Spot Weld Failure Mechanisms Due to Different Types of Loading Conditions

Ir. Dr Aravinthan Arumugam

***Ir. Dr Aravinthan Arumugam** is Academic Department Head for Mechanical Engineering at the KDU University College. He has been actively involved in welding research and consultancy for the past 10 years. He has also published journal and conference papers on his research area.*

Motoring industries use the spot welding process to join the automotive Body-In-White (BIW). The spot welding process is a joining process where metal sheets to be joined are placed in-between two water-cooled copper electrodes and pressed into intimate contact by an electrode force.

Later, the current will be turned on and the resistance to current flow through the metal sheets will produce the heat required for localised melting at the interface of the sheets. After a certain time, the current is turned off but the electrode force is maintained to cool and solidify the molten metal. This will form the spot weld, after which the electrodes are separated and the joined metal sheets are removed. Figure 1 (a) shows the spot welding process and Figure 1 (b) shows an example of a spot welded vehicle body part.

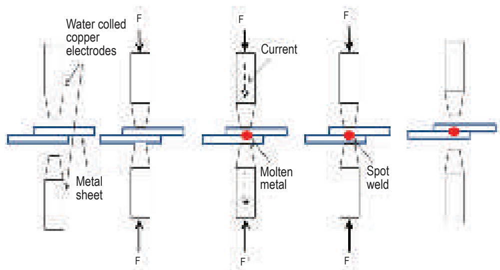


Figure 1: (a) Spot welding process.

Figure 1: (b) Spot weld on automotive part.

There are about 4,000 to 6,000 spot welds in a vehicle, which bear various types of loads (static load, impact load and fatigue load) during the life span of a vehicle.

SPOT WELD FAILURE MODES

The integrity and safety of a motoring vehicle's structure depends on the strength of the spot weld, referred to as its ability to with stand external load without failing. Spot welds, when in service, fails by means of two failure modes: Interfacial failure (failure due to crack propagation through the centreline of weld) as in Figure 2 (a) and weld pull-out failure (failure due to weld pulled out from one sheet) as in Figure 2 (b) (1).

The motoring industry has always preferred the spot welds to fail via weld pull-out failure as this failure has a higher capability to absorb energy before failure (2). The spot weld diameter is the deciding factor on which failure mode, a spot weld could potentially fail. The spot weld diameter depends on the combination of three main process parameters: Welding current, weld time and electrode usually known as the welding schedule. Increase in spot weld diameter, either by increasing welding current or weld time or decreasing the electrode force, has been reported to lead to an increase in weld strength (3). Depending on the selected welding schedule, there will be a particular weld diameter, known as the critical diameter (4), beyond which the weld is guaranteed to failure by weld pull-out. There are motoring standards which recommended the diameter to achieve pull out failure. The AWS/ANSI/AISI standards state the recommended weld diameter $d = 4t^{0.5}$ and Japanese JIS Z3140 states $d = 5t^{0.5}$ where t is the sheet thickness.

(a) (b)

Figure 2: (a) Interfacial failure and (b) Weld pull-out failure.

Motoring industries commonly use peel test and chisel test for spot weld destructive testing and ultrasonic test for spot weld non-destructive testing. The spot weld destructive test gives quantitative evaluation of the spot weld (weld diameter and weld strength) while the spot weld non-destructive test evaluates spot weld qualitatively (good weld, loose weld, stick weld etc). This article will concentrate on the spot weld destructive tests, namely lap shear test, U-tension test and coach peel test. It will analyse the weld pull-out failure mechanism on spot welds made with the same welding schedule when tested under different loading conditions.

SPOT WELD TESTED UNDER DIFFERENT LOADING CONDITIONS

To analyse the spot weld at different loading conditions, three different weld samples were prepared as in Figure 3 (a).

Weld sample A is a coach-peel test sample where a bending moment will be used to initiate Mode I: Opening failure to the weld.

Weld sample B, which is a lap-shear test sample, will subject the spot weld to Mode II: In-plane shear failure.

Finally weld sample C is a U-tension sample (KSII test) which will initiate uniform normal force around the circumference of the weld, leading to Mode I: Opening failure.

The material used for the test samples is mild steel and the samples were prepared according to AWS standards. The welding schedule is as follows: Welding current- 6 kA, weld time – 20 cycles and electrode force – 2.5 kN. This welding schedule was chosen as it would produce a weld pull-out failure, which would be discussed in this article. The experiment was carried out on a pedestal type spot welding machine (50 kVA). Two water-cooled copper electrodes of 6 mm in diameter were used. Figure 3 (b) showed the samples being tested with a Universal Testing Machine (UTM). All samples were tested under quasi-static load.

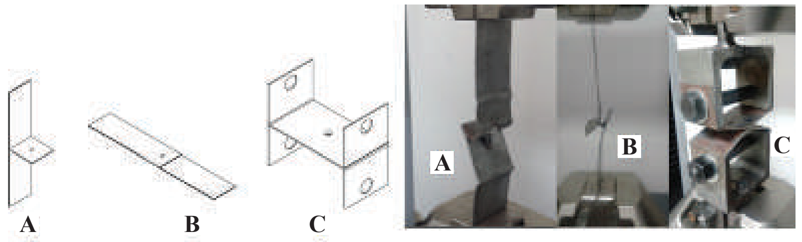


Figure 3: (a) Different types of weld samples and (b) samples tested with UTM.

OBSERVATIONS AND DISCUSSIONS

Figure 4 showed the force-displacement curves plotted when the samples were tested. Each test had five repetitions and the curves represented the average curve for each test.

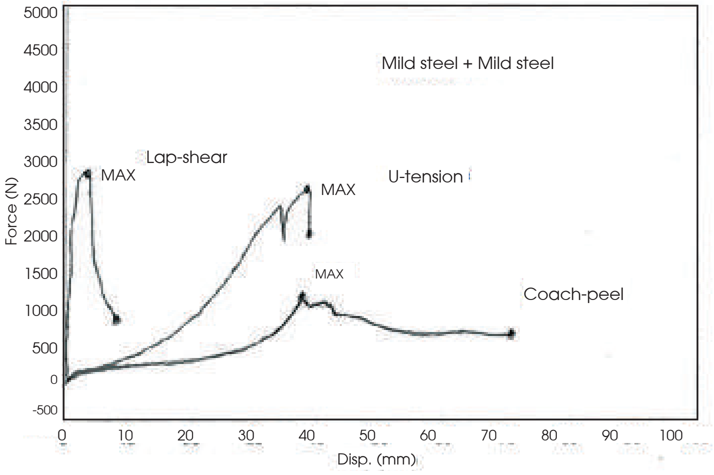
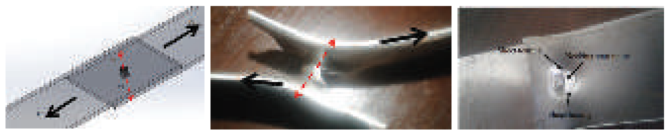


Figure 4: Force-displacement curves for different loading conditions.

The peak load of the curve (MAX) was considered as the weld strength of the weld. The area under the curve represented the amount of energy absorbed to cause failure. The test results showed that lap-shear test gave the highest weld strength compared to the other test even though the spot welds for all samples were produced with the same welding schedule. The result above can be explained when failure mechanism is analysed in detail.

1. WELD PULL-OUT FAILURE IN LAP-SHEAR TEST

When the lap-shear sample was pulled at both ends by a tensile force, F_T, in the case of the weld pull-out failure, the weld would be subjected to a tensile stress (σ_T) as in Figure 5 (a). As could be seen in the lap-shear curve in Figure 4, the tensile stress would increase until the maximum tensile strength of the weld (peak load) was achieved. Consequently, due to plastic deformation, necking started to occur and the common location for necking was at the base metal or the Heat Affected Zone (which would now be called HAZ) of the weld as both these areas had lower hardness compared to the hardness of the weld itself (5). Necking proceeded through the sheet thickness, as in Figure 5 (b), leading to thinning of metal and initiation of crack. The crack further propagated along the weld circumference until the weld tore off from one of the sheets as in Figure 5 (c).

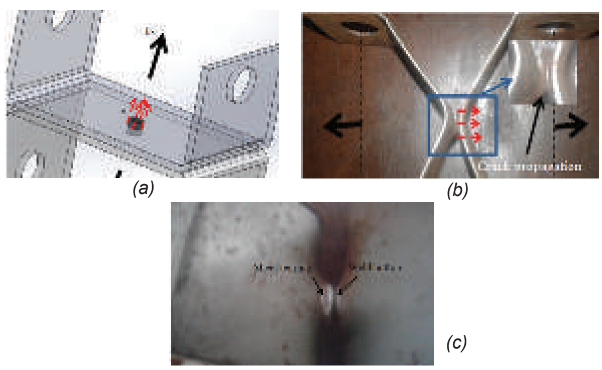


(a) (b) (c)

Figure 5: (a) Tensile stress on spot weld due to tensile force, (b) Necking occurring through sheet thickness and (c) Sheet tearing along weld circumference.

2. WELD PULL-OUT FAILURE IN KSII TEST

When the U-tension sample was pulled by a normal force, F_N, to obtain a weld pull-out failure, the weld circumference was subjected to shear stress as in Figure 6 (a). Referring to the U-tension curve in Figure 4, the shear stress would increase until the maximum shear strength of weld was achieved (peak load). Due to the high shear stress around the circumference of the weld, Figure 6 (b), and localised shear strain mainly at the HAZ, a crack would be initiated and propagated around the weld circumference in order to pull out the 'weld button' through thickness shearing, from the one of the sheets as shown in Figure 6 (c).



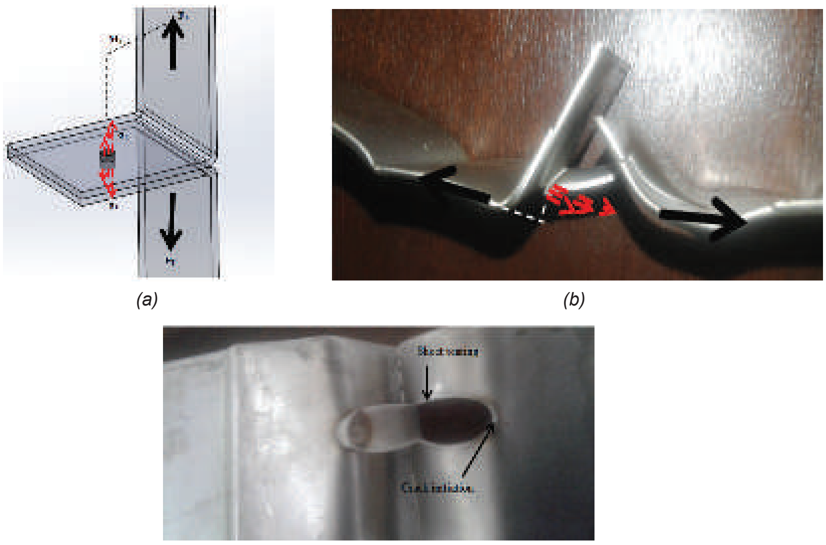
(a) (b) (c)

Figure 6: (a) Shear stress along the circumference of weld, (b) Crack initiation and propagation and (c) weld button pulled out.

The weld strength due to KSII test was lower than the weld strength for lap-shear test as according to Von Mises Criterion; shear yield stress was √3 time lower than the tensile yield stress in the case of a simple tension.

3. WELD PULL-OUT FAILURE IN COACH-PEEL TEST

In the case of the coach peel test, both ends of the sample were pulled by a tensile force, F_T. However, unlike in the lap-shear test, as the force was not in the same plane as the weld, a bending moment, M_b, acted on the weld. The bending moment created a non-uniform tensile stress along the weld diameter due to the peeling action as illustrated in Figure 7 (a). As observed from Figure 4, the coach-peel curve had a longer displacement compared to the curves of the lap-shear test and KSII test. The reason for this was at the initial stage of the test, when the bending moment was used to deform the L-shaped sample before affecting the weld, Figure 7 (b). The maximum load for failure in the coach peel was lowest compared to those of the lap-shear and KSII, because the increase in bending stress initiated a crack near HAZ. The crack propagated along the sheet thickness, causing sheet tearing around weld circumference at a lower load as shown in Figure 7 (c).



(a) (b) (c)

Figure 7: (a) Bending moment created a non-uniform tensile stress along the weld diameter, (b) bending moment was used to deform the L-shaped sample and (c) sheet tearing around weld circumference at a lower load.

Figure 8 shows the spot weld failure by means of weld pull-out for lap-shear test, KSII test and coach peel test respectively. The figure clearly shows the weld pull-out failure is different in each test due to the difference in the failure mechanism. For KSII test, as the weld was pulled out from the other sheet due to thickness shearing around the weld circumference, the spot weld had a circular shape. For the lap shear test and coach peel test, the spot welds had two sections, a semi-circular section where metal necking occurred or metal tearing due to peeling action was initiated and the other section where a portion of metal from the other sheet remained intact at the circumference of the weld, due mainly to sheet tearing which occurred in both these tests. It was also observed from all the welds in Figure 8, that weld failure mainly occurred at the HAZ.

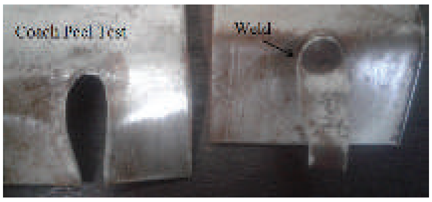


Figure 8: Spot weld pull-out failure in samples tested with lap shear test, KSII test and coach peel test.

Figure 9 shows the weld strength and energy for failure for the welds tested with the three different loading conditions. Weld tested with lap shear test showed superior load bearing capacity and energy absorption capability. This could be due to the necking prior to failure which required huge amount of energy for the plastic deformation to occur. Coach peel test showed the lowest load bearing capacity and energy absorption as this test depended on crack initiation and propagation. Once crack was initiated, low energy was required to cause failure.

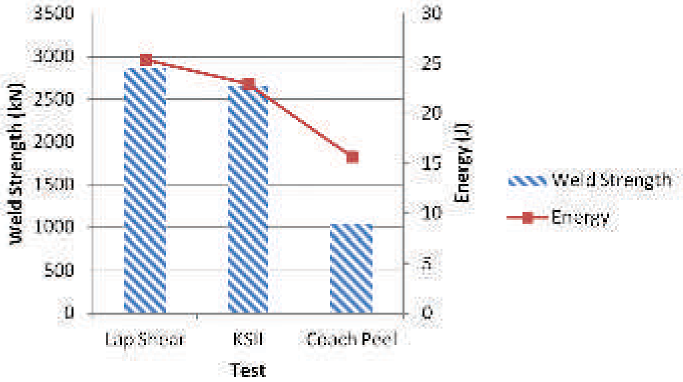


Figure 9: Weld strength and energy absorbed before failure for different tests.

CONCLUSION

a) In lap shear test, spot weld is subjected to tensile stress and necking which occurs at the HAZ due to plastic deformation propagates along the sheet thickness and initiate sheet tearing around weld circumference. The driving force to produce weld pull-out failure is the tensile stress.
b) In KSII test, shear stress at weld circumference and localised shear strain at HAZ will cause the weld to be sheared through the sheet metal thickness. The driving force to produce weld pull-out failure is the shear stress.
c) In the case of the coach peel test, the spot weld will experience non-uniform tensile stress along the diameter of the weld. Crack initiated due to bending moment will propagate due to peeling action, leading to sheet tearing at weld circumference. The driving force to produce weld pull-out failure is the bending stress.
d) Weld tested with lap shear test shows highest load bearing capacity and energy absorption capability.
e) Weld tested with coach peel test shows the largest displacement to failure. ■

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