Effect of Weld Design on the Fatigue Strength of Laser and Resistance Spot Welded Tubular T-Joints for Automotive Applications

Laser beam welded T-joints have higher fatigue resistance than resistance spot-welded T-joints when laser weld pattern and location are optimized

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ABSTRACT. The increasing interest in laser beam welding for automotive applications has directed the attention of many researchers to investigating the durability of laser beam welded components. In this study, a comprehensive experimental study, augmented by finite element analysis, was performed to assess the effect of laser weld pattern and location on the durability of box section T-joints. Two laser beam weld configurations were assessed: straight and optimized. Additionally, for comparison purposes, fatigue of resistance spot-welded T-joints was also evaluated. In-plane bending, at an R ratio (R = min/max load) of -1, was employed for all the tests. Test results showed that, on the basis of comparable weld area, laser weld configuration has a strong influence on the fatigue resistance of the T-joints. An optimized laser weld configuration was shown to provide fatigue resistance superior to a resistance spot-welded T-joint. In order to incorporate the advantages of laser beam welding, optimization of weld design should be part of the early stages of vehicle development.
Fig. 1 — Photograph and schematic of the T-joint prior to fatigue testing. A — Laser beam welded at center pillar-to-rocker joint with straight bead pattern.

Fig. 1 — B — laser beam welded with optimized bead pattern.

Fig. 1 — C — single side resistance spot welded at front and back faces of joint.
mined through finite element analysis (FEA) optimization and practical laser processing limitations. For comparison purposes, resistance spot-welded T-joints (S) (Fig. 1C) possessing comparable weld area (approximately 397 mm$^2$) was also included in this study. Since the rocker is tubular, resistance spot welding of the pillar to roll-formed rocker was accomplished using the single side resistance spot welding (SSRSW) process, which is a variation of the conventional RSW process.

Following a description of experimental procedures, which include specimen fabrication and fatigue testing methods, the finite element analysis (FEA) procedure is given. This is followed by showing the experimental and numerical results. Calculated compliances from FEA were compared with experimental measurements to verify the accuracy of weld representation in FEA. Photographs of fatigued laser beam and resistance spot-welded T-joints are presented. Finally, the effects of weld pattern and location on the durability of T-joints are discussed.

Experimental Procedure

Specimen Fabrication

A bare 1.15-mm (0.045-in.) gauge cold-rolled low carbon steel (SAE 1005) was used to stamp the pillar outer and inner. Dimensions are as indicated in Fig. 1. The pillar reinforcement and rocker used 1.5-mm (0.059-in.) and 1.6-mm (0.063-in.) cold-rolled steels (SAE 1005), respectively. We fabricated the latter into 76.2 x 76.2-mm (3.0 x 3.0-in.) roll-formed tubes from which 500-mm (19.68-in.) sections were cut to represent the rocker part of the specimen.

Laser Beam Welded T-Joint

Specimens L1 and L2 were prepared as follows: 1) RSW the front face of pillar outer to reinforcement as in specimen S; 2) RSW pillar reinforcement to top face of rocker; 3) laser beam welding (LBW) front face of pillar to rocker joint; 4) LBW pillar side flanges to the top side of rocker; 5) LBW pillar inner to the back face of rocker; and 6) RSW pillar outer and inner reinforcement. The parts were welded with a 3-kW CO$_2$ laser. Fixtures were used to ensure metal fitup. A typical laser weld with bead width of 1.2 mm (0.047 in.) was produced at a welding speed of 38 mm/s (90 in./min). Table 1 lists the LBW parameters that gave the best results based on weld bead appearance and/or completeness of penetration.

Resistance Spot-Welded T-Joint

Specimen S was fabricated as follows: 1) resistance spot welding (RSW) pillar outer to reinforcement using six spot welds on the front face of the pillar; 2) SSRSW pillar reinforcement to the top face of the rocker using three welds; 3) SSRSW pillar flange-to-rocker using four welds; 4) SSRSW pillar side flanges to the top face of the rocker using two welds on each flange; 5) SSRSW pillar inner to back face of the rocker through three welds; and lastly 6) RSW pillar outer, inner and reinforcement along the two long side flanges. Specimens were prepared using a single-phase, microprocessor-controlled AC electrical resistance welding unit. In order to compare the fatigue resistance of laser beam and resistance spot-welded T-joints, it is necessary to select a foundation. An equivalent weld area was used as the basis for comparison. Consider the laser weld with bead width of 1.2 mm (0.047 in.) and total bead length of 331 mm (13 in.) on the pillar flange-to-rocker; the resistance spot weld having equivalent weld area as the laser weld (approximately 397 mm$^2$) should have a nugget diameter of 6.78 mm (0.267 in.). A 6.8-mm (0.268-in.) diameter was formed under the optimum welding schedule of 10 kA current and 10 cycles of weld time. Minor modifications of the welding current were necessary in order to obtain desired weld nugget size.

Fatigue Testing

The specimen gripping method and position are shown in Fig. 2A. In our test jig, both ends of the rocker were held stationary by the two large clamps that surrounded the tube, and the pillar end was attached to the lower end of the ram by another pair of clamps. The axial servo-hydraulic actuator shown in Fig. 2B app-
plied a push-pull loading to the pillar end.

All specimens were tested to failure under load control using an MTS 20-kip testing machine. All fatigue tests were conducted under an $R = -1$ ($R = \text{min}/\text{max}$ load) loading condition at 1 to 5 Hz. Three specimens were tested at each load level. Compliance was monitored continuously by detecting changes in displacement. The data acquisition system was connected to a computer programmed to receive and store load and displacement data. These data were then stored on a floppy disk.

Macroscopic Examinations

Macroscopic examinations were performed visually and recorded using a still camera with the aim of determining the crack initiation and growth sites.

Finite Element Analysis

Finite Element Model

The complex weld connection and loading applied to the T-joint required the use of the finite element method to analyze stress distribution. Stress analyses results can be used not only to predict the crack initiation and growth sites but as an index to represent the fatigue initiation life of the T-joint.

A large finite element model was constructed by assembling several segments of the structure as substructures. Figure 3A shows the finite element model. The four-node shell element was selected for use with the ABAQUS finite element computer code (Ref. 4). The model contains 4801 nodes and 4546 elements. A rigid link is used to join two parts of the mesh when corresponding nodes on the two parts are to be welded. The rigid link makes the rotation equal, but leaves the displacements independent of each other. An extensive finite element analysis was conducted, and we found that nine rigid links (Fig. 3B) can be used to represent a resistance spot weld. Two parallel lines of nodes representing the joining of pillar to rocker through laser beam welds (Fig. 3C) were connected through multi-pinned rigid links (Ref. 5). The loads and boundary conditions imposed on the model were: 1) The ends of the roll-formed rocker were fixed; and 2) a concentrated bending load was applied in-plane at the pillar center to simulate the loading experienced in the experiments. The material was assumed to be linear elastic. All computations were performed on an IBM computer.

Weld Bead Configuration

The procedure for determining the optimal laser bead configuration is a two-step process. The first is standard finite element stress analysis under constant weld area constraint to arrive at the optimum shape and location for the weld bead. This optimum configuration results in lower stress values compared to the straight bead case. The second is a feasibility study based upon manufacturing and plant throughput constraints. Extensive stress analyses of various weld configurations and processing evaluation resulted in the choice of a U-shaped weld pattern (Fig. 1B), hereafter referred to as “optimized weld pattern.”

Results and Discussion

Failure Criterion

The initial compliance (compliance = 1/stiffness) of a joint has often been used as an index in structural evaluations. Compliance of a T-joint can be determined using the following formula:

$$c = \frac{\delta}{F^2}$$

where $\delta$ = deflection, $F$ = applied force, and $l$ = specimen arm length.

Since joint compliance is an important consideration in vehicle structure design, a semi-arbitrary change of 10% in joint compliance during fatigue cycling was used to define joint failure (Ref. 6). The compliance response of every specimen was monitored at the beginning and throughout the test. Upon the initial cycling, residual stress relaxation and/or the breaking of contacts between the two sheets that formed during the welding process by the vaporized or expelled material could change the joint compliance. Thus, the changes in compliance for fatigue life less than about 100 cycles were ignored. Specimen failure was identified as the number of cycles at which specimen compliance increased by 10% from its initial value (i.e., $C_i/C_f = 1.1$, where $C_i$ and $C_f$ represent the current and initial stabilized compliance). Specimens which did not exhibit any compliance change after about 2 x 10^6 cycles were termed as “run-out,” and the test was stopped.

Figure 4 shows the compliance change vs. fatigue life for laser beam (L1 and L2) and resistance spot-welded (S) specimens under a moment level of 920 N.m. Each curve in the figure from one test was representative of typical specimen behavior. As shown, at the beginning of the test, there was little change in
compliance. As the testing proceeded, there was a gradual change in compliance. As the fatigue life exceeds $6.6 \times 10^5$, $7.3 \times 10^5$, $6.3 \times 10^5$ cycles, for specimens L1, L2, and S, respectively, compliance increases noticeably. This compliance increase is attributed to the growth and coalescence of fatigue cracks at the critical locations in the specimen. Since a compliance increase leads to a decrease in the vibration frequency response of the structure (frequency $\sim (1/\text{mass} \times \text{compliance})^{1/2}$), it is reasonable to select compliance change as an index to define fatigue failure. The 10% increase in compliance was chosen mainly based upon the consideration of global vehicle structural performance. It was observed that a 10% increase in compliance generally corresponded to 1- to 2-Hz reduction in structural natural vibration frequency. One of the vehicle dynamic requirements is to separate the body structural frequency from the other parts (i.e., suspension) frequency. In order to avoid the frequency overlap, we chose 10% increase in compliance as the failure criteria even though it is stringent in terms of useful fatigue life. As shown in Fig. 4, the fatigue failure definition employed here gave a conservative fatigue life at a given load level, and may correspond to the initiation and early growth of small cracks in the joint.

Fatigue Test Results

Fatigue test results for T-joints with straight (L1) and optimized (L2) weld patterns are plotted in Fig. 5. Data points associated with an arrow indicate tests that were stopped before the specimens failed. A curve fitting analysis was performed to obtain load vs. life relationship for each specimen type. In order to determine whether weld pattern and location on the pillar flange-to-rocker affects the fatigue strength of T-joints, test statistics was used. Details of the test statistics are described in Ref. 7. For the sake of clarity and continuity, however, the relevant features of the test statistics are recapitulated briefly here.

Let $d_1$ be the standard deviation in fatigue life for numbers of specimen ($k_1$) with straight weld pattern, and $d_2$ be the standard deviation in fatigue life for numbers of specimen ($k_2$) with optimized weld pattern. The total standard deviation in fatigue life for all the specimens ($K = k_1 + k_2$) is defined as $D$. The test statistics for the analysis of variance is denoted $F^*$:

$$F^* = \frac{(k_1 - 2)(K - d_1^2) + (k_2 - 2)(K - d_2^2)}{(K - 2)(K - 4)} \times \frac{(K - 4)}{(k_1 - 2) d_1^2 + (k_2 - 2) d_2^2}$$

(2)

The $F^*$ value obtained from Equation 2 is compared with tables of the F-distribution (Ref. 8). If the value of $F^*$ is greater than the F-value obtained from the statistical tables, the two sets of variances are significantly different at the chosen level of confidence. Fatigue test results for specimens L1 and L2 are shown in Fig. 5. The $F^*$ value is 25.7, obtained using Equation 2. This is to be compared with 3.74, the F-value for the sample size of 18 in Fig. 5 for 95% confidence level. This comparison shows that fatigue strength of laser-welded T-joint is significantly affected by weld pattern and location. Fatigue strength of specimen L2 was far superior to that for specimen L1.

For comparison purposes, resistance spot-welded T-joints (S) were also fabricated and tested, and the data were included in Fig. 5. Due to the current shunting difficulty, resistance spot welds were located at the midline of the pillar flange-to-rocker. As shown in Fig. 5, fatigue strength of specimen S is slightly superior to that for specimen L1, but not as good as specimen L2. The optimized weld bead configuration used in specimen L2 was determined through extensive finite element analyses and consideration for practical laser processing parameters. The optimized weld bead configuration resulted in lower local stress concentration than that of a bead located at the midline of the pillar flange-to-rocker. Thus, an optimized weld pattern would result in increased fatigue resistance.

Note in Fig. 4 that specimens L1 and S had comparable initial compliance, but slightly greater initial compliance than specimen L2. The initial compliance of a structure has often been used in the automotive industry to correlate with fatigue resistance. If initial compliance is used to represent fatigue durability, one would expect that for the same load applied, specimens L1 and S would have about the same fatigue resistance. This clearly is not the case for the data shown in Fig. 5, where specimen S exhibited much greater fatigue resistance than specimen L1. The key to this apparent inconsistency is shown in Fig. 6. Compliance change rate was determined from compliance vs. fatigue life, as in Fig. 4, by an incremental polynomial procedure. A polynomial was fitted through the data points using least squares regression techniques. The first derivative of this polynomial was then evaluated to obtain a compliance change rate, $dc/dN$. A plot of $dc/dN$ vs. fatigue life is shown in Fig. 6 for specimens L1, L2 and S. As shown, even though the initial compliance of specimen S is comparable to that
Fig. 6 — Compliance growth rate (dc/dN) as a function of cycles for laser beam (L1 and L2) and resistance spot welded (S) T-joints.

Fig. 7 — A cross-section of a fatigued laser beam weld.

Fig. 8 — A — Von-Mises stress contour for a laser beam welded T-joint with straight weld pattern under an in-plane stress of 10^5 N/cm^2; B — photograph of a fatigued specimen.

of specimen L1 (Fig. 4), the much slower compliance increase rate resulted in greater fatigue resistance in comparison to specimen L1. Hence, the initial compliance (or stiffness) cannot always be quantitatively used as an index to represent structural durability.

Comparison of Calculated Compliance with Measured Values

Compliance values for specimens L1, L2 and S were obtained from finite element analysis (FEA) and are compared with measured values in Table 2. As shown, FEA underestimates the compliance for all specimens. Although calculated compliance values are generally less than the measured values, all calculations are well within a scatter factor of 1.37. There are two reasons for the apparent discrepancies in the analytical and experimental results. First, T-joints were modeled in this study as defect-free conditions. Figure 7 shows a cross-section of a weld bead for fatigued laser beam welded specimens. As shown, even though the specimens were carefully fabricated in the laboratory, there is a small joint clearance (i.e., joint clearance refers to the distance between the faying surfaces of a joint). The compliance of T-joints would increase with existence of weld discontinuities. The finite element model, shown in Fig. 3A, does not contain these weld discontinuities. Second, it may be a result of using the rigid links for weld representation. Use of the three-dimensional brick element representing the welds would result in better agreement between prediction and experiment. Nonetheless, the use of nine rigid links to model the resistance spot weld and two parallel rigid links to represent the laser beam weld in finite element analysis provide reasonable compliance values.
Stress Analysis and Fractography

Because the pillar flange-to-rocker is the most critical and highly stressed region, we only show the elemental stress distributions of pillar inner and outer flanges. Figure 8A shows the Von-Mises stress contours for pillar inner-to-rocker flanges of specimen L1 under an in-plane stress of $10^5$ N/cm² (145 ksi). As can be seen in Fig. 8A, the maximum local stress is located at the end of the weld bead (indicated by number 2). This is the most critical location where one would anticipate a fatigue crack to initiate. Figure 8B shows a fatigue tested L1 specimen. Crack observations showed that cracks initiated at the tip of the weld bead located on the pillar inner, and propagated along the weld bead. Compared to Fig. 8A, the current predicted fatigue critical locations agree well with the experimental results.

Figure 9A and 9B shows the Von-Mises stress contours and fatigue tested sample for specimen L2. As shown, although similar crack initiation sites at the tip of the weld bead are observed, calculated stress magnitudes are much smaller than that for specimen L1.

Figure 10A shows the Von-Mises stress contours for specimen S under in-plane bending. As shown, there are two maximum Von-Mises stresses located at the center pillar inner and outer flanges. Compared to Figs. 8A and 9A, the maximum local stresses are smaller than that of specimen L1, but greater than that of specimen L2. Figure 10B shows the fatigue tested S specimen. Cracks initiated at locations A and B (at the weld HAZ), and propagated along the top edge of the single side resistance spot welds. The coalesced crack propagated toward the outside diagonal edges of the pillar inner flange. This is in agreement with finite element stress analyses.

Effect of Weld Pattern and Location

Fatigue life of a T-joint can be divided into two portions: crack initiation life, which is spent in developing and growing small cracks from welds, and the crack propagation life, which is spent in growing cracks to failure. This division of fatigue life is supported by results shown in Fig. 4. Compliance is associated with initiation of fatigue cracks, and appears as a monotonic increasing function of crack growth. The relative importance of initiation and propagation life depends upon the local stress field and stress intensity (or stress distributions) around the weld bead. Initiation life of welded components can be modeled by local strain approach (Refs. 9, 10), and propagation life is related to the stress intensity around the crack tip (Refs. 11, 12). Therefore, in order to have desirable fatigue properties, it is necessary to avoid high local maximum stresses at the pillar flange-to-rocker, as well as ensuring uniform stress distributions around the weld bead.

With this in mind, consider the effect of weld configuration on the fatigue performance of T-joints. Figure 11 illustrates four different weld configurations on the pillar to rocker flange. Cases I and IV are essentially the weld configurations used for specimens L1 and L2, respectively. Unlike case I, case II welds are moved toward the bottom edge of the flanges joining pillar outer to rocker and pillar inner to rocker. Case III is similar to case II, the difference being it has an inverted U-shaped weld pattern on the pillar inner flange. Normalized maximum stress concentration around the weld bead are calculated and compared in Table 3. The maximum stress for each case is normalized by the maximum Von-Mises stress in case IV.

Stress distributions around the weld beads for these four cases are also compared. They are qualitatively proportional to the results of local stress con-

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**Table 2 — Calculated and Experimental Values of Compliance of T-joints**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Calculated ($\mu$rad/N·m)</th>
<th>Experimental ($\mu$rad/N·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser-welded (L1)</td>
<td>2.82</td>
<td>3.59 ± 0.15</td>
</tr>
<tr>
<td>Laser-welded (L2)</td>
<td>2.53</td>
<td>3.46 ± 0.10</td>
</tr>
<tr>
<td>Resistance spot-welded (S)</td>
<td>2.72</td>
<td>3.53 ± 0.17</td>
</tr>
</tbody>
</table>
centrations; that is, the larger the local stress concentration, the greater is the difference in stress distribution around the weld bead. As seen in Table 3, case I has high stress concentrations at the tip of the weld bead. As shown earlier in Fig. 5, a joint with such weld pattern is weaker than the resistance spot welded T-joint. The situation is slightly improved in case II. A weld bead located adjacent to the bottom edge of the pillar flange has a lower notch severity than that of a bead located at the midline of the pillar flange. Much better results will be obtained with the case III weld pattern. Stress concentrations at the pillar inner flange are minimized by the inverted U-shaped weld. A joint with case IV weld pattern performs best. This weld can more effectively redistribute the stress over the entire pillar outer flange-to-rocker. A joint with case IV weld pattern has greater fatigue strength than resistance spot welded T-joint — Fig. 5. These results suggest that appropriate weld pattern and location could redistribute the load in the T-joint, and consequently, improve the fatigue resistance. Therefore, in order to incorporate the advantages of LBW, designing for optimal laser weld location and bead pattern should be part of the early stages of product planning.

It should be noted that the above results apply to the in-plane bending condition. Weld configurations, which give good durability under in-plane loading, may not result in desirable performance for the same joints under other loading conditions. Furthermore, unidirectional loading is a rarity. Most welded assemblies are subjected to a combination of multidirectional stresses. Therefore, a testing program to evaluate the multiaxial fatigue of T-joints would be very desirable.

Conclusions

1. Laser beam welded T-joints can have higher in-plane bending fatigue resistance than resistance spot-welded T-joints if laser weld pattern and location are optimized.
2. Laser weld design optimization should be a part of the early stages of vehicle development.
3. Weld location and pattern on the pillar outer flange-to-rocker have a strong influence on in-plane bending fatigue resistance of the laser beam welded T-joints.
4. Initial compliance of T-joints cannot always be used quantitatively as an index to represent structural durability.
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References


WHITE PAPER ON REACTOR VESSEL INTEGRITY REQUIREMENTS FOR LEVEL A AND B CONDITIONS

This WRC Bulletin presents an overview developed by the ASME Section XI Task Group on Reactor Vessel Integrity Requirements of the methods for protection against brittle fracture of reactor vessels given in the ASME Code.

The Task Group reviewed the basis of the current Code method for brittle fracture protection as defined in ASME Section III, Appendix G, the historical background of the method, and the current regulations for material reference toughness, assumed reference flaw size, and plant operating criteria.

Based on the review, recommendations are provided for improving the requirements in the Code using present-day knowledge related to vessel integrity by considering the benefits of advanced technology in areas such as fracture mechanics and nondestructive evaluation and for determining plant operating pressure-temperature limits while maintaining the necessary requirements to assure vessel integrity.

The focus is primarily on pressurized water reactors rather than boiling water reactors, although information is provided for both.

This Bulletin is a companion to WRC Bulletin 386 which includes papers prepared by international experts on nuclear plant safety issues.

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