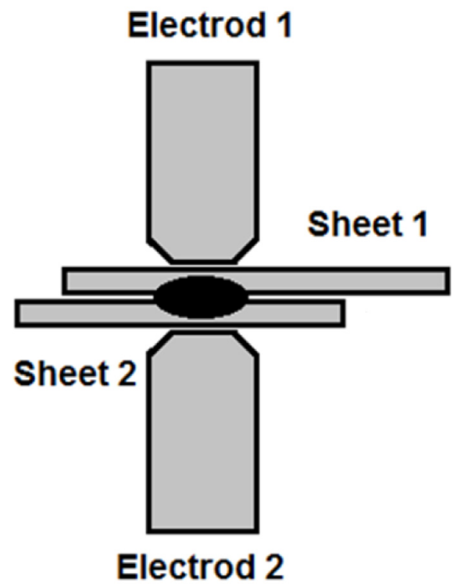

Fig. 1. Considered area in numerical simulation.

Table 1
Standard chemical composition of steel H180Y.

C	Si	Mn	P	S	Al	Ti	Ti+Nb+V+B
0.01	0.3	0.7	0.06	0.025	0.01	0.12	0.22

In this research, an appropriate 3D finite element model was developed using ANSYS software to simulate resistance spot-welding. Electrode force was first applied to determine the initial contact condition between the electrode-sheet and the sheet–sheet interface. Fully-coupled electro-thermal analysis was used to determine the electrical current and temperature distribution. Next, the residual stress distribution was evaluated in the squeezing, heating and cooling steps. Post-weld tensile loading and unloading on the welds was done to determine the effects of external loading on the welded joint in a FE model.

2. Finite element analysis

In this study, welding and post-weld tensile loading of a shear tension specimen as a standard fatigue test sample was considered numerically. The specimen was made of two flat steel sheets joined using a spot welds. A schematic of a section of the joint, sheets and electrodes is shown in Fig. 1.

For the numerical simulation, the material properties of H180Y, a cold-rolled steel strip of high strength, were used. The chemical composition of H180Y steel is shown in Table 1. Steel offers excellent forming and aging properties is widely used in the automobile industry.

Because the alloying elements in H180Y steel sheets are low, the thermal and electrical properties of AISI 1100 steel were used for numerical simulation of welding. The tensile test on H180Y steel was done at room temperature and test result is shown in Fig. 2. The physical and mechanical properties of the material will be changed at the weld nugget area and heat affected zone (HAZ) during welding sequence because its temperature dependency. Fig. 3 shows the trend of mechanical and physical properties at different temperature which were taken into account in the study.