Control of Photonic Package Alignment With Asynchronous Laser Spot Welds

Phillip W. Fuerschbach

***Abstract*—The precise alignment of an optical fiber to a laser diode for maximum optical coupling is often accomplished with synchronous laser spot welds in three symmetric locations. To improve precision and reduce operational complexity, the utility of single-beam spot welds made in an asynchronous manner has been investigated. Independent measurements of fiber tip post weld shift have been made using eddy current sensors and CCD camera imaging analysis. For the cylindrical radially aligned Kovar ferrules examined, post weld shift has been found to be independent of both the location and number of prior spot welds. Post weld shift direction has been shown to be relatively consistent and predictable when the fiber containing ferrule is properly restrained. It has been demonstrated that through the application of an axial restraining force on radially aligned ferrules, post weld shift can be reduced to less than 2 μm. Analytical equations have been presented that predict the magnitude of the measured post weld shift and also serve to guide engineers in optimal design geometries and preferred welding conditions.**

***Index Terms*—Active alignment, electronic packaging, fiber optic, laser welding, post weld shift, spot weld, weld distortion, weld shrinkage.**

I. Introduction

LASER-WELDED photonic package advantages include readily automated assembly, low heat input, noncontact line of sight joining, no contamination from adhesives or fluxes, and virtually no heating or cooling time required. Laser welding can produce a high-toughness joint with weld strengths equal to or greater than the package case material. The laser welds can also be made hermetic by overlapping individual spotwelds until a continuous weld bead is obtained.

Many commercial fiber optic packages are welded with a laser that delivers two or three equal energy beams to the work piece synchronously through the use of separate optical fibers. By positioning identical focused laser beams at equidistant positions around the part perimeter and through synchronous pulsing of each fiber, multiple welds are made simultaneously. Since the welds are on opposite sides of the part, post weld shift is thought to be minimized. [1] Post weld shift is a positional displacement that occurs after welding due to heat input from the weld and resulting shrinkage in the fusion zone. It is believed that shrinkage strains from each weld are canceled out via the synchronous weld approach, and fiber alignment prior to welding is maintained. However, in many instances, further alignment is required, and one fiber is then used to make additional alignment spot welds to optimize coupling to the fiber. The effect of these alignment welds on fiber transmission can be used in a knowledge system to optimally select the ideal circumferential position for the next weld. This method of using the inevitable post weld shift to actively improve transmission through intelligently chosen spot welds was first described by Chaoui *et al.* [2] Newport later commercialized this approach with their patented "laser hammer" technology which is widely used in the photonics industry. [3] Active alignment using laser welding to rigidly attach diode lasers to fibers while simultaneously maximizing coupling is a very compelling approach since it completes two important assembly tasks in one step.

The employment of a single fiber welding laser for asynchronous spot welding has potential as an alternative method to reduce both the cost and complexity of these alignment systems. The capacity to increase fiber coupling through the prudent selection of subsequent realignment welds can also be enhanced by better understanding of the magnitude and shift direction that results from each weld. This investigation was prompted by the need to actively align a TO type diode laser to optical fiber. The use of a cylindrical radially aligned package has inherent design advantages for assembly with laser welding. Since the parts are held rigidly together in the axial direction, joint gap can be minimized. Since weld shrinkage for a butt weld is in a direction transverse to the joint, weld shrinkage should occur in the axial direction and have only a small effect on lateral alignment.

It is impractical to investigate package alignment factors using actual laser diodes because of diode cost and limited diagnostic information. Ferrules were attached to 125-μm fibers that enabled measurement of the post weld shift while exploring process variables including spot weld location, restraint load, and their effect on post weld shift direction and magnitude.

II. Experiments

Measurements to determine the approximate magnitude and direction of part movement after spot welding were made initially using eddy current position sensors as demonstrated successfully by Valk *et al.* [4] Two Cu–Ni–Zn alloy empty ferrules were simply butt welded together on end. One ferrule was held rigidly in a Master Grind MG-5CV-S1 rotating collet index fixture that was rotated to enable welds around the ferrule perimeter. Spindle runout with this device is specified to be less than 1.3 μm. The other ferrule was not restrained, and

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The author is with the Nuclear Weapons Complex Planning and Integration Department, Sandia National Laboratories, Albuquerque, NM 87185-0413 USA (e-mail: pwfuers@sandia.gov).

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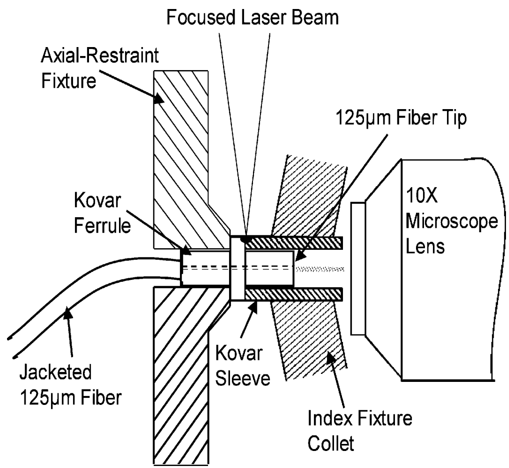

Fig. 1. Experimental setup for spot welding, restraint application, part rotation, and camera imaging of post weld shift.

movement of this ferrule was measured with two Kaman model KD2300 eddy current sensors (ECS), each located 135° from the weld and 90° apart from each other. The voltage output of the eddy current sensors was related to positional displacement by moving the ferrules with indexing micrometers and developing a least-squares fit calibration algorithm.

Laser welds for the ECS measurements were made with a 250 W Raytheon SS525 Pulsed Nd:YAG Laser without fiber beam delivery. For single-pulse welds, the control panel on the laser was set so that the shutter would allow one pulse to be released from the laser cavity while the laser was fired continuously at a high and more stable average power. For all SS525 laser welds, a 150-mm focal length lens and 3-ms pulse duration were used.

Measurements of actual fiber tip movement after welding were made with a model DFW-SX900 Sony 1392 × 1040 pixel CCD camera. The fiber tip was magnified with a 10 × microscope lens and extension tube to expose about 10% of the CCD array. Image capture was connected to a PC for subsequent image analysis. For CCD camera measurements, the fiber was coupled with a Uniphase 1-mw HeNe laser.

As shown in Fig. 1, 125-μm multimode optical fibers were attached to custom Kovar machined ferrules with epoxy and then polished to obtain a flat end. Ferrules and sleeves were obtained with sharp edges to minimize weld joint gap and maintain consistency. Kovar sleeves were prepared with a 0.125-mm internal clearance to allow the ferrule to move radially inside the sleeve during alignment. The sleeves were rigidly held with the same rotating collet fixture used for the ECS measurements. The ferrule holding collet was modified to enable close positioning of the camera imaging lens. Axial restraint on the ferrule was determined by measuring the deflection in the restraint fixture shown in Fig. 1, and computing the reactions for a simply supported beam to calculate the load.

A fiber delivered 40 W LASAG SLS 200C Pulse Nd:YAG laser was used for welding the Kovar fiber holding ferrules to mating Kovar sleeves. This Nd: YAG laser is designed for spot welding and features real time pulse energy compensation to assure consistent pulse energy output. The laser was fitted with a 400-μm fiber and a 100 mm focal length lens. The Class IV laser head was mounted on an adjustable trestle above the parts with the welding laser beam axis orthogonal to the table. The experimental setup was mounted on a vibration isolation table to reduce noise for the camera shift measurements. Welds for both the ECS and camera measurements were made in the same rotational sequence and perimetric positions which are illustrated in Fig. 8. The intent of this approach was to offset post weld shift from one side to the other.

The camera shift measurements were made using Canvas 8.0 imaging software to locate the center point of the illuminated fiber tip image. The slightly irregular circular fiber tip was traced to provide a value for the area of the fiber. The diameter of a true circle containing the same area was calculated and overlayed onto the fiber tip. The center point of that circle was used to the determine the fiber tip position and pixel location on the screen. This position locating method was used to compare the pre- and post-weld images. Knowing the fiber tip diameter to be 62.5 μm and the diameter of the overlaying circle in pixels provides a conversion factor from pixels to micrometers so that the determined shift could be represented in micrometers. Post weld shift magnitude was determined by applying the theorem of Pythagoras to the vertical and lateral components of post weld shift.

III. Results and Discussion

A. ECS Measurements

Published ECS measurements of post weld shift by Valk *et al.* [4] demonstrated the advantages of corrective asymmetric spot welds for a circular lap weld configuration. By applying synchronous laser pulses at two locations on the perimeter, 120° apart, they observed a post weld shift that was centered between the two welds and normal to the perimeter. For the weld geometry investigated here, the anticipated post weld shift direction is not obvious since the normal shrinkage transverse to the weld joint would be expected to cause only an axial shift between the two parts.

The initial ECS measurements in this study proved instructive since they quickly quantified the direction and magnitude of post weld shift for the radial butt weld geometry examined here. Results of the ECS measurements are given in Figs. 2 and 3. For the welds shown in both figures, the unrestrained ferrule is moving up towards the incident laser beam but somewhat offset from directly vertical. It will be shown later that similar post weld shift measurements with the CCD camera did not result in the same offset from vertical that is apparent in Figs. 2 and 3. It is thought that the directional error is due to either fluctuations in the zero level or a slight miscalibration of the ECS algorithm.

The magnitude of the post weld shift in Figs. 2 and 3 is typically less than 10 μm which is significant when single-mode fiber alignment is the goal. To facilitate final alignment to less than 1 μm it is clear that a reduction in shift magnitude is key. Fig. 2 also suggests a simple way to accomplish that. It is apparent that post weld shift magnitude for 2.7-J welds is greater than the shift for 2.0-J welds. This result is not unexpected since weld shrinkage is known to be proportional to weld size. [5] Since weld penetration and weld area have been shown to be

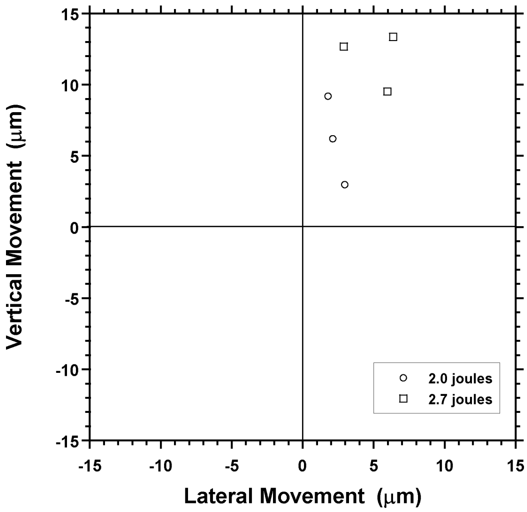

Fig. 2. Effect of laser pulse energy on ECS measured post weld shift for butt-welded alloy ferrules. No restraint applied, weld position #3.

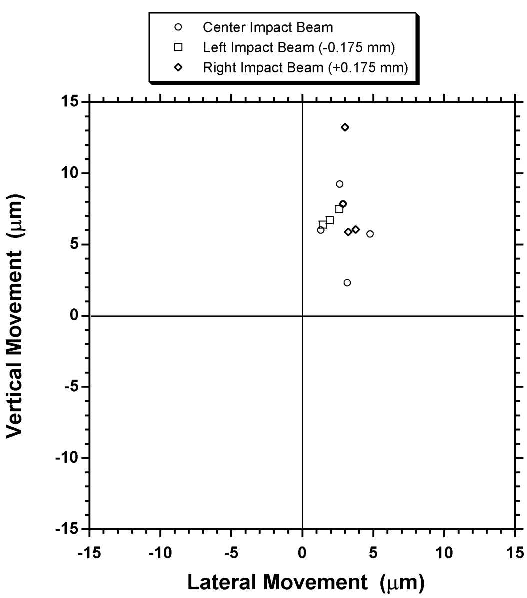

Fig. 3. Effect of beam position on ECS measured post weld shift for butt-welded alloy ferrules, No restraint applied, weld position # 2.

directly proportional to pulse energy, [6] it is reasonable to expect that by lowering pulse energy and reducing the weld dimensions, the post weld shift magnitude can also be reduced.

Fig. 3 also reveals that slight changes in the location of the laser weld on the part perimeter have no discernible effect on the direction of the post weld shift. Two of the welds in Fig. 3 were indexed 0.175 mm to each side of the apex to simulate a production application where the precise determination of the apex may be an uncontrolled variable. These results indicate that an approximate determination of the apex is sufficient to produce a consistent shift direction.

B. CCD Camera Measurements

To help verify the ECS measurement direction and magnitude results, and to develop a more direct measurement of fiber optic tip shift, CCD camera measurements were undertaken. The CCD camera measurements were made using actual fiber containing ferrules, another welding laser, and other changed setup conditions. The magnitude and direction of fiber optic tip shift as measured with the CCD camera for restrained and unrestrained ferrules is given in Figs. 4 and 5. It is apparent in Fig. 4 that tip movement is similar in magnitude but quite different in direction from the ECS measured ferrule movement shown in Figs. 2 and 3. In fact, the vertical movement is opposite in direction. It is thought that the ferrule tip is moving down while the opposite end is moving up because the ferrule is rotating slightly about an axis through the weld as shown in Fig. 6. This type of rotational movement is common in butt welds between two flat plates. The movement is related to weld shrinkage and is known as angular distortion.

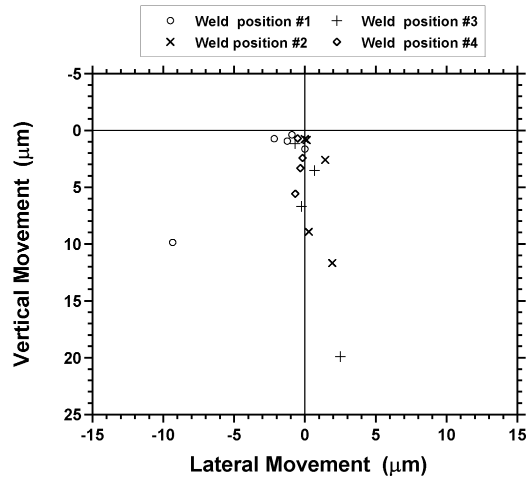

Fig. 4. Post weld shift of unrestrained Kovar ferrules as measured with CCD camera. 1.2 J, 2.0 ms. Initial fiber tip position at (0,0).

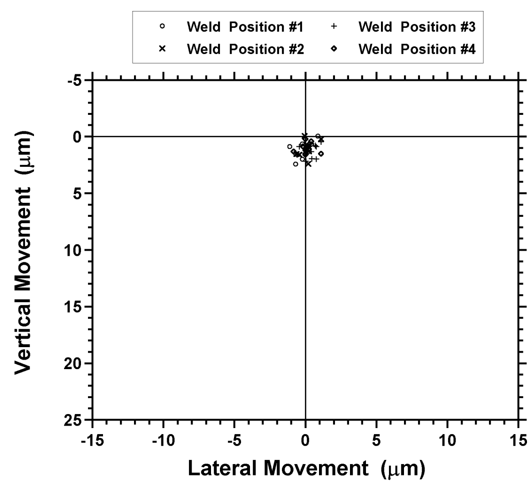

Fig. 5. Post weld shift of restrained Kovar ferrules as measured with CCD camera. 1.7 J, 2.0 ms. Initial fiber tip location at (0,0).

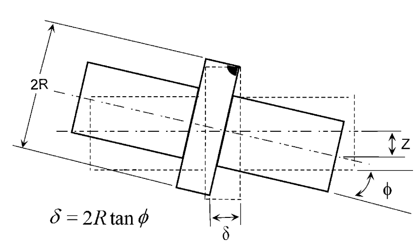

Fig. 6. Rotational movement of optical ferrule due to transverse shrinkage of weld. Movement is exaggerated for clarity.

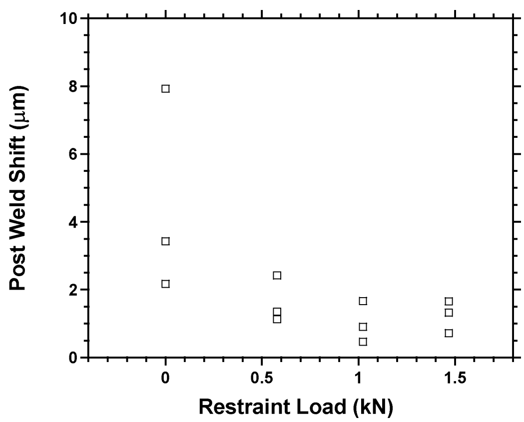

Fig. 7. Resultant post weld shift magnitude of Kovar ferrules as measured with CCD camera. Weld Position #2, 1.7 J, 2.0 ms.

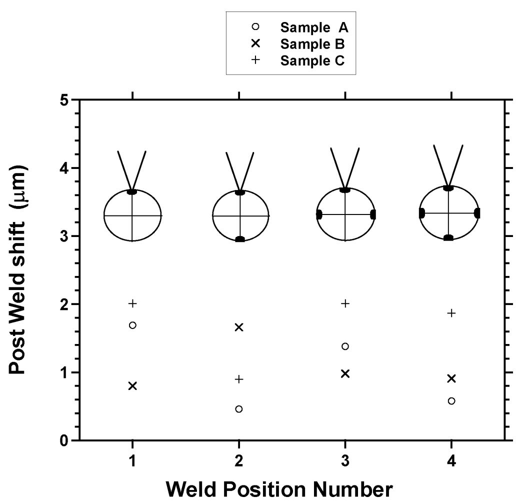

Fig. 8. Effect of weld position and location of prior spot welds on resultant post weld shift magnitude. 1.7 J, 2.0 ms, 1.0 kN load.

It is also apparent in Figs. 4 and 5 that the movement is not offset in any specific direction as was the case for the ECS measurements. One can see that the ferrule moves consistently down after each laser pulse even for the welds that are not restrained. For the welds in Fig. 5 that are restrained, it is evident that post weld shift magnitude is significantly decreased due to the load, as is the variation in magnitude. The reduction in shift magnitude is even more impressive when one considers that the welds in Fig. 4 were made with less energy (1.2 J) than those in Fig. 5 (1.7 J) and should exhibit even more weld shrinkage.

The effect of specific load levels on post weld shift can be observed in Fig. 7. As in Fig. 5, it is clear that some degree of restraint is crucial to achieve consistency in post weld shift magnitude. However, increasing the level of that restraint does not appear to decrease post weld shift since no change in magnitude can be discerned among the three loads selected. A minimum level of post weld shift appears to have been reached and increased axial restraint apparently does not eliminate that minimum shift.

The effect of weld position and the presence of prior tack welds on post weld shift can be seen in Fig. 8. For the three replicate welds shown, the magnitude of post weld shift does not appear to be affected by the number of prior tack welds or their perimetric position. Indeed, post weld shift from the first weld is virtually the same as post weld shift from the fourth weld. These results again indicate that post weld shift is consistent and can be predicted at any location even after several other welds have been made.

Since post weld shift direction is generally consistent and predictable, the method of corrective alignment through the considered use of laser pulses at a desired location is undoubtedly warranted. These results for asynchronous pulses plainly indicate that active alignment can be employed in the same manner it is employed using two or more synchronous pulses. If the post weld shift is the same for each weld, then welds that are made asynchronously and sequentially should have the same resultant post weld shift as welds that are made synchronously. Since only one spot welding beam is used with this approach, the cost and complexity of the multiple fiber and weld head systems is avoided. Precision may also be improved with asynchronous spot welds since it is easier to maintain and characterize one laser head than three.

C. Post Weld Shift Analysis

FEA models of shrinkage and distortion are valuable [7], [8] tools for these complex problems but can be difficult to implement for some photonic assemblers. A more straightforward method is desired to account quantitatively for the shrinkage distortion observed here, but in a way that is intuitive and will serve to aid in evaluation of package designs.

Several researchers [9], [10] have presented determinations of shrinkage without reference to stress that have often yielded close approximations to actual shrinkages in traditional arc welds. Since there are similarities to the weld joint design examined here, we will apply the same analysis to this problem but modify the equations to account for the spot weld geometry. We can expect that the laser spot weld region will shrink transverse to the weld joint, from the heat input to the same degree that it expands from that heat. We can roughly approximate the shrinkage by considering linear thermal expansion due to the weld heating. The transverse shrinkage is composed of shrinkage of the surrounding heat affected metal and shrinkage of the weld.

The shrinkage/expansion in the weld metal δ_{weld} can be approximated by the following expression:

$$\delta_{\text{weld}} = \alpha \Delta T\, w_p \tag{1}$$

where α is the coefficient of thermal expansion, ΔT is the change in temperature of the fusion zone, and w_p is the transverse width of the weld pool. For the Kovar weld shown in Fig. 9, $w_p = 0.5$ mm, $\Delta T = (1427 - 23\ ^\circ\text{C})$, and $\alpha = 4.9E - 6\ \text{C}^{-1}$, the weld fusion zone shrinkage is calculated to be: $\delta_{\text{weld}} = 3.4\ \mu$m.

If we assume that the weld heat is uniformly distributed over a hemispherical heat affected zone (HAZ) region adjacent to the weld, the shrinkage adjacent to the weld pool, δ_{HAZ}, is given by the following expression:

$$\delta_{\text{HAZ}} = \frac{1.5\, Q\, \alpha}{\pi\, w_{\text{HAZ}}^2 \rho\, c_p} \tag{2}$$

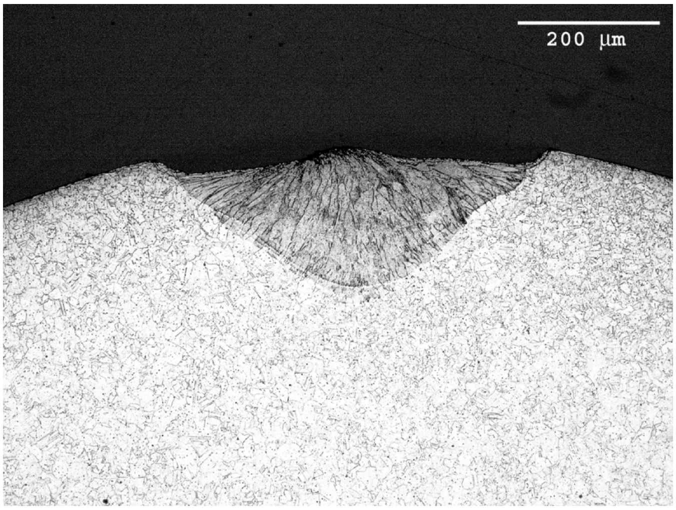

Fig. 9. Optical micrograph of typical laser spot weld between Kovar ferrule and sleeve. 1.2 J, 2 ms.

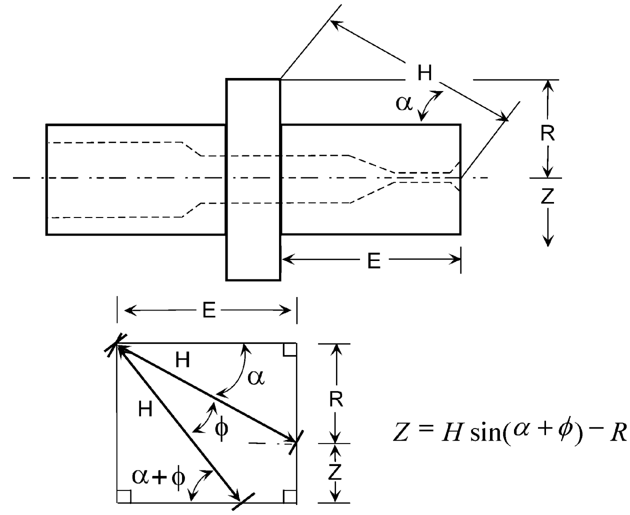

Fig. 10. Geometry of fiber tip motion due to angular rotation of ferrule about the weld.

where Q is the absorbed laser pulse energy, ρ is the density, c_p is the specific heat, and $w_{\rm HAZ}$ is the transverse width of the HAZ region.

For the weld in Fig. 9 and a 50% energy absorption, $Q = 0.6$ J. The transverse width of the HAZ region was estimated using the continuous point source solution to the conduction heat flow equation. For the 50 °C maximum temperature contour, $w_{\rm HAZ} = 1.57$ mm, with $\rho = 8.36{\rm E} - 6$ kg/mm^3, and $c_p = 648$ J/kg°C, the weld HAZ shrinkage is calculated to be $\delta_{\rm HAZ} = 0.10$ μm

Summing the fusion zone shrinkage and the HAZ shrinkage gives the total transverse shrinkage: $\delta = 3.5$ μm. Unlike conventional arc seam welds that require a much larger heat input, the transverse shrinkage for the laser spot weld is very small and primarily due to shrinkage in the weld pool rather than to shrinkage in the HAZ region.

An estimate of the angular distortion, ϕ (see Fig. 6) can be determined from the following geometric expression:

$$\delta = 2R \tan \phi \quad (3)$$

where δ is the combined weld and HAZ shrinkage, and R is the radius of the ferrule. Using the value for R for the ferrule in Fig. 10, the angular distortion is calculated to be: $\phi = 0.072°$.

Finally, for the geometric relationship illustrated in Fig. 10, the vertical motion of the tip Z can be given as

$$Z = H \sin(\phi + \alpha) - R. \quad (4)$$

As in [3], ϕ is the angular distortion, and H, R, and α are geometric constants determined by the ferrule design. Substituting the design parameters from Fig. 10 into [4], the vertical motion of the tip is calculated to be: $Z = 3.0$ μm.

For this particular ferrule design, the post weld shift is approximately equal to the transverse weld shrinkage δ. The magnitude of the calculated post weld shift compares favorably to the average post weld shift for the welds given in Fig. 4. Note that the restrained welds in Fig. 7 have a slightly smaller post weld shift than 3.0 μm, even though the weld energy is somewhat higher. We can postulate that the axial restraint load is responsible for the decrease in the post weld shift.

In general, (1)–(4) can be used to estimate the affect of changes in weld parameters and design constraints on post weld shift. For the particular design examined here, the majority of the transverse shrinkage was due to the weld fusion zone shrinkage. Therefore, it is advantageous to look to equation (1) for reduction strategies. First, one can see that a material like Kovar which has a relatively low CTE will exhibit less post weld shift than a material like stainless steel. Second, it is obvious in (1) that post weld shift is directly proportional to weld size. Since a minimum weld size will obviously be required, the more valuable advisement is that maintaining consistency from shot to shot is critical to predict post weld shift, and to achieve submicrometer active alignment.

IV. Conclusion

For the radially aligned butt-welded package investigated here, we can conclude the following.

1) Application of a restraint force on the ferrule during welding reduces both the magnitude and variance of post weld shift.
2) Post weld shift magnitude is independent of the location and number of prior tack welds.
3) Post weld shift direction is relatively consistent and predictable when welds have a minimum degree of restraint.
4) From analytical methods that are independent of stress, estimates of post weld shift have been determined that are reasonably consistent with measured values of post weld shift.
5) Based on the results in this investigation, an alignment method using asynchronous laser spotwelds appears to be a simple and practical approach to the task of active alignment with laser welding.

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Phillip W. Fuerschbach received the B.Sci. degree in mechanical engineering from the University of New Mexico, Albuquerque.

He is currently a Principal Member of the Technical Staff with the Nuclear Weapons Complex Planning and Integration Department, Sandia National Laboratories, Albuquerque, NM, where he has worked since 1978. He is best known for employing calorimetry to characterize automated arc and laser welding processes in terms of several fundamental dimensionless parameters including melting efficiency and energy transfer efficiency. He also has developed methods to characterize laser beam propagation in materials processing lasers and established the importance of focused laser spotsize in determining beam absorption and weld pool formation. He has authored over 50 technical publications in welding and has developed welding optimization and analysis software (SOAR) that is licensed to many industrial, university, and government laboratories. He currently is a member of the AWS R&D Committee and serves as a principal reviewer for the *Welding Journal*.

Mr. Fuerschbach is the recipient of the 1992 American Welding Society (AWS) William Spraragen Award, the 1997 and 1999 James F. Lincoln Gold Medals from AWS, and the 2001 Arch T. Colwell Merit Award from SAE. He is a Fellow of the American Welding Society.