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Effect of Forging Force on Fatigue Behavior of Spot Welded Joints of Aluminum Alloy 5182

Using experimental and finite element analysis methods, the effects of electrode forging force are investigated on fatigue behavior and residual stress of spot welded joints of aluminum alloy 5182. Results show that applying forging force significantly reduces the residual stresses in the heat affected zone and the fatigue cracks no longer initiate from there; instead, all cracks begin from the nugget edge. In addition, the mitigation of residual stress by forging force decreases the driving force for crack propagation and leads to longer fatigue life. It can be concluded that applying forging force appropriately has a positive effect on the fatigue strength of resistance spot welded joints.
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Keywords: resistance spot welding, aluminum alloys, residual stress, fatigue behavior, forging force

1 Introduction

As a means to achieve vehicle emission and fuel economy objectives, reducing the weight of an auto body has become a primary consideration in the automotive industry. The aluminum alloys, with their low density (one-third that of steel), high strength-to-mass ratio, resistance to corrosion, and good recyclability, have been employed in manufacturing many new types of lightweight vehicles [1]. Resistance spot welding (RSW) is widely used in the production of aluminum body-in-white, and there are typically over 5000 spot welds in one auto body. When a vehicle is running on the road, these spot welds will endure fatigue load resulting from bumping and vibration. If the fatigue strength of the spot welds can be substantially improved, the number of spot welds will then be dramatically reduced, which is very beneficial for the economic and efficient production of automobiles.

Due to the nonuniform heating and cooling processes during resistance spot welding, residual stresses will form in the spot region [2,3]. The welding residual stress in the spot welded joints will act in conjunction with the exterior fatigue load and accelerate the initiation and propagation of fatigue cracks in the car body [4–6]. Therefore, the welding residual stresses have got to be reduced to improve the fatigue strength of spot welds. In fusion welding, there are several different types of methods to mitigate the welding residual stress, such as preheating before welding, adopting an auxiliary heat source during welding and heat treatment after welding, etc. [7,8]. Nevertheless, as far as the resistance spot welding is concerned, due to its characteristics of short welding period, fast speed, and high degree of automation, the methods mentioned above are all inapplicable. So far, there is little openly published work on the factors affecting the residual stresses and on the measures to mitigate the residual stresses in resistance spot welded joints of aluminum alloys.

In the welding process, the heat expansion of heated materials is restrained by the surrounding unheated materials, so the compressive plastic strains are induced in the weld. Residual stress is then caused by the incompatible strains between the weld and the surrounding zone. In fusion welding, by applying a rolling force on the just-finished weld, tensile plastic strains can form in there and compensate part of the compressive plastic strains formed during welding, and the residual stress can then be mitigated. Enlightened by this technique, a procedure is proposed in the present study to increase the electrode force and apply a forging action in the spot weld when the spot weld is formed and the electric current is shut off during the RSW of aluminum alloys. By this procedure, the tensile plastic strain is anticipated to form in the spot weld, residual stress is therefore reduced, and fatigue strength of joints can then be improved. Although such forging procedure is sometimes used in resistance spot welding of aluminum alloys, it is mainly to reduce welding splash and solidification defects like cracks and porosity. It has not been used to improve fatigue strength of spot welds, and the effects of forging force on fatigue behavior and residual stresses have not been investigated so far, either experimentally or numerically.

Based on the analyses mentioned above, experiments are performed first in the present study to demonstrate the effectiveness of applying electrode forging force in improving the fatigue strength of spot welded aluminum alloy joints. Its influences on the initiation and propagation behavior of fatigue cracks are also investigated. To better understand and interpret the experimental phenomena, the finite element method is then employed to inves-

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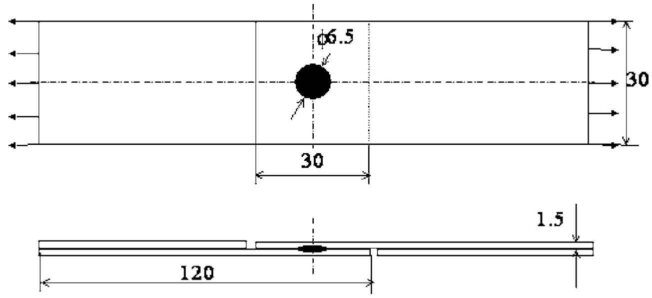


Fig. 1 Shape and dimensions of the overlapped spot welded joints (unit: mm)

tigate the variation of the residual stress brought by forging procedure and to reveal the substantial reasons for those experimental results.

2 Fatigue Test

2.1 Preparation of Spot Welded Joint. In the present study, the aluminum alloy AA5182 sheet with thickness of 1.5 mm, adopted widely in the fabrication of auto body, is used to produce resistance spot welded joints. The surface of the sheet material is covered with a light mineral oil. Because the sheet surface conditions are critical for welding quality in resistance spot welding of aluminum, the surface is treated by applying alcohol and then acetone and then air dried prior to welding. The electrodes are made of Cu-0.15%Zr alloy, and the electrode tips are domed shape with a radius of tip surface curvature of 50 mm and an end diameter of 10 mm.

The shape and dimensions of the overlapped specimen used in our fatigue tests are shown in Fig. 1. To avoid the bending of specimen during the test caused by geometrical eccentricity, two aluminum plates with same thickness of 1.5 mm are glued to the both ends of the specimen. Test samples are produced under two welding conditions: (a) the conventional process parameters without electrode forging force and (b) the novelly proposed procedure applying forging force after shutting the electric current off. The welding process parameters used in resistance spot welding are listed in Table 1.

Table 1 Process parameters used in studies

Process parameters	Values
Thickness of aluminum alloy sheet, mm	1.5
Welding current, kA	29
Electrode force, kN	5.0
Forging force, kN	10.0
Welding time, cycles	5 at 60 Hz
Electrode end diameter, mm	10.0
Power source	MFDC

Under the new welding condition, the electrode force is applied immediately after shutting off the current and without delay. And the nominal forging force is twice the electrode force under conventional welding condition, i.e., 10 kN, in our experiments. The variations of electrode force and electric current during resistance spot welding are recorded and shown in Fig. 2, from which it can be seen that, during welding phase, the electrode force increases a little beyond the assigned value (5.0 kN) to 6.5 kN because the specimen expands when heated by the joule heat that generated from the resistance to electric current flow. In addition, the electrode force increases further to 10.0 kN gradually but not abruptly after the welding current is shut off, and this varying period lasts for about six cycles.

2.2 Conditions for Fatigue Test. Fatigue tests are carried out on the overlapped specimen under tensile-tensile load conditions. Five load levels are determined with maximum load of 0.90, 1.08, 1.26, 1.44, and 1.62 kN, respectively, and the ratio of minimum load to maximum load is 1:20. Three specimens are used for each load level. The numbers of load cycles are recorded when the specimens fracture. The fatigue test stops if a specimen does not fracture after 1×10^7 load cycles.

2.3 Results of Fatigue Test. The influences of electrode forging force on the fatigue behavior of spot welded aluminum alloy joints are investigated from viewpoints of fatigue life and the modes of fatigue fracture. From the fatigue tests, the load versus cycle number curves and the initiation and propagation modes of fatigue cracks are obtained and given out in Figs. 3 and 4, respectively.

2.3.1 Load Versus Cycle Number Curve. In Fig. 3, it is obvious that the fatigue life of spot welded joints is improved by applying electrode forging force. This effect is especially notable under lower load level. For instance, when the maximum fatigue load is 0.9 kN, the number of load cycles endured by joints with forging procedure is over ten times of that without forging. That is

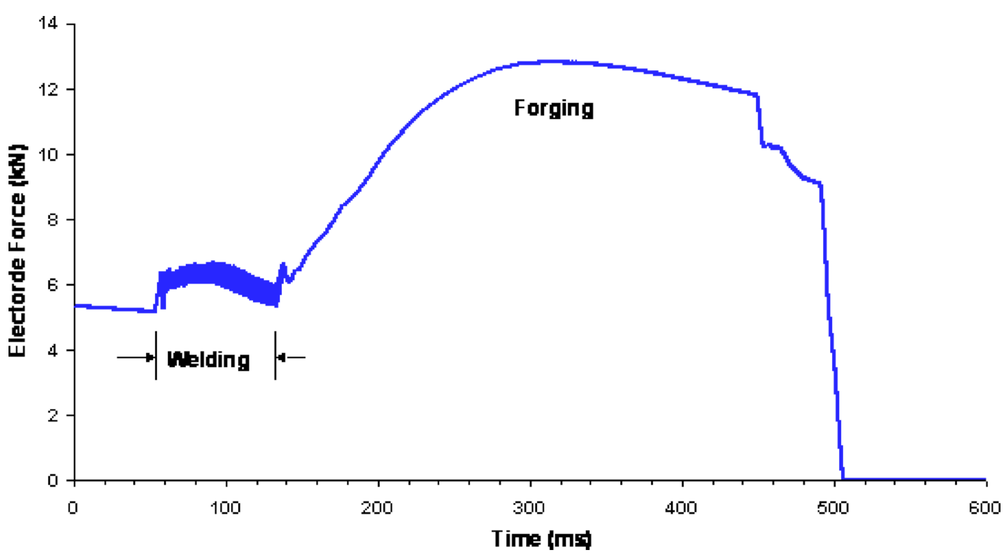


Fig. 2 Variations of electrode force and electric current during RSW process

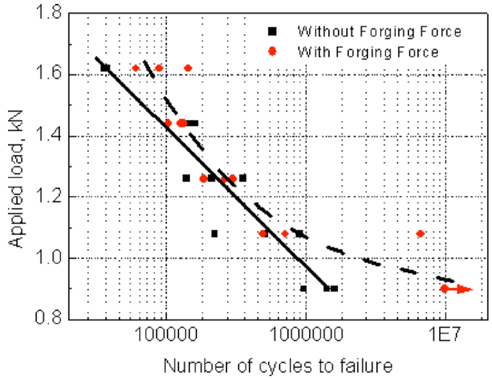


Fig. 3 Fatigue test results for the two types of joints

to say, the fatigue strength of joints is improved significantly by applying forging action in the weld spot zone of AA5182 RSW joints.

2.3.2 Two Initiation Modes of Fatigue Cracks. Two initiation and propagation modes of fatigue cracks are found when the fatigue cracks are observed under optical microscope. In the first mode (mode I shown in Fig. 4), the fatigue crack initiates within the heat affected zone (HAZ) outside the periphery of nugget, while in the second mode (mode II shown in Fig. 4), the crack begins right from the periphery of nugget.

It is believed that in the first mode the initiation of fatigue crack is mainly caused by the softening of the material in the heat affected zone (HAZ) around the weld nugget. Microhardness results are shown in Fig. 5 for a spot weld of AA5182, in which the black lines show the boundary between the weld pool and HAZ. It can be found that the microhardness in both the HAZ and nugget is lower than that of base metal [9]. The strength of AA5182 aluminum alloy is gained by cold working and solid solution strengthening. In resistance spot welding, the alloy in the HAZ is heated and annealed, and its strength is therefore decreased. Under such situation, the fatigue cracks are apt to initiate within this region. As for the second mode, generally it is considered as the results of severe stress concentration caused by geometrical incontinuity at the periphery of the weld nugget [10], which provides very favorable condition for fatigue crack to initiate in there.

When examining the fatigue crack initiation modes separately for spot welded joints with and without forging force, it is found that both mode I and mode II fatigue crack initiations exist in the spot welded joints under conventional welding condition, while under novel welding procedure with forging force, only mode II crack initiation is observed, i.e., all fatigue cracks initiate from the periphery of the nugget when applying forging force in resistance spot welding of aluminum alloy AA5182.

As we know, the improvement of fatigue strength and the change of fatigue crack initiation mode must have something to do with the influences of forging force on residual stress and strain conditions in joints. Taking advantage of the potential of the numerical method in obtaining the insightful information during the welding process, which is impossible using even the most ambitious experimental method alone, the finite element method is employed in this study to investigate the influence on residual stress and strains of applying forging force in resistance spot welding of aluminum alloy AA5182.

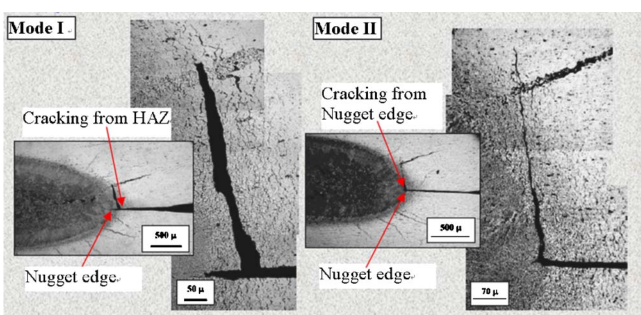


Fig. 4 Two modes of fatigue crack initiation in spot welded joints

3 Finite Element Analysis

3.1 Finite Element Model. The Ansys/MP commercial finite element analysis code was employed in the present numerical analysis. Because the resistance spot welding is a complex process involving strong coupling among multiple disciplines including electric, thermal, mechanical, and even metallurgical phenomena, an incrementally coupled electrical-thermal-mechanical algorithm has been developed previously to incorporate all these coupling effects, in addition to the variation in current flow path caused by thermal expansion of workpieces [11,12]. Details of the algorithm and the contact resistance model based on the fundamental theory of electric contact used in finite element analysis are described in Ref. [11]. In the finite element analyses before, only the heating period was computed to address the nugget initiation and growth while the cooling period after heating was often neglected. In this study, because the residual stress and strain are concerned, the finite element analysis has to be expanded to the complete welding process that includes both heating and cooling periods.

Taking the axisymmetry created by the cylinder electrode into account, the resistance spot welding process is simplified to an axisymmetric problem. Figure 6 shows the upper-half of the two-dimensional finite element meshes used in the computations. The mesh consists of 1088 nodes and 930 solid elements, which has been shown by a mesh convergence study to provide a sufficiently refined mesh.

Assumptions for the boundary conditions in electrical-thermal analysis are as follows:

i. The voltage at the bottom end of the lower electrode is set to zero, and a direct current of 29 kA is applied at the top end of the upper electrode.
ii. The electric current flow and heat transfer across the electrode/sheet and sheet/sheet interfaces are only allowed for the parts in contact with each other. Whether the nodes

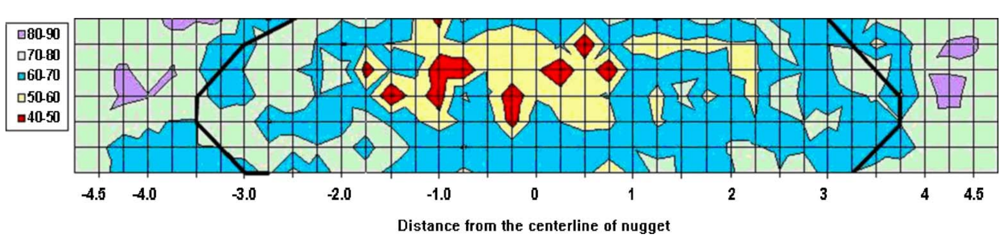


Fig. 5 The microhardness pattern of spot welds; the black lines show the boundary between the weld and surrounding area

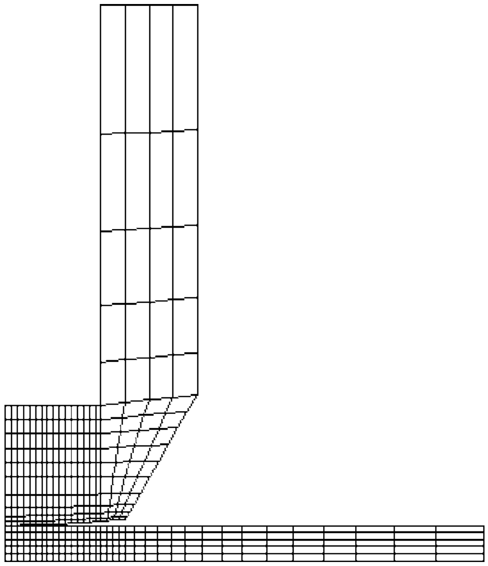


Fig. 6 Mesh used in finite element analysis

at the interfaces are in contact or not is determined with the node to surface contact elements in thermal-mechanical analysis of a time step; in the electrical-thermal analysis of the following time step, the parts in contact are coupled to allow the current flow through, while parts not in contact are not coupled and therefore no current can flow through.

iii. The convective heat transfer to the surrounding air is ignored, therefore the outer surfaces for both electrode and sheets are assumed to be adiabatic. The effect of the cooling water in the electrode cavity is taken into account by assigning the ambient temperature $(20°C)$ to the inner surfaces of the electrode.

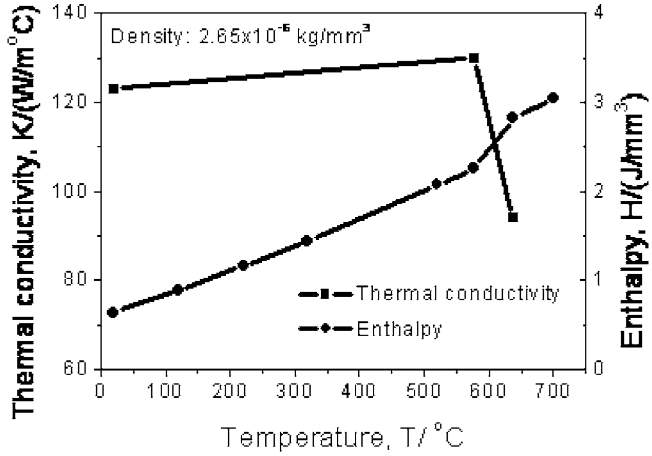
And, assumptions for the boundary conditions' thermal-mechanical analysis include:

i. Electrode force is applied as a uniformly distributed pressure at the top end of the upper electrode; the temperature calculated from electrical-thermal analysis is applied as a body load.
ii. Axial displacements at the bottom end of the lower electrode and radial displacement at the centerline are all constrained.

The workpiece is 1.5 mm thick aluminum alloy AA5182, and the electrode is made of Cu-Zr alloy, which are the same as in experiments. The temperature-dependent electrical, thermal, and mechanical properties for them are cited from *Metals Handbook* [13], as shown in Fig. 7. Extrapolations are used for those properties parameters after melting. The welding conditions used in numerical simulations are the same as the experimental conditions listed in Table 1. All computations are performed on a Pentium IV personal computer. For each case, the computational time is about 8 h.

3.2 Results of Finite Element Analysis. With the finite element model described above, the complete resistance spot welding processes are modeled under two welding conditions, i.e., with and without forging force after shutting off the electric current. The residual stress and residual plastic strain are obtained and shown in Figs. 8 and 9, respectively.

3.2.1 Distribution of the First Principal Residual Stress. Figure 8 shows the distribution of the first principal residual stress σ_1 at the faying surface, i.e., the contact interface between two work-



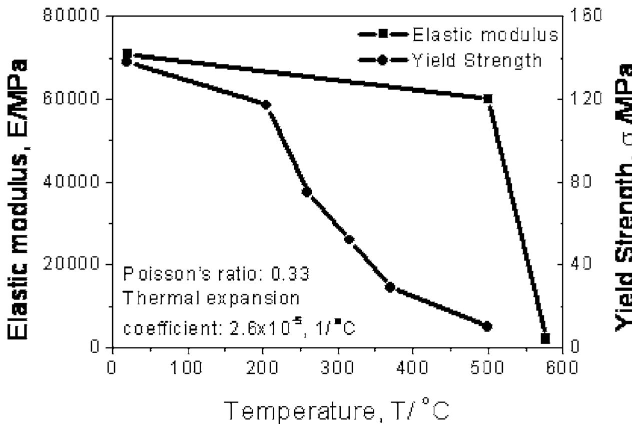


Fig. 7 Materials properties used in finite element analysis: (*a*) material properties for thermal analysis and (*b*) material properties for thermal mechanical analysis

pieces, along the radial direction under two welding conditions.

It can be found that under conventional welding conditions without forging force, the residual stress basically decreases within the nugget with a diameter of 6.5 mm. A stress valley is formed inside and near the nugget periphery (r=3.0 mm), with the valley residual stress of 100 MPa or so. This distribution characteristic coincides with the results in previous experimental measurement and finite element analysis on the resistance spot welding of mild steel sheets [2,3]. In addition, due to the presence of geometrical discontinuity, a residual stress peak exists at the nug-

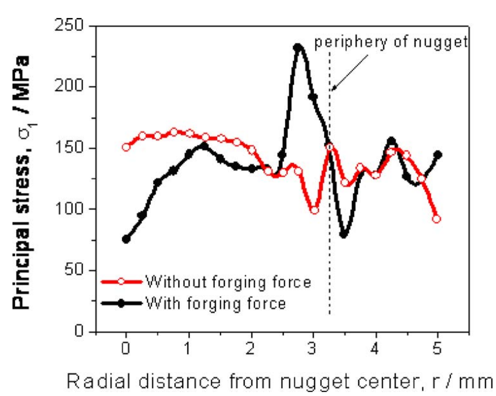


Fig. 8 Distribution of the first principal residual stress σ_1 in the radial direction

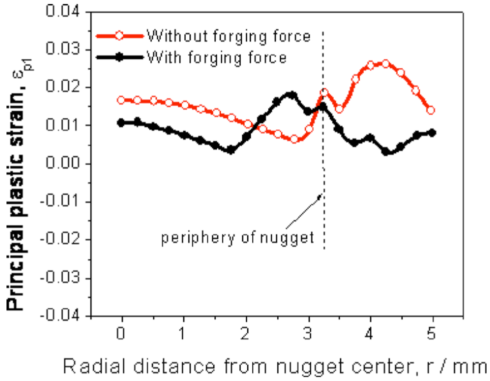


Fig. 9 Distribution of the first principal residual plastic strain ε_{p1} in the radial direction

get edge (r=3.25 mm).

Comparing the results for two welding conditions, it can be easily seen that applying forging force changes the distribution of the first principal residual stress in the weld spot region. In the mid part of the nugget ($0<r<2.25$ mm), the first principal residual stress is decreased by applying forging force. In the region inside and near to the nugget edge ($2.25\leqslant r\leqslant 3.25$ mm), a distinct stress peak is formed under the action of forging, which is completely different from that under conventional welding conditions where a stress valley is formed instead. Under both welding conditions, stress valleys are present in the region outside and near to the nugget edge. But, the valley stresses are different for those two welding conditions: applying the forging force reduces the valley stress from 125 to 75 MPa. Another point that should be noted is that the residual stress at the nugget edge (r=3.25 mm) is unaffected by the application of forging force. Under both conditions, the residual stresses at the nugget periphery are about 150 MPa.

3.2.2 Distribution of the First Principal Residual Plastic Strain. Figure 9 shows the distribution of the first principal residual plastic strain ε_{p1} at the faying surface along the radial direction under two welding conditions.

Similar to the residual stress, the first principal residual plastic strain decreases within the nugget for the increased distance to the centerline ($0\leqslant r\leqslant 2.75$ mm) when the forging force is not applied. A plastic strain valley is formed inside and near the nugget edge, with the valley residual plastic strain of about 0.006. Such a plastic strain distribution is the same as that predicted by Sun et al. [14] in their studies on the resistance spot welding of a 2.0 mm thick aluminum alloy sheet. At the periphery of the nugget (r =3.25 mm), peak residual plastic strain presents just as the residual stress.

Through comparisons between the residual plastic strains resulting from two welding conditions, it is evident that exerting forging force changes not only the magnitude but also the distribution pattern of the residual plastic strains within the joint region (both inside and outside the nugget). Under conventional welding conditions that are without forging force, the maximum residual plastic strain is located at some distance outside of the nugget; in contrast, when the forging force is applied, the maximum plastic strain shifts to some distance inside of the nugget periphery. Meanwhile, the maximum residual plastic strain is decreased from 0.025 to 0.016. Except for a small region of $2.10<r<3.10$ mm in the nugget, where the residual plastic strains are increased somewhat, the other regions of the joint, including the mid part of the nugget, the nugget edge, and the region nearby, all have apparently lower residual plastic strains when the forging procedure is taken after shutting of the welding current.

4 Discussion

Fatigue tests on the resistance spot welded aluminum alloy joints show that the fatigue cracks are apt to initiate from the periphery of the nugget or within the heat affected zone near the nugget edge. Therefore, it is the stress and strain conditions in addition to the local mechanical properties of these sensitive zones that determine the fatigue performance of the joints. From the finite element analysis results, it has been demonstrated that applying forging force will affect the distribution and magnitude of the residual stress and residual plastic strains around the nugget edge, by which it will be able to influence the fatigue behavior of the joints.

Though a significant residual stress peak is formed inside and close to the nugget edge by forging force, the residual stresses in the heat affected zone outside of the nugget periphery, in which the fatigue cracks propagate, are remarkably reduced. Besides, no matter at the nugget edge or in the heat affected zone outside of the nugget edge, the residual plastic strains are decreased when forging force presents. The decreases in residual stress and residual plastic strain make lower the actual loads endured by joints during fatigue tests. So the driving forces for fatigue cracks to initiate and propagate are decreased, and the initiation and growth of the cracks are retarded. Therefore, the fatigue life of joints is increased. Apparently, applying forging force has positive significances to the fatigue strength during the RSW of aluminum alloy 5182.

Moreover, the finite element analysis predicts that the first principal residual stress σ_1 at the nugget edge is not changed by the application of forging force, which stays at the stress level of about 150 MPa. In contrast, the first principal residual stress greatly decreases from 125 MPa to about 75 MPa in the heat affected zone outside of the nugget edge when the forging force presents. The unchanged residual stress at the nugget edge beside the significant decrease of residual stress in the HAZ explains very well the reason why the fatigue cracks all initiate from the nugget edge and not from the heat affected zone.

5 Conclusions

In this study, experimental and finite element methods are adopted to investigate the influences of forging force on the fatigue strength, initiation and growth behavior of fatigue cracks, and the residual stress and residual plastic strain in the resistance spot welded joints of aluminum alloy 5182. On this basis, the following conclusions are drawn:

1. Results from finite element analysis indicate that applying forging force will not bring notable influence on the first principal residual stress at the nugget edge, but will remarkably decrease that in the heat affected zone. And the forging force simultaneously reduces the first principal residual plastic strains in both nugget periphery and heat affected zone.
2. The decreases in residual stress and residual plastic strain make lower the actual loads endured by joints during fatigue tests. The driving forces for fatigue cracks to initiate and propagate decrease, consequently the initiation and growth of the cracks are retarded, and therefore the fatigue life of joints is increased.
3. Under conventional welding conditions, fatigue cracks may initiate from either the nugget edge or the heat affected zone; when forging force is applied, all fatigue cracks initiate from the nugget edge. This results from the unchanged residual stress at the nugget edge beside the significant decrease of residual stress in HAZ.
4. Appropriately applying forging force after the welding current is shut off has positive significances to the fatigue strength of the resistance spot welded joints of aluminum alloy 5182.

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