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# IMPROVEMENT OF FATIGUE LIFE IN POST-WELD COLD WORKED ALUMINUM RESISTANT SPOT WELDS

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**ABSTRACT**–Aluminum Resistance Spot Weld (Al RSW) is an enabling technology for body assembly of low mass fraction vehicles. Due to the unreliable durability of spot-welded joints, applications of Al RSW are limited. This study presents experimental investigation on the use of a post-weld cold working process to improve the fatigue strength of Al RSW. The post-weld cold working process includes special shaped indenters that are pressed or driven into the structure to induce compressive residual stresses. The mechanical properties of the post-weld cold worked Al RSW were investigated, including the experimental results of fatigue and micro-hardness tests. Comparisons of the mechanical properties and qualitative results between the as-welded RSW specimens and the post-weld cold worked RSW specimens are discussed. The post-weld cold worked Al RSW samples had an increase in both microhardness and fatigue life.

**KEY WORDS :** Spot weld, Cold working, Aluminum, Fatigue, Residual Stress, Microhardness

## 1. INTRODUCTION

There is a strong interest in the use of lightweight materials in the construction of automobiles, particularly the body, in order to reduce weight and improve fuel economy and reduce exhaust emissions. The use of aluminum offers considerable potential to reduce the weight of an automobile body. Automotive industry's prototyping and testing of aluminum body structures have verified performance reliability and provided valuable feedback to guide improvement. The automotive body structures need significant amount of assemblies that require a proper joining technology, which is a key for the lightweight automotive body manufacturing (Song *et al.*, 2004; Kang, 2005). Similar to current steel spot welding, aluminum resistance spot welding (Al RSW) becomes increasingly attractive because the process is fast and economical (Cole and Sherman, 1995; Thornton *et al.*, 1996). However, even with the potential advantages of Al RSW, vehicle manufacturers still use the rivet joining technology for the aluminum body due to the unreliable durability of spot-welded joints (Wang *et al.*, 1995).

Recently, a patented post-weld cold working process represents a new approach for improving the fatigue lives of steel RSW, using stress waves to impart beneficial residual stresses (Spitsen *et al.*, 2005). In this study, the fatigue behavior of spot-welded 5052 Al alloy sheets is examined. The effect of the post-weld cold working process parameters on the fatigue strength of the Al RSW is then investigated.

## 2. Experimental Procedures

### 2.1. Specimen Preparation and Welding

The selected workpiece material for this study was Aluminum 5052 with a sheet thickness of 0.77 mm. Aluminum 5052 is common material for truck bodies and panels. The chemical composition of the workpiece material is given in Table 1. The configuration and dimensions of the specimens are given in Figure 1. The mechanical properties of the "as received" Al 5052 are shown in Table 2.

The spot welding was done on a 150 KVA single phase AC pedestal welding machine. The transformer of this machine had seven tap settings for the change of current levels. The electrodes used were male, truncated cone type with a 6.4 mm face diameter. The welding conditions were selected based upon a weld lobe study conducted on the aluminum specimens. After the lobe study (Kim *et al.*, 2005), the weld schedule used for preparation of all the fatigue test samples was chosen.

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Table 1. Chemical composition of Al 5052 (wt.%).

| | | | |
|---|---|---|---|
| Fe | 0.4 | Cr | 0.15-0.35 |
| Si | 0.25 | Zr | 0.1 |
| Cu | 0.1 | Others | 0.2 |
| Mn | 0.1 | Al | Rem. |
| Mg | 2.2-2.8 | | |

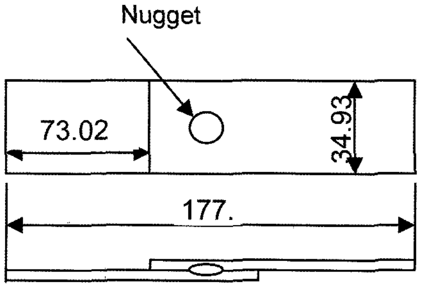


Figure 1. Geometry of test specimens (mm).

Table 2. Mechanical properties of Al 5052.

| Elastic Modulus (GPa) | Tensile Strength (MPa) | Yield Strength (MPa) | % Elongation | Hardness (HK) |
|---|---|---|---|---|
| 70 | 193 | 89 | 25 | 80 |

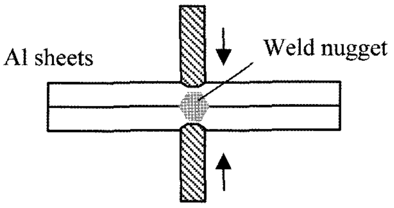
Table 3. Al spot welding process parameters.

| Weld Force (kN) | Weld Time (Cycles) | Hold Time (Cycles) | Welding Current (kA) |
|---|---|---|---|
| 2.45 | 4 | 10 | 9.3 with tap at 5 |

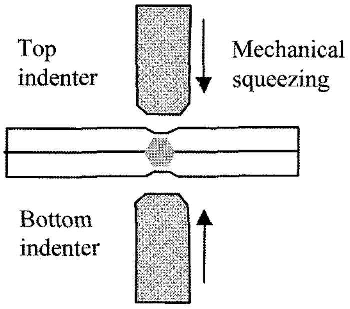
This schedule is listed in Table 3. The welding current of 9.3 kA was used with a transformer tab setting 5. The welding current profile used had 2 cycles of preheating followed by 2 cycles of cooling and finally 4 cycles of welding. The average weld button size was 4.5±0.20 mm.

### 2.2. Post-weld Cold Working Process

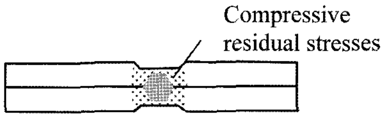
In this study, the post-weld cold working process was performed after spot welding. Figure 2 shows a schematic diagram of the post weld cold working process. This new approach incorporates the cold working process using an indenter with a cylindrical tapered-end shape that was developed for RSW applications. In a typical production application, the indenters are positioned concentric to the RSW location. Using a hydraulic press, the indenter is then pressed or driven into the structure until a specific load and/or displacement is reached (Easterbrook *et al.*, 2001; Meyer, 2002).



(a) AL RSW



(b) Post-weld cold working process



(c) RSW with compressive residual stresses

Figure 2. The schematic of post-weld cold working process.

### 2.3. Experimental Design

In the initial stages of the post-weld cold working, experiments were conducted on a number of samples determined from a design of experiment approach to investigate the effect of post-weld cold working process parameters on the Al RSW mechanical properties. Two input variables were identified – indenter pressure (IP), and indenter size (IS). The factors and levels of the 2 level design matrix are shown in Table 4. Due to the variation of indenting pressure of the hydraulic press it was observed that the IP input parameters varied slightly.

### 2.4. Fatigue Testing

Fatigue tests of both as-welded and post-weld cold worked specimens were conducted using a Shimazdu electo-hydraulic machine under the following test conditions:

Table 4. Post-weld cold working experiments matrix.

| Level | IP (indenting pressure, MPa) | IS (indenter size in diameter, mm) |
|---|---|---|
| Low (–1) | 300±10 | 4.6 |
| High (+1) | 450±15 | 7.1 |

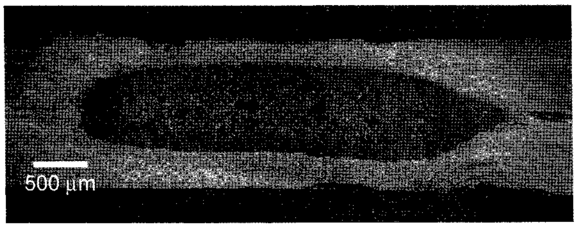
0.1 load ratio, 25 Hz frequency, and sine wave cyclic loading. In the low load condition, the number of cycles to failure was determined when a fatigue crack appeared on the outer surface of the specimen. However, in the high load condition, cracks did not appear on the outer surface of the specimen. For the high load condition, the number of cycles to failure was determined when the weld joint completely failed. The fatigue endurance limit was defined as the load where no crack was detectable after $1\times10^7$ cycles.

## 3. RESULTS AND DISCUSSION

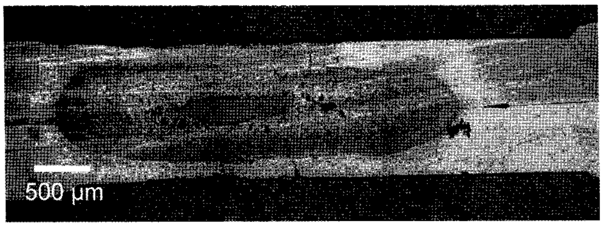
### 3.1. Microstructure

Microstructures of an as-welded specimen and post-weld cold worked specimen with 7.1 mm IS, 450 MPa IP are shown in Figures 3(a) and 3(b) respectively. Figure 3(a) shows satisfactory spot welment formation. The spot weldment contains three zones, which are nugget, heat affected zone (HAZ), and base metal. It was proven that the porosites that are often visible in the nugget do not have a significant influence on the mechanical properties (Gean *et al.*, 1999; Radaj, 1990). Thermal cracking which is a frequent quality problem in Al RSW (Senkara and Zhang, 2000) was not found in the HAZ.

Figure 3(b) shows that the 7.1 mm indenter mechanically squeezed the base metal zone as well as the nugget zone during the post-weld cold working process. Particularly of interest in these figures is the difference in the faying surface notch radii, the faying surface is often the site for crack initiation. The as-welded specimen in Figure 3(a) has a relatively large notch radius whereas the post-weld cold worked specimen in Figure 3(b) has a much smaller radius. Therefore, the cold working process causes the radius of the notch at the intersection of the faying surface and fused zone to decrease.



(a) As-welded Al RSW

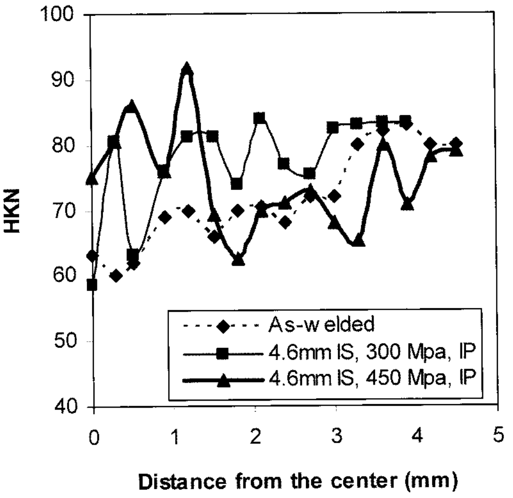


(b) Post-weld cold worked Al RSW
(7.1 mm IS, 450 MPa IP)

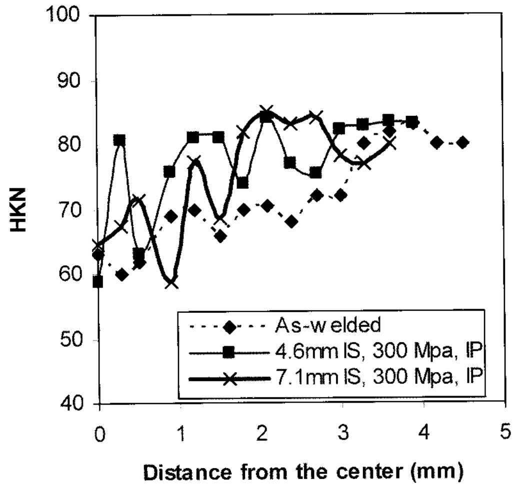
Figure 3. Microstructure.

### 3.2. Microhardness

Microhardness test results are shown in Figure 4. Microhardness in the nugget area is generally lower than that in the base metal area. Fusion zones in Al RSW have much larger grains due to welding as shown in Figure 3. Investagated was the effect of post-weld cold working parameters on the Knoop microhardness profiles of as-welded and post-weld cold worked samples for varying indenter sizes and pressures. As shown in Figure 4(a), it is clearly shown that an increase in IP directly causes a



(a) Effect of IP



(b) Effect of IS

Figure 4. Knoop microhardness of post-weld cold worked RSW.

greater increase in the microhardness. It is shown the 450 MPa IP specimens generally have a higher hardness than the 300 MPa specimens. Hardness in the cold worked area by the 300 MPa IP was measured to be approximately 10% higher than that of the non-cold worked area. A 20% increase was found in the cold worked area by the 450 MPa IP. This is an indication that the strain hardening takes place during the cold work process, which results in an increased strength of the Al RSW.

In Figure 4(b), the increased microhardness for the 7.1 mm IS extends into the base material whereas the 4.6 mm IS experiences only a local hardness increase near the center of the nugget. The increase in the hardness values by cold working may lead to the enhancement of the Al RSW tensile-shear properties. From the previous study (Kim *et al.*, 2005), the combination of 4.6 mm indenter size and 450 MPa indenting pressure increases the maximum load by 25% in the tensile-shear testings. The maximum load is the most commonly monitored variable in tensile-shear testing of RSW. Therefore, the strain hardened Al RSW by cold working has higher static tensile-shear properties.

## 3.3. Fatigue Testing

The specimens used for the fatigue tests had a nugget size of 4.5±0.2 mm. The L-N curves of as-welded specimens and post-weld cold worked specimens with varying IP (300 MPa and 450 MPa) at 4.6 mm IS are shown in Figure 5. The number of cycles to failure vs. maximum net fatigue test load is plotted. As shown in the figure, fatigue life of cold worked specimens increased compared with that of the as-welded specimens. For example, the fatigue life of the specimen treated at 450 MPa IP is $2.9\times10^6$ cycles at 686 N, while the as-weld fatigue life is $3.9\times10^4$ cycles at the same load condition (686N). This is an improvement of approximately 73 times.

Figure 6 shows the L-N curves of as-welded specimens and post-weld cold worked specimens at 7.1 mm IS. This figure also shows that fatigue life of the cold worked specimens increased in comparison with the as-welded specimens. Interestingly, fatigue life of the specimens treated at 300 MPa IP is 10 times greater than the as-welded specimens at the same fatigue load condition. The superior fatigue resistance of the post-cold worked specimens is possibly due to the fact that compressive residual stresses were induced during the post-weld cold working process which would delay the crack initiation and/or crack propagation. Even though the post-weld cold worked specimen has a much smaller notch radius than the as-welded specimen, the sites of the crack initiation and propagation are identical between the two groups (Kim *et al.*, 2005).

Fatigue life data for the post-weld cold worked specimens are more scattered than those for as-welded specimens at a given load. The effect of weld quality, also known as nugget size, on fatigue life of the post-cold work processed low carbon steel RSW was investigated by some of the authors (Blake *et al.*, 2005). As a result of post-weld cold working there was mild improvement in the fatigue life of the samples with undersized welds (nugget sizes $< 3\sqrt{t}$, t = sheet metal thickness) but there was substantial improvement in the fatigue life of the samples with adequately sized welds (nugget sizes $>3\sqrt{t}$). This means the fatigue life of the post cold

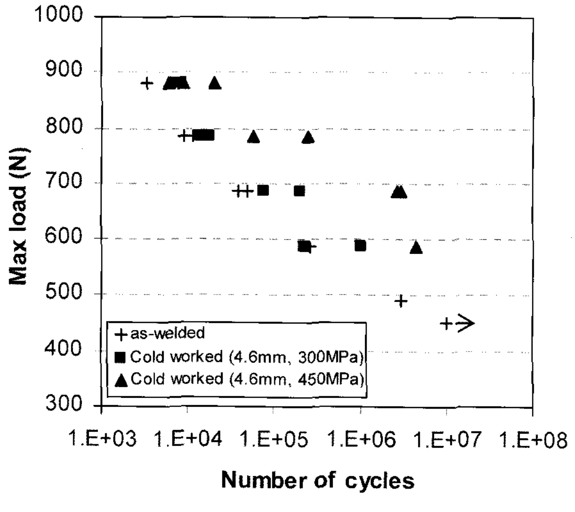


Figure 5. L-N curves for as-welded Aluminum and post-weld cold worked RSW specimens with 4.6 mm IS (An arrow indicates a run-out specimen).

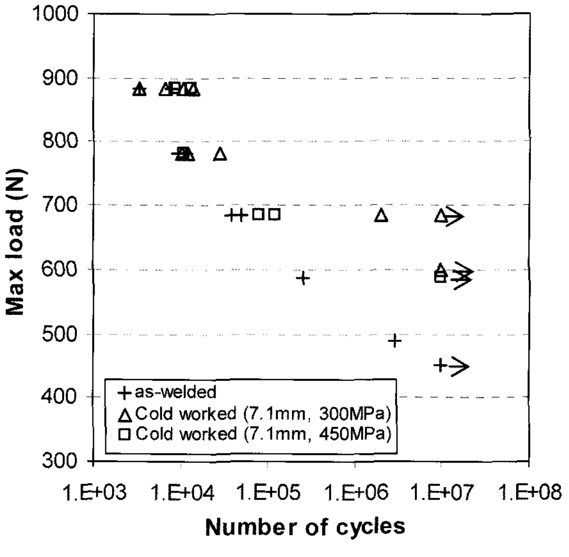
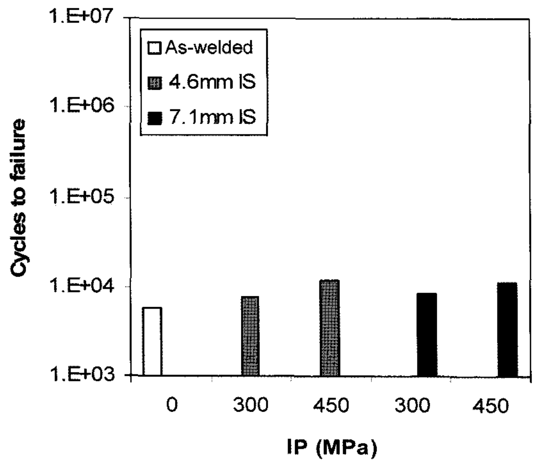
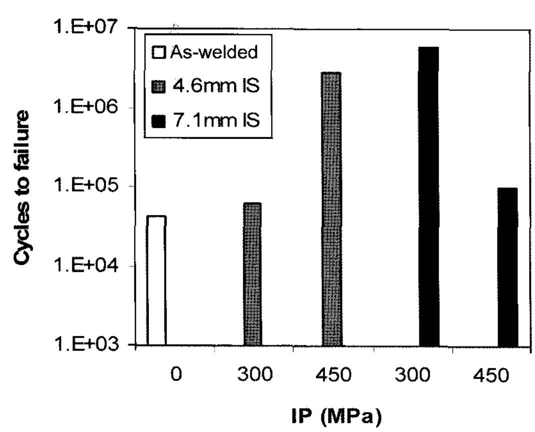


Figure 6. L-N curves for as-welded Aluminum and post-weld cold worked RSW specimens with 7.1 mm IS (An arrow indicates a run-out specimen).



(a) With max. fatigue load of 882 N



(b) With max. fatigue load of 686 N

Figure 7. Effect of IS and IP on average fatigue life for post-weld cold worked specimens vs. as-weld specimen.

worked samples is sensitive to welding quality. The reason for the scattered fatigue data maybe is due to the various Al weldment sizes and shapes.

Fatigue life improvement for each design of experimental parameter has a different trend. Figure 7(a) shows as-welded specimen fatigue life and cold worked specimens fatigue life with 4.6 mm, 7.1 mm IS and 300 MPa, 450 MPa IP, respectively, at maximum fatigue load condition of 882 N. As shown in the figure, fatigue life for all the cold working parameters at a maximum fatigue load condition (882 N) is higher than the as-weld specimens. Figure 7(b) shows the fatigue lives of as-weld specimen and the post-weld cold worked specimens with 4.6 mm, 7.1 mm IS and 300 MPa, 450 MPa IP, respectively, at a maximum fatigue load condition of 686 N. As shown in the figure, fatigue life increased clearly for each of the cold working parameters (IS and IP) compared with that of the as-welded specimen. It is shown that post-weld process did not drastically increase fatigue life in the high fatigue load condition when compared with the low fatigue load condition where there is a clear increase. From this observation, it can be considerd that the compressive residual stresses created during the post-weld cold working process are more beneficial at lower fatigue loading conditions than higher fatigue loads. However, the post-weld cold working process still increase the fatigue life in the high fatigue load condition, which cannot be the case in the post-weld cold worked steel RSW (Spitsen *et al.*, 2005). This may be due to the increased hardness of Al RSWs.

Fatigue life of the 4.6 mm IS specimens increased as the IP increased. The effect of IP at the low fatigue load condition (686 N) is more obvious than at the high fatigue load condition (882 N). However, higher IP has a beneficial effect on the fatigue life of specimens subjected to high fatigue loading. The 7.1 mm IS tends to produce a lower fatigue life than the 4.6 mm IS specimens. This shows that larger IS and higher IP have not increased fatigue life extensively. The diameter of 7.1 mm IS indenter is significantly larger than the diameter of the fused zone of the RSW by approximately 60%. Therefore most of the induced compressive residual stresses is distributed into the base metal. This decreases the favorable assistance to the suspension or retardation of the fatigue crack initiation or propagation near the fusion zone.

The residual stress distribution after the post-weld cold working process is not clearly understood yet. Finite element (FE) model is being developed to complement and verify the experimental results, and it is the subject of continuing research.

## 4. CONCLUSIONS

Aluminum 5052 resistant spot welds were post-weld cold worked in order to improve their fatigue properties. The results can be concluded as;

(1) The post-weld cold working process increased the microhardness of Al spot welds by approxiamently 15%. The increase in the hardness values by cold working may lead to enhance the Al RSW tensile-shear properties as well as fatigue strength.
(2) In general, the post-weld cold worked specimens have an increased fatigue life when compared with the as-welded specimens. Compressive residual stresses induced during the post-weld cold working process increase fatigue life significantly.
(3) The post-weld Al RSWs showed a moderate increase in fatigue life at the high fatigue load condition when compared with the low fatigue load condition where there is a clear increase.
(4) Fatigue life data of the cold worked specimens are

more scattered than those of the as-weld specimens. This is due to the interaction between the post cold work process and the Al RSW weld quality.

(5) The optimum parameters of the cold working process with respect to fatigue life of the Al RSW are 300MPa IP with 7.1mm IS.

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