Novel technique for laser lap welding of zinc coated sheet steels

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When zinc coated steels are laser welded, zinc adjacent to the weld bead is vaporized and will cause serious weld pool disruption in lap welding unless special measures are applied such as provision of a joint gap for vapor venting. A novel alternative technique has been developed to stabilize laser lap welding: this involves addition of a small amount of aluminum to the faying surface region, so that a liquid Al–Zn alloy of high boiling point is formed, thus lowering the Zn vapor pressure. Lap welds have been made with good process stability using Nd: yttrium–aluminum–garnet and direct diode lasers, and with added Al in the form of inserted foil or previously applied cold sprayed coatings. The development is described in U.S. Patent Application No. 11/226,834. Process optimization is currently under way to define optimum aluminum addition rates that will reliably suppress defects while minimizing Al uptake into the steel weld pool.

Key words: laser lap welding, Zn-coated steel, weld porosity, aluminum layer, vapor suppression

I. INTRODUCTION

Laser welding has immense potential to improve productivity in manufacturing of auto bodies and similar welded components. However, its widespread adoption is being hampered by a significant technical problem that has defied simple, economical solution. During laser welding, corrosion-resisting zinc coatings on the sheet surfaces adjacent to the weld pool will boil. Lap joints predominate in welded automotive assemblies: if zinc vapor is trapped in the faying surface region during lap welding, it will vent through the weld pool causing gross porosity or even periodically ejecting the liquid steel.

Steel's combination of strength, fabricability, and moderate cost make it a highly dominant automotive structural material. To provide enhanced corrosion resistance and product durability, most automotive sheet steels are now zinc coated, usually galvanized or galvannealed. The combination of laser welding and advanced high strength coated steels could provide huge product advancements, however realization of this potential depends on consistent management of the zinc vapor problem.

Mitigating lap welding process stability problems normally involves special fixturing or embossed parts to create a consistent small gap between the parts through which the zinc vapor can be safely discharged. Since the special measures needed to ensure consistent vapor venting are inconvenient or costly in high-volume manufacturing, an urgent need exists for a better approach to ensuring reliable, high quality welding.

As a fundamental alternative to mechanical approaches to zinc vapor management, numerous researchers have investigated chemical or physical methods of suppressing vapor discharge. This involves adding another substance to the welding environment to absorb, dissolve, or react with the zinc. Up to the present, such methods have usually proven ineffective or caused unacceptable negative side effects. However, it has recently been discovered in the authors' laboratory that addition of small amounts of aluminum in the faying surface region prior to lap welding can permit defect-free welding of tightly clamped lap joints with minimal effects on weldment metallurgy. This method of welding process stabilization appears to be both easy to apply and reliable in action, and as such it may be the critical breakthrough that allows wider adoption of laser lap welding.

II. TECHNICAL BACKGROUND

Pure zinc boils at 906 °C, while low carbon steels have a liquidus temperature around 1530 °C. Galvannealed steels in which the hot dipped coating is heat treated to form zinc–iron intermetallics display lower zinc activity but still generate high Zn vapor pressure at the steel melting point and are just as hard to lap weld as steels with unreacted zinc coatings. The thinking behind physical-chemical methods of managing Zn vapor is to reduce vapor pressure by combining the Zn with another substance. This is exemplified by one of the earlier proposed concepts, that of adding oxygen to the welding environment. Since zinc has somewhat greater affinity for oxygen than iron, if the interfacial zinc films do reliably contact and react with the added oxygen to form zinc oxide, disruptive vapor generation could be greatly reduced. The feasibility of this method has been demonstrated, both by addition of iron oxides to the faying surface region,[1] and by addition of oxygen to the inert shielding gas environment surrounding the weld.[2] However, while the approach obvi-

TABLE I. Laser system characteristics.

Laser machine	Laser type	Power (kW)	Focal length (mm)	Beam size at focus (mm)
Nuvonyx ISL-4000L	Diode	4000	80	0.5×12
Haas HL3006D	Nd:YAG	3000	200	0.6

ously works, it is not without its problems in terms of oxidation-related physical and chemical changes to the weld itself.

Alternatively, the activity and hence vapor pressure of the interfacial zinc films could be reduced by dissolving the zinc in another substance. For instance, copper has previously been suggested as an interfacial addition for this purpose.[3] While copper could reduce interfacial zinc activity by *in-situ* formation of a liquid brass alloy, its actual effectiveness should be low because its melting temperature of 1083 °C is too high, above the boiling point of zinc. Copper is also a problematic addition because it promotes solidification cracking of steel.[4]

Aluminum has a nearly unique profile of advantages as a process stabilizing additive. It has a low melting temperature to facilitate rapid interaction with liquid zinc. It has complete and uncomplicated liquid solubility for zinc plus a very high boiling temperature (2450 °C) to minimize the vapor pressure of liquid Al–Zn solutions. It is readily available, relatively nontoxic, and complementary to Zn in protection of steel from corrosion. Since the zinc vapor pressure generated by interfacial Zn–Al liquid adjacent to a steel weld pool should be nearly in proportion to the Zn/Al atomic ratio present, as little as 60 at. % of Al present in the faying surface crevice should be sufficient to raise the local boiling temperature well above the adjacent steel's melting temperature, thus preventing disruptive release of Zn vapor.

Clearly, the presence of aluminum in the path of the welding process may lead to some dissolution into the liquid steel and alloying of the completed weld. Aluminum does have recognized metallurgical effects as an alloying element in steel. Above the small amounts used for deoxidation, its best known use is as a carbide precipitation inhibitor to promote retained austenite in high strength transformation induced plasticity steels.[5] In this application, it is also known that Al in amounts at or above 1.5% by weight may prevent full austenitization leading to retention of delta ferrite.[5] Below that level, Al is considered to have minimal effect on transformation behavior or resultant properties.[6] Excessive pickup could therefore have significant and possibly negative effects on weldment properties and should be avoided. However, the small amounts of Al necessary to suppress Zn vapor evolution were considered unlikely to be problematic, and this assumption has been largely confirmed in development studies to date.

III. WELDING DEVELOPMENT STUDIES: RESULTS AND DISCUSSION

Investigation of the lap welding behavior of Zn coated steel sheets and of various proposed approaches for process stabilization was carried out by test-welding small lap joint assemblies, generally using pairs of rectangular coupons approximately 40 mm × 100 mm in size inserted in a bolted fixture capable of applying high clamping loads. When required, inefficient clamping was simulated by inserting shims between sheets. Welding was carried out using one of two lasers: a 4 kW direct diode laser or a 3 kW Nd:yttrium–aluminum–garnet (YAG). Characteristics of these systems are summarized in Table I. Welding was normally carried out with the beam focal plane at the top surface of the lap assembly and flowing argon at 14 l/min on the top surface for shielding.

A. Trials using aluminum foil

Initial testing of the hypothesis that faying surface addition of Al could stabilize the welding process was accomplished very simply by insertion of one or two thicknesses of commercial purity aluminum foil, 25 μm thick, between pairs of coated steel sheets prior to insertion in the welding fixture. The weldment geometry used is illustrated schematically in Fig. 1. The steel initially used was an advanced high strength grade, DP600, 1 mm thick with galvannealed coating on both sides with nominally 45 g/m^2 of zinc per side. Actual coating weight was verified at 42/43 g/m^2. Initial welding trials were done using the Nuvonyx diode laser operating at 4 kW beam power, and with travel speeds in the range 0.5–1.0 m/min. Figure 2 illustrates the typical surface appearance of a weld made using this material and equipment. A comparable weldment made without Al addition and displaying severe porosity is shown in Fig. 3. Surfaces of finished welds typically showed some evidence of some minor weld pool instability, but the type of gross expulsive porosity that is characteristic of such welds was virtually eliminated when Al foil was present.

Shear testing of these initial welds served to confirm the practical benefits of the Al addition in terms of increased joint strength, Fig, 4. Coupon examination after mechanical testing showed that the strength increase resulted directly from increased nugget shear area, due both to the absence of gross fusion zone porosity and a general increase in weld penetration, due to the improved thermal contact between

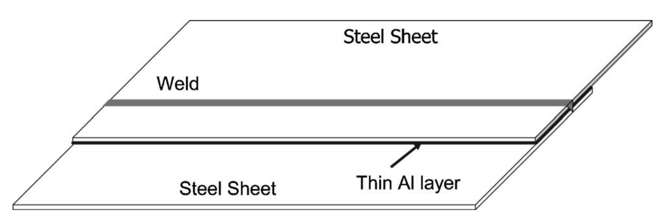

FIG. 1. Schematic diagram of weld coupon assembly for lap welding.

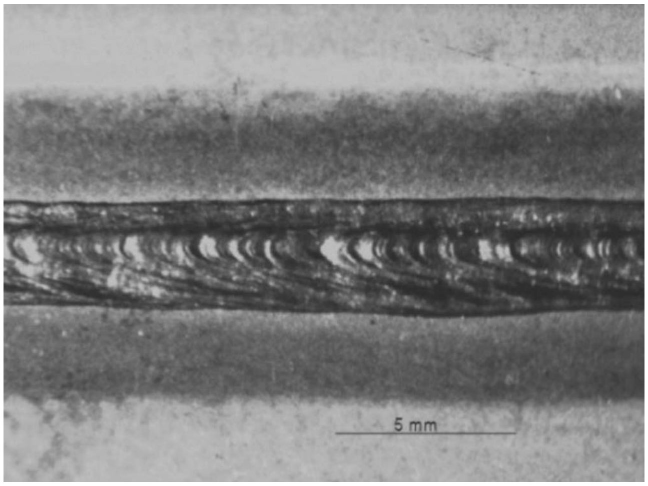

FIG. 2. Surface appearance of a lap weld on 1.0 mm galvannealed steel, made with a 4 kW diode laser, welding speed 0.7 m/min, with 25 μm Al foil inserted between tightly clamped sheets.

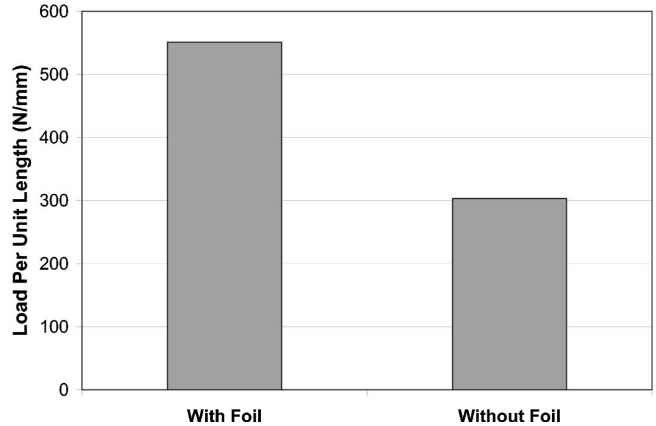

FIG. 4. Results (averages of three samples) of shear testing of diode laser lap welds made on tightly clamped 1-mm-thick DP600 galvannealed steel sheets, with and without 25 μm Al foil inserted between sheets.

lapped sheets afforded by the presence of the interfacial Al film. Typical shear test fracture faces are shown in Figs. 5 and 6.

The diode laser provides a beam energy density suitable for conduction mode welding, so an important next step in the development process was to verify the effectiveness of Al as a process stabilizer in high speed keyhole-mode welding. Trials were therefore also carried out on the same steel described above, using inserted Al foils in lap joints welded with the 3 kW Nd:YAG laser at welding speeds from 2 to 7 m/min. The typical surface appearance of such a weldment is shown in Fig. 7, and a transverse cross section of the same weld appears in Fig. 8. Again, the presence of the Al produced a dramatic improvement in welding process stability and substantial freedom from porosity defects. Examination and scanning electron microscopy–energy-dispersive x-ray analysis microanalysis of material found in the faying surface crevices adjacent to the weld bead on cross sections of both diode and YAG laser welds confirmed that a liquid Al–Zn alloy high in Al had been formed, thus verifying the correctness of basic assumptions about role and mode of action of the added aluminum. Sectional views of a typical diode laser weldment at the intersection of crevice and weld fusion zone are shown in Fig. 9. The residual high-Al solidified liquid remaining in the crevice area, adjacent to the weld bead, was typical of all lap welds made with added Al, and energy-dispersive x-ray analysis confirmed that this liquid comprised predominantly Al with dissolved Zn, Fe, and Mn.

In the early development work, the use of inserted aluminum foil reduced but in some cases did not completely eliminate welding process instability. It was theorized and has subsequently been determined that this resulted from inconsistent contact between the workpieces and foils, leading to inconsistent interaction between Al and Zn in the crevice. While the fixture developed ample force to keep sheets tightly in contact beneath the toes of the clamp bars, the material between the bars ($\sim$25 mm) could move slightly in response to thermal expansion forces. Recognizing the importance of local fitup, systematic studies were done in which the tightness of assembly of the steel/

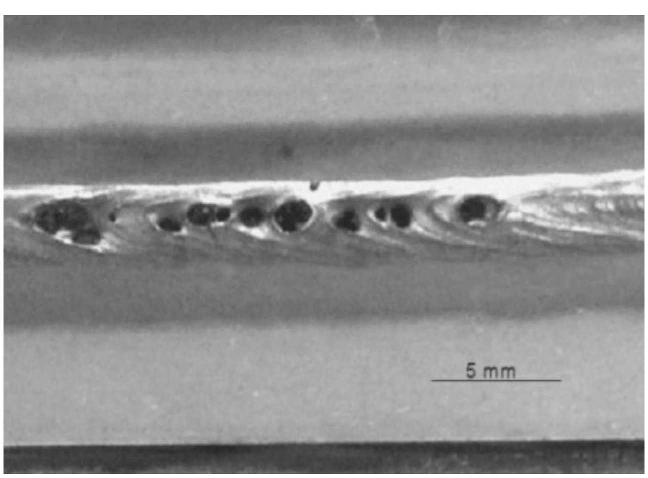

FIG. 3. Surface of a lap weld similar to that shown in Fig. 2 except without Al foil. Typical severe porosity due to zinc vapor evolution is visible.

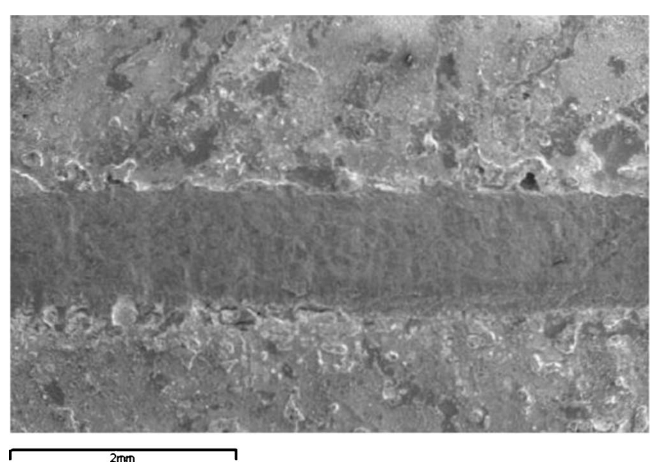

FIG. 5. Typical interfacial shear fracture appearance of diode laser lap welds made on 1-mm-thick galvanneal coated DP600 steel with Al foil clamped between sheets. Welding speed was 0.7 m/min.

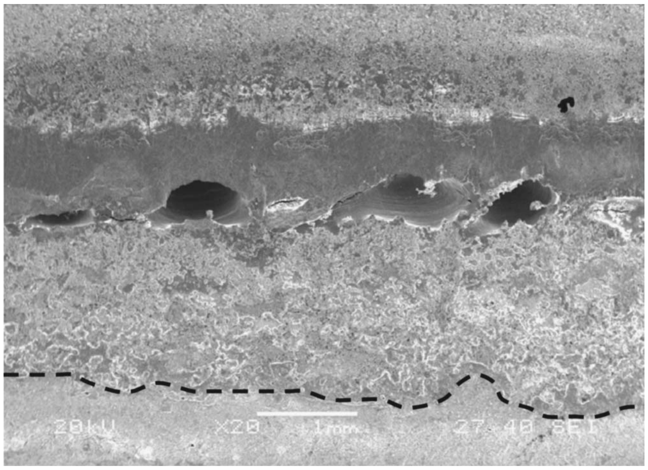

FIG. 6. Typical interfacial shear fracture appearance of weldments similar to that shown in Fig. 5, but without addition of Al to suppress Zn vapor evolution. The outlined area beside the weld has had its galvanneal coating removed by evaporation of the Zn. Welding speed 0.7 m/min.

foil/steel stack at the weld location was varied using shims. The incidence of severe porosity was clearly increased in locations where the Al was not forced tightly into contact with the steel surface. Recognizing that automotive weldments are typically much larger, more complex in shape and variable in terms of component fitup than the laboratory weldments in this work, a need was confirmed for improved ways of applying Al and ensuring consistent Al–Zn interaction. This issue was addressed as discussed below.

B. Aluminum addition by cold spray coating

The foregoing experiments suggested that further process stability improvements could be achieved if Al could be added as a coating on the galvanized steel surface prior to joint assembly. This was expected to ensure reliable and consistent Al–Zn interaction regardless of the local joint fitup. While completing the Al foil welding trials described above, the authors became aware of a novel "cold spray" process for applying surface coatings by very high velocity projection of unheated particulate materials.[7] This process appeared to be potentially very appropriate for applying small amounts of Al to galvanized surfaces, since it operates at moderate temperature thus avoiding melting or excessive oxidation of particulate or workpieces.

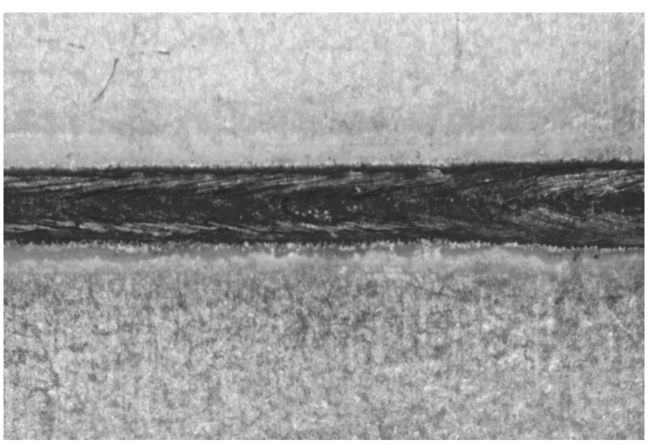

FIG. 7. Surface appearance of a lap weld made on 1.0 mm galvannealed steel using a 3 kW Nd:YAG laser, welding speed 5.0 m/min, with 50 μm Al foil inserted between the sheets.

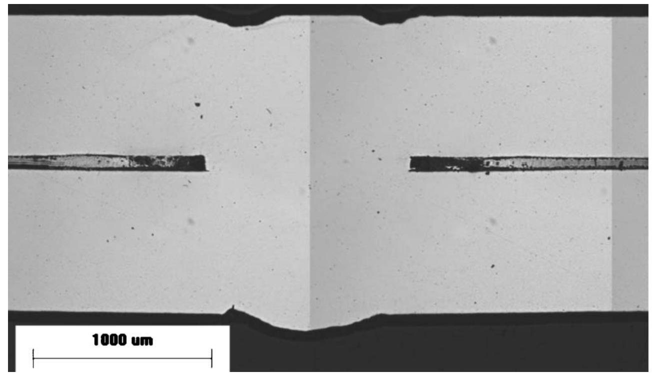

FIG. 8. Transverse cross-sectional view of the lap weld illustrated in Fig. 7, showing freedom from vapor-induced defects.

Cold spray technology is currently being developed and/or marketed by several organizations: arrangements were made with one of them to have a quantity of weld test coupons precoated with aluminum. Technical characteristics of the cold spray system used to locally overcoat Al onto the steel coupons are described in Ref. 7. To facilitate preliminary experiments, stripes of aluminum (commercial purity, gas atomized 25 μm powder) approximately 15 mm wide were applied to several galvanized and galvannealed steel grades by hand manipulation of a cold spray gun, aiming for a deposited thickness of 50–100 μm. Coated steel coupons were assembled together in pairs, clamped together and welded with the diode laser. Finished welds displayed excellent process stability and complete freedom from vapor-induced weld pool disruption or porosity. Typical surface appearance of these welds is illustrated in Figs. 10 and 11. Weld cross sections showed excellent mixing of Al and Zn liquids in the crevice, but they also showed a tendency to excessive dissolution of Al into the steel weld beads (i.e., the presence of some delta ferrite in the weld metal indicated Al pickup of about 1–1.5% by weight. Additional test welds were therefore carried out using the available set of coated coupons, reducing the quantity of Al present in the crevice by 50% by pairing coated and uncoated coupons. These welds also displayed stable process operation and freedom from Zn-induced porosity together with much lower weld bead Al pickup.

IV. CONCLUSIONS AND FUTURE PLANS

A U.S. Patent Application, serial no. 11/226,834 dated September 14, 2005, has been made for an invention comprising the use of aluminum faying surface additions in laser lap welding to suppress zinc vapor evolution during joining of zinc coated steels.

Research to date has confirmed that faying surface aluminum additions do act as claimed in the vicinity of a laser lap weld, forming an Al–Zn liquid of elevated boiling temperature in the crevice. When the Al is added in the form of an inserted foil, tight clamping is required to ensure reliable

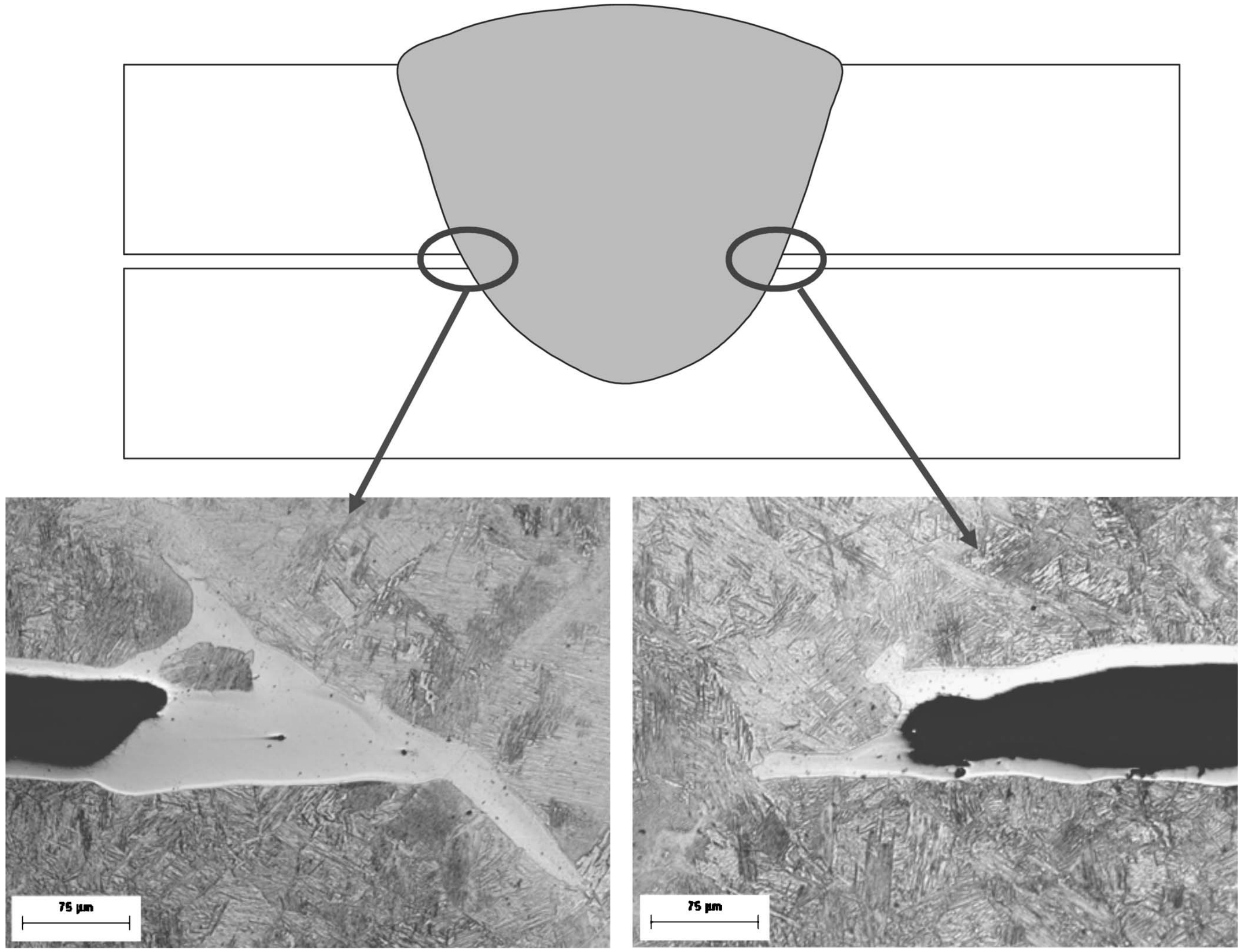

FIG. 9. High-magnification views of the crevice—weld fusion zone intersection regions of a diode laser weld made at 0.7 m/min, showing the solidified high-Al liquid films.

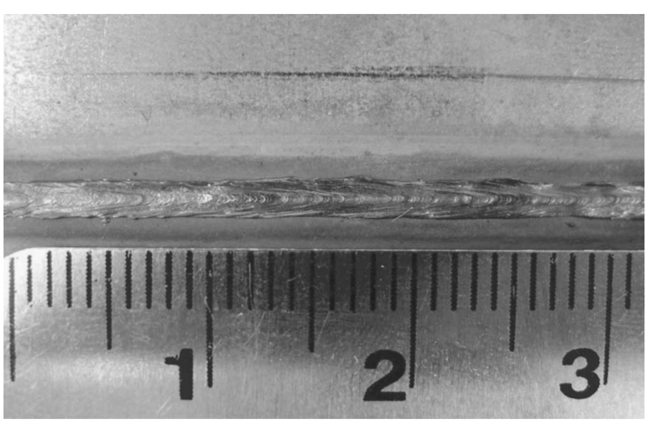

FIG. 10. Surface appearance of a diode laser lap weld on 1.0 mm galvannealed steel sheets (GA45–45g/m^2 zinc coating) precoated with 70 μm thickness of Al by cold spray before welding. Welding speed was 0.7 m/min.

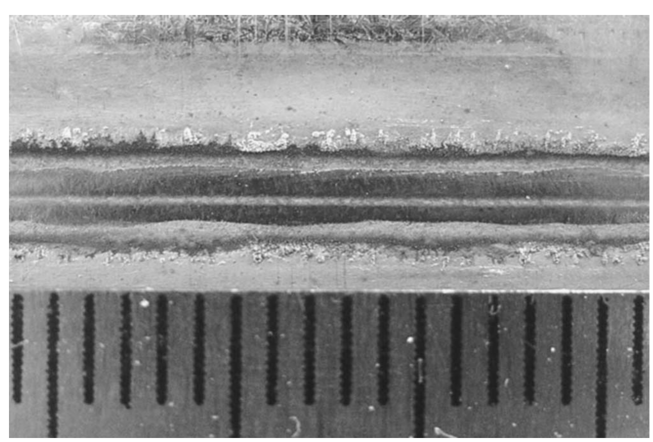

FIG. 11. Surface appearance of a diode laser lap weld on Al spray coated steel sheets, similar to Fig. 10 except 1.1 mm hot dip galvanized sheets with G170–70 g/m^2 zinc coating. Welding speed was 0.55 m/min.

interaction of Al with Zn on both faying surfaces. However, when Al is precoated on faying surfaces using a technology such as cold spray, process stability is not dependent on clamping efficiency, allowing good quality welds to be made with any type of fixturing.

An extended development program is currently under way in which the amount of aluminum in the joint crevice is systematically varied for laser welds on steels having various types and thicknesses of zinc coatings. This will permit definition of formal process tolerance windows within which risks of weld porosity and of excessive weld bead Al content are both minimized. In terms of corrosion, lap welds with an Al–Zn film in the crevice are expected to show superior service performance compared to conventional welds in which zinc has been vented away leaving no galvanic protection near the weld. The practical benefit of the increased galvanic protection will also be quantified.

Looking forward to production applications of this innovation, local spot coating of parts with Al can be readily visualized using a robot-deployed cold spray, plasma spray, or similar deposition technique. Local application of aluminum foil "bandages" to parts to be welded may also be feasible if a contact adhesive is identified that does not itself evolve problematic vapors upon heating.

ACKNOWLEDGMENT

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