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Detection of Fatigue Crack Initiation in a Spot-welded Joint by Monitoring its Compliance

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Abstract
Several techniques for the detection of fatigue crack initiation have been used for spot-welded joints so far. The visual observation of the crack, the monitoring the strain, the electrical potential drop and the compliance are these. Among these, the compliance monitoring technique is attractive due to its convenience. In this paper, the fatigue crack initiation lives for different types of spot-welded specimens, i.e. tensile shear specimen and 45° cross tension & shear specimen, were determined using this technique. The results were compared to the strain gauge measuring results and the visual inspection results. Finally, the finite element analysis was performed to check the size of the crack at the 5% increase in compliance.

Keywords: Spot-welded joint, Fatigue crack initiation, Compliance, Tensile shear, Cross tension and shear.

Introduction

Spot-weld is still widely used in the production of passenger car body. It is being applied to advanced high strength steel and will be applied even to magnesium alloy[1]. The fatigue strength is one of the important qualities that the spot-welded joint should have. If it is not sufficient, a fatigue crack will be initiated at the edge of the nugget on the inner surface. It will grow toward the outer surface and eventually lead to a fracture of the joint.

The fatigue life can be divided into the crack initiation life and the final fracture life. The former is more important than the latter since the latter depends on the specimen width also as well as on the stress at the edge of the nugget. The former can be estimated more consistently from the finite element solution. The S-N curve for the spot-welded nugget is needed in the estimation.

The fatigue test should be done to provide the S-N curve for the specific spot-welded nugget. It is not easy to determine accurately the number of cycles at the crack initiation since the crack cannot be seen from outside. Conventionally in the industry, the strain on the outer surface at the edge of the nugget is monitored with a small strain gauge applied on it. It requires additional time and cost. Besides that, the strain is affected by the location of the gauge.

The fatigue crack initiation and subsequent growth increases the electrical resistance of the joint. Using this, the potential drop technique was used to monitor the crack[2]. It also decreases the natural frequency of the joint[3, 4]. Using this, the dynamic response was used to monitor the crack. However, these also require additional time and cost.

In the fatigue test, the force and displacement data are saved automatically without additional work. As the fatigue crack grows in the spot-welded joint, the displacement would increase for the same force level. Compliance is the ratio of the displacement to the force or the reciprocal of the stiffness. Gaul et al.[5] showed that the fatigue crack area in Tensile Shear specimen increased linearly with the decreasing specimen stiffness. Behravesh et al.[1] determined the fatigue crack initiation life for spot-welded tensile shear and cross tension specimens as 5% increase in compliance as proposed by Ford motor company. Li et al.[6] investigated the stiffness drop patterns for self-piercing riveted joints.

In this paper, a technique for detecting the fatigue crack initiation in the spot-welded tensile shear and 45° cross tension & shear specimens by monitoring compliance is investigated. One of the sheets is made of advanced high strength steel. The technique is verified by comparing the results the strain gauge and the visual observation results. Finally the size of the crack at the 5% increase in compliance is identified by the finite element analysis.

Determination of Crack Initiation Life in Fatigue Test

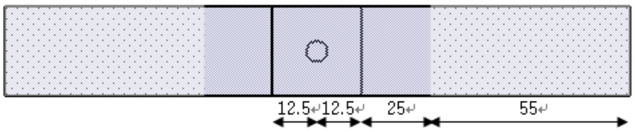
Two kinds of specimens are used in fatigue tests. One is a conventional tensile shear (TS) specimen and the other is a newly-designed 45° cross tension & shear (CTS) specimen. The latter was designed to transmit the tensile and shear force of the same magnitude at the same time.

The different steel sheets in grade and thickness as listed in Table 1 are spot-welded together. This combination will initiate a fatigue crack in high-strength sheet 2 which is thinner.

The crack initiation life is determined in three ways, i.e. by monitoring the compliance of the spot-welded specimen, the strain on the outer surface near the nugget and observing the crack initiation.

Tensile shear specimen

The tensile shear specimen shown in Fig. 1(a) is a conventional one that transmits shear force and bending moment through the nugget. The specimen is gripped with the upper grip first and then gripped with the movable lower grip on the table as shown in Fig. 1(b). The load range and frequency as listed in Table 2.



(a) Tensile Shear Specimen

(b) Gripped Specimen

(c) Fatigue Fractured Specimen

Fig.1. Tensile Shear Specimen and Fatigue Test

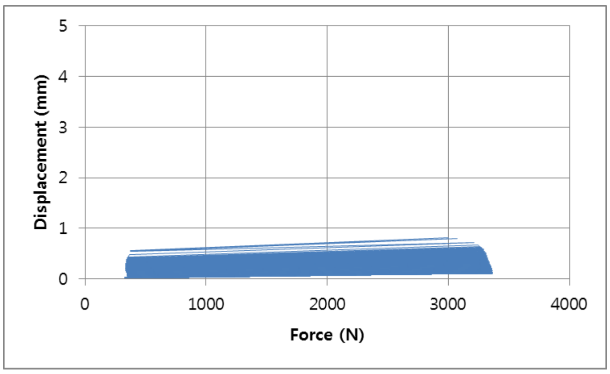


Fig.2. Force vs. Displacement

TABLE.1. Spot-welded Steel Sheets and Nugget Diameter

	Sheet 1	Sheet 2
Tensile Strength (MPa)	440	980
Thickness (mm)	1.6	1.2
Nugget Diameter (mm)	6	6

TABLE.2. Loading on TS Specimen and its Fatigue Life

Max. Load (kN)	333
Load Ratio	0.1
Frequency (Hz)	20
Crack Initiation (cycles)	67,603
Final Fracture (cycles)	103,053

i. Compliance

The peak and valley of the periodic force and displacement were recorded. The displacements were plotted against the forces in Fig. 2. Both the intercept and slope of the line in each cycle were increased as the test proceeds. In other words, both the permanent deformation and compliance increased as the crack grows.

The compliance is normalized with respect to the initial compliance and the time is normalized with respect to the time at final fracture. The normalized compliance is plotted against the normalized time in Fig. 3. In this case, the compliance began to increase at around the normalized time 0.3 and increased by 5% at the normalized time 0.656. It corresponds to 67,603 cycles. Here the crack initiation life is defined as the number of cycles corresponding to the compliance increase by 5%.

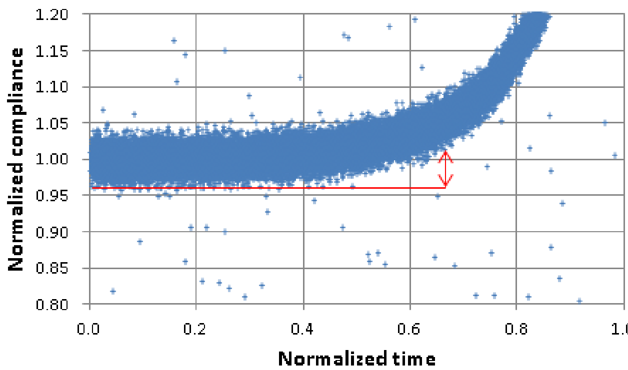


Fig.3. Normalized Compliance vs. Normalized Time

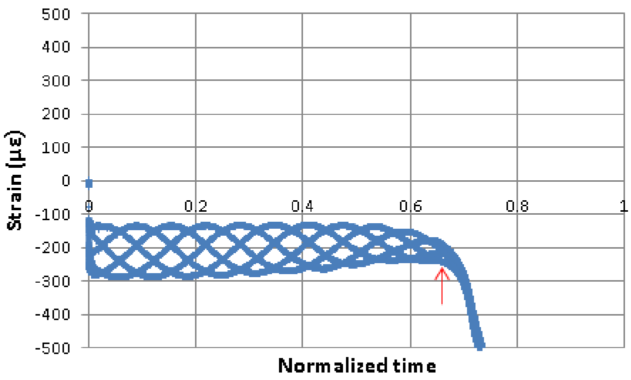
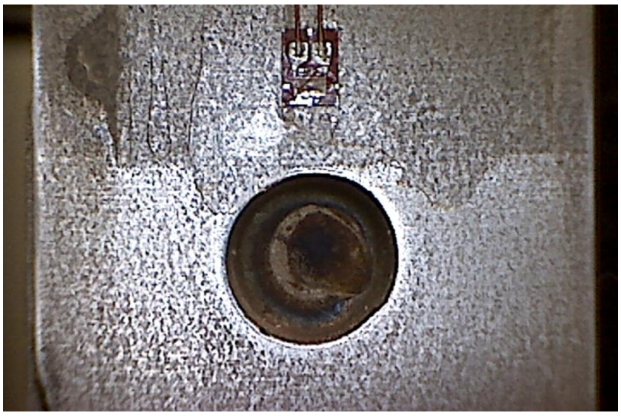
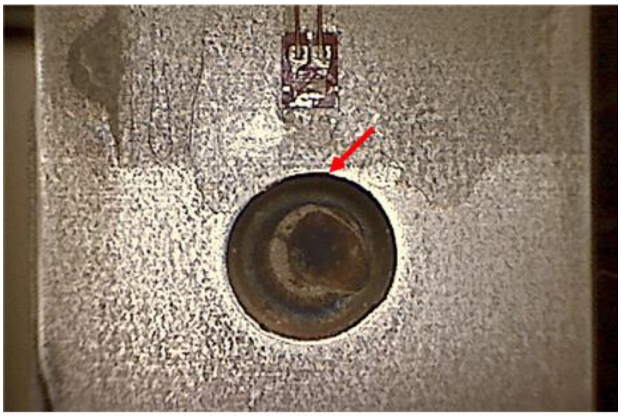


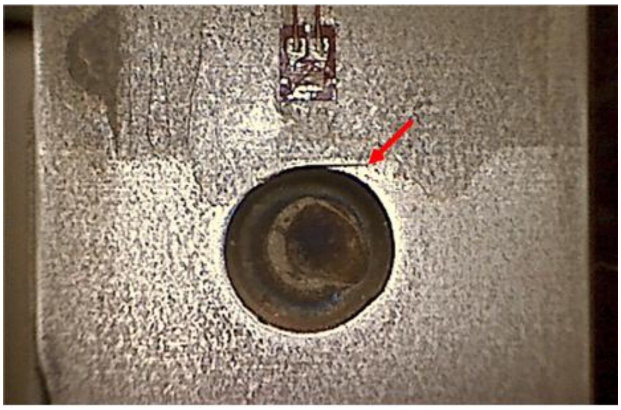
Fig.4. Strains vs. Time (100 Hz)



(a) 60,000 Cycles (=0.58 Normalized Time)



(b) 70,000 Cycles (=0.68 Normalized Time)



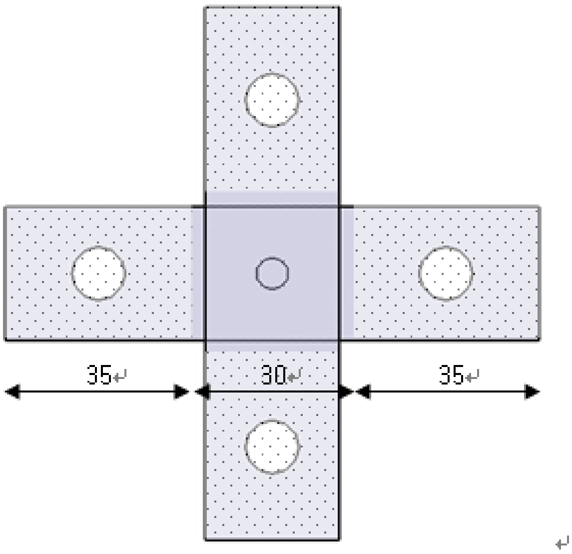
(c) 80,000 Cycles (=0.78 Normalized Time)

Fig.5. Photographs of a Fatigue Crack on the Outer Surface

ii. Strain

A strain gauge with gauge length of 1 mm is installed on the outer surface near the nugget to detect the crack initiation on the inner surface. The distance from the nugget edge to the center of the gauge is about 4 mm. At the location, the strain is compressive as shown in Fig. 4. Since the sampling rate is 100 Hz and test frequency is 20 Hz, the strain is read five times over a cycle. Actually the test frequency is slightly over 20 Hz and the strain curve is shifted. Apparently five strain curves themselves vary cyclically. The amplitude of these curves begins to decrease at around the normalized time 0.3 and decrease suddenly at around the normalized time 0.656. It is in agreement with the compliance monitoring result.

Photos are taken at every 1,000 cycles. At 60,000 cycles, no crack was seen in Fig. 5(a). At 70,000 cycles, a crack was seen on the outer surface in Fig. 5(b). At 80,000 cycles, the crack becomes longer in Fig. 5(c). It is in agreement with the compliance and strain monitoring results.



(a) Cross Tension and Shear Specimen

(b) Clamped Specimen and Pin-connected Grip

(c) Fatigue Fractured Specimen

Fig.6. 45°Cross Tension and Shear Specimen

Cross tension & shear specimen

The cross tension specimen shown in Fig. 6(a) is also a conventional one. In this paper, it is rotated by 45° so that it transmits tensile and shear force of the same magnitude through the nugget as shown in Fig, 6(b). Since the grips are pin-connected to the actuators, the specimen transmits no bending moment. The load range and frequency as listed in Table 3.

i. Compliance

The displacements were plotted against the forces in Fig. 7. As before, both the intercept and slope of the line in each cycle were increased as the test proceeds.

The normalized compliance is plotted against the normalized time in Fig. 8. In this case, the compliance began to increase from the beginning. The specimen is clamped with four bolts into the holes of the specimen. Slippage of the specimen with respect to the grip occurs. Bent sheets and elongated holes can be seen in Fig. 6(b). A constant-slope region exists between the normalized time 0.02 and 1.12. Assuming that the slippage occurs steadily through the test, we can extend this constant-slope line. As before, we can define the crack initiation as deviation from the constant-slope line by 5%. Here the unstable region around the normalized time 0.3 is disregarded. The compliance deviated from the line by 5% at the normalized time 0.470. It corresponds to 26,673 cycles.

ii. Strain

A strain gauge with gauge length of 1 mm is installed on the outer surface near the nugget. The distance from the nugget edge to the center of the gauge is 0.5 mm. At the location, the strain is initially compressive. As the sheet is folded below the strain gauge as shown in Fig. 6(c), the strain at the strain gauge will become tensile. As before, the strain is read five times over a cycle. Actually the test frequency is slightly over 20 Hz and the strain curve is shifted. The amplitude of these curves decrease suddenly at around the normalized time 0.470 in Fig. 9. It is in agreement with the compliance monitoring result.

Photos are taken at every 1,000 cycles. At 20,000 cycles, no crack was seen in Fig. 10(a). At 30,000 cycles, folding over the width was seen on the outer surface in Fig. 10(b). At 40,000 cycles, the crack is seen in Fig. 10(c). It is in agreement with the compliance and strain monitoring results.

Let's look into the phase shift phenomena in strains closely. The strain vs. time curve over two cycles are plotted in Fig. 11(a) and (b). The time difference is 120 s. The peaks are indicated by arrows. We can see that the peak is shifted slightly to left after 120 s. It results in five strain curves in Fig. 9.

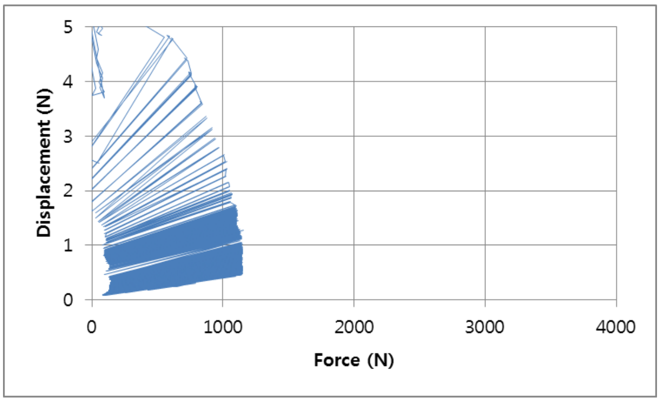


Fig.7. Force vs. Displacement

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TABLE.3. Loading on CT&S Specimen and its Fatigue Life

Max. Load (kN)	1.11
Load Ratio	0.1
Frequency (Hz)	20
Crack Initiation (cycles)	26,673
Final Fracture (cycles)	56,750

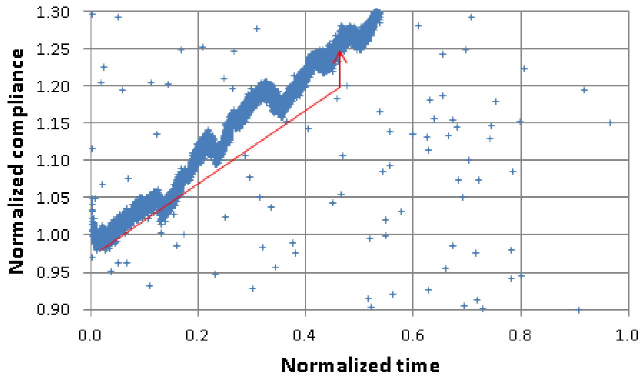


Fig.8. Normalized Compliance vs. Normalized Time

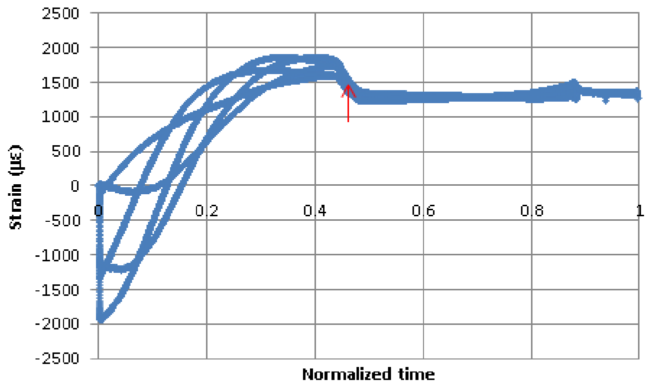
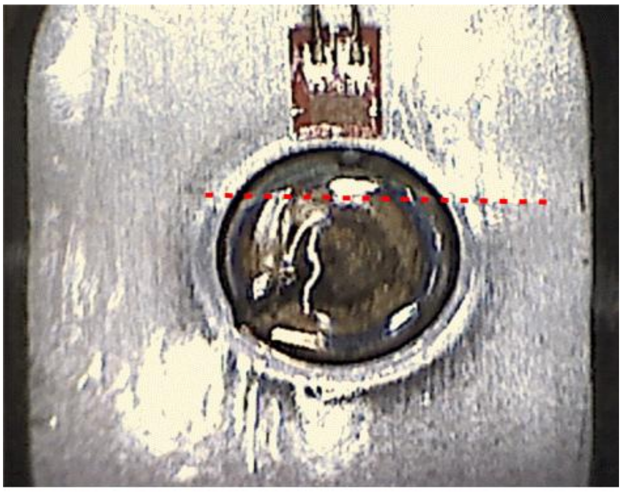


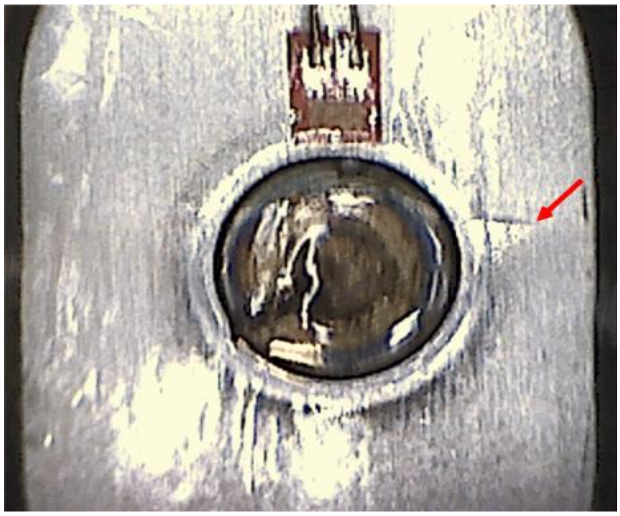
Fig.9. Strains vs. Time

Let's look into the phase shift phenomena in strains closely. The strain vs. time curve over two cycles are plotted in Fig. 11(a) and (b). The time difference is 120 s. The peaks are indicated by arrows. We can see that the peak is shifted slightly to left after 120 s. It results in five strain curves in Fig. 9.

(a) 20,000 Cycles (=0.35 Normalized Time)



(b) 30,000 Cycles (=0.53 Normalized Time)



(c) 40,000 Cycles (=0.70 Normalized Time)

Fig.10. Photographs of a Fatigue Crack on the Outer Surface

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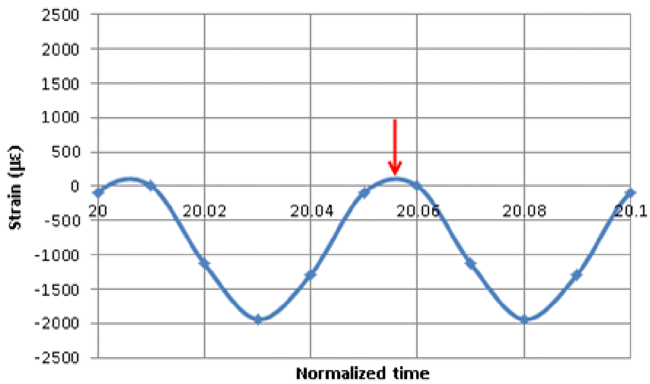
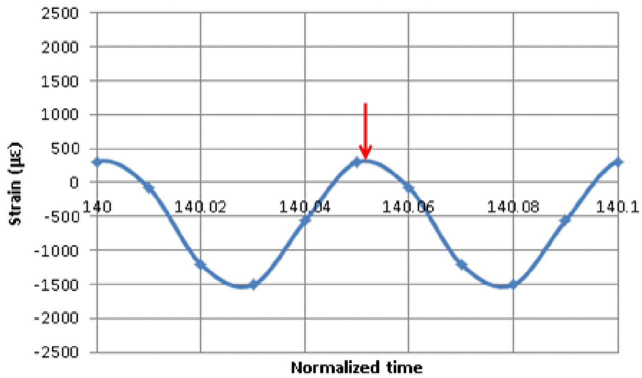
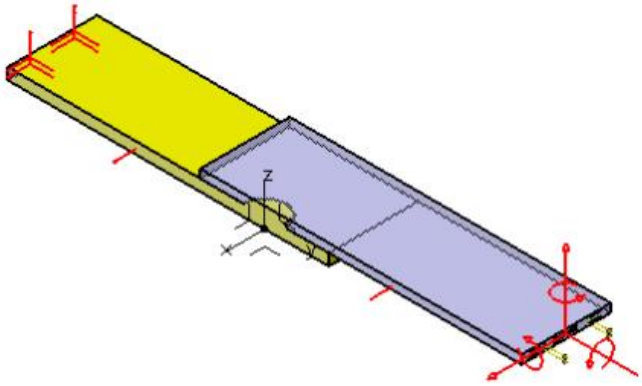


(a) 20.0~20.1 s

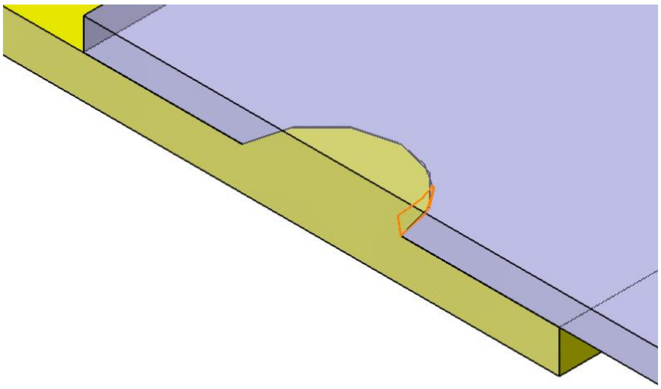


(b) 140.0~140.1 s

Fig.11. Phase Shift of Strains



(a) Finite Element Model



(b) Semi-elliptical Crack from the Inner Surface along the Edge of the Nugget

(c) Major Axis and Minor Axis of the Semi-elliptical Crack

Fig.12. Finite Element Model for TS Specimen

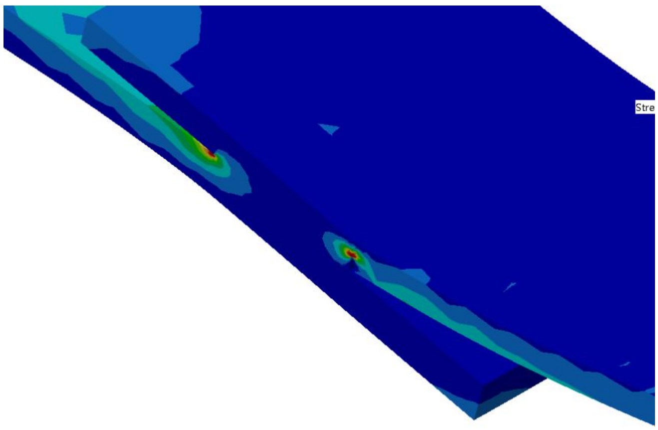


Fig.13. Max. Principal Stress Plot on the Deformed Shape

Determination of Crack Size at Crack Initiation by Finite Element Analysis

The size of the crack at the 5% increase in compliance is identified by the finite element analysis.

Tensile shear specimen

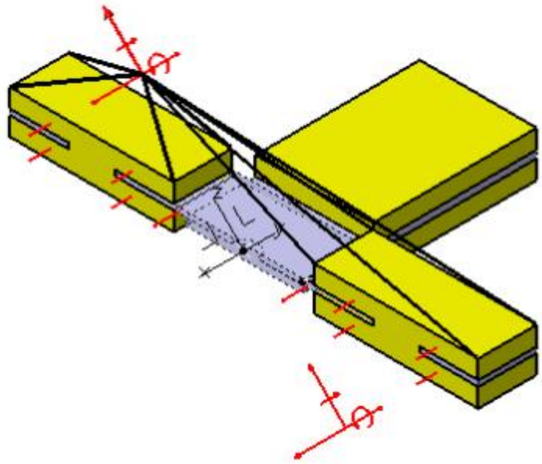
Since the specimen is symmetric about x=0. Only a half is modeled as shown in Fig. 12(a). One end is clamped and the other end is uniformly displaced.in the y-axis direction. A semi-elliptical crack from the inner surface along the edge of the nugget is created as a slot with a gap 0.02 mm. Max. principal stress is plotted on the deformed shape in Fig. 13.

It is found that the major axis and minor axis of the semi-elliptical crack at 5% increase in compliance are a=2.15 mm, c=0.60 mm. It corresponds to a/t=0.5 and c/a=3.6. It is roughly in agreement with the visual observation results in Fig. 5.

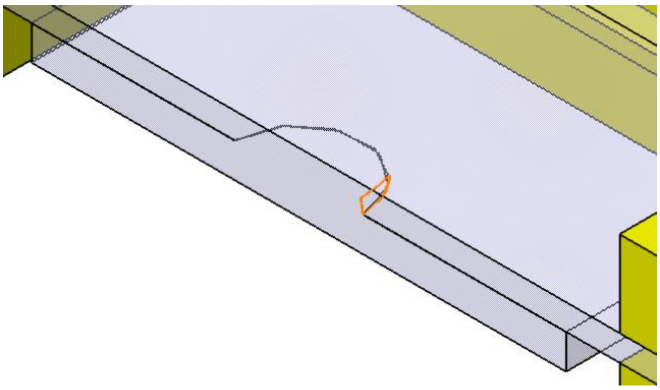
Cross tension & shear specimen

Similarly, only a half is modeled as shown in Fig. 14(a). To model the bolted grip better, the grip as well as the specimen is modeled. A semi-elliptical crack is created similarly. Max. principal stress is plotted on the deformed shape in Fig. 15.

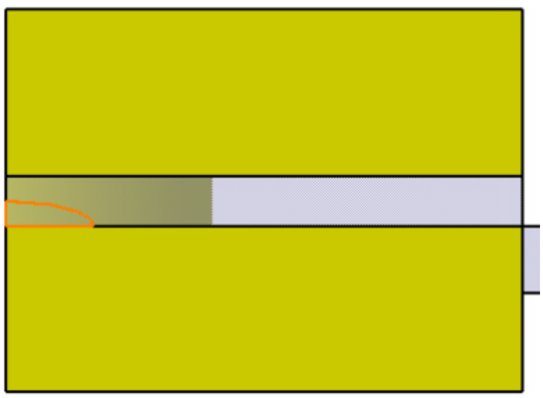
It is found that the major axis and minor axis of the semi-elliptical crack at 5% increase in compliance are a=2.10 mm, c=0.60 mm. It corresponds to a/t=0.5 and c/a=3.5. It is roughly in agreement with the visual observation results in Fig. 10.



(a) Finite Element Model



(b) Semi-elliptical Crack from the Inner Surface along the Edge of the Nugget



(c) Major Axis and Minor Axis of the Semi-elliptical Crack

Fig.14. Finite Element Model for TS Specimen

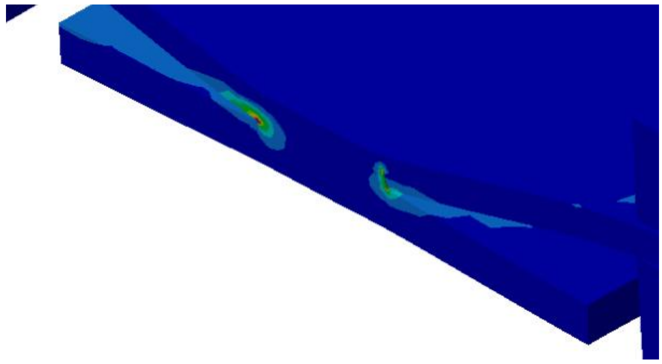


Fig.15. Max. Principal Stress Plot on the Deformed Shape

Conclusion

A technique for the detection of the fatigue crack initiation in the spot-welded joint by monitoring its compliance is applied to a conventional tensile shear (TS) specimen and a newly-designed 45° cross tension & shear (CTS) specimen made of different steel sheets in grade and thickness.

The normalized compliance of the tensile shear specimen remained constant at the beginning and later began to increase. The amplitude of strain on the outer surface remained constant at the beginning and later began to decrease and at last decrease suddenly. The fatigue crack initiation life taken as the number of cycles at 5% increase in compliance is in agreement with that at the sudden decrease in strain on the outer surface.

The normalized compliance of the cross tension & shear specimen began to increase with constant rate due to slippage from the beginning. Assuming that the slippage occurs steadily through the test, we can define the crack initiation life as the number of cycles at deviation 5% from the extended line. The fatigue crack initiation life is in agreement with that at the sudden decrease in strain on the outer surface.

Finally the size of the crack at the fatigue crack initiation life is identified by the finite element analysis. The semi-elliptical crack from the inner surface with a/t=0.5 and c/a=3.5~3.6 yields 5% increase in compliance.

Acknowledgement

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