The Effect of an Al Tip in Arc Stud Welding on the Properties of the Welded Joint

ABSTRACT

Arc stud welds act as shear connectors in composite steel-concrete beams, which are now widely used in the construction of buildings. The relevant standards only specify the body of the carbon steel studs. To achieve weldability, it is normal practice for the manufacturers to use aluminum inserts as the tip for the studs. However, there can be a concern on the effects of too much aluminum on the integrity of the stud weld connections, especially in the event of seismic loads. In this study, shear studs 19 mm in diameter made of AISI 1010 steel are produced with five different aluminum tips weighing from 0 to 0.64 g and are welded to steel beams. Weld penetration, soundness, and the location of shear fracture of welds in bend tests, the hardness profile, and the microstructure for the weld samples are used as the characterizing parameters. The results showed that indeed, in drawn arc stud welding, there is an optimum range for aluminum tip weight. With no or too little aluminum, due to lack of effective deoxidation, the weld would become porous and fail both in the soundness and bend tests. On the other hand, with a large aluminum tip, due to the formation of brittle phases, the weld metal hardness will increase significantly and the arc stud weld will fail in the bend test. In addition, it is shown that the aluminum content of the weld metal can be affected by arc stud welding process parameters.

KEYWORDS

• Effect of Al • Stud Welding • Welded Joint • Arc Welding • Composite Beam
• Metal Deck

Introduction

Composite metal deck concrete floors, due to speed of fabrication, lower weight, and economy, are now widely used in the construction of tall steel buildings. Arc-welded carbon steel studs play an important role in the integrity of such structures (Refs. 1–4). The studs, also called shear connectors, in the event of an earthquake, transfer the longitudinal shear force between steel and concrete and resist slipping between concrete and steel — Fig. 1. Thus, it is important that the stud welds have sufficient strength and ductility. The design of the tip of the stud can have a crucial role in the operation of arc stud welding. However, in standards, the design of the tip of the stud is left to the manufacturer, but it is required that the stud demonstrate good weldability. For small-diameter studs, it is normally sufficient just to make the tip conical. For arc-welded studs larger than 12 mm, using an aluminum tip is a normal practice — Fig. 2.

After the Northridge earthquake in 1994, causes of failures in some beam-to-column welded connections were studied by many researchers and authorities (Ref. 6). As a result, major changes were introduced in corresponding AISC and AWS standards regarding welded connections in seismically loaded steel structures. Metallurgical research has shown one of the contributing factors to brittle behavior of welded connections has been high Al content in flux cored arc welding (FCAW) consumables. High Al in FCAW has been shown to have deleterious effects on the toughness of the weld metal (Ref. 7).

There can be a genuine question about the effects aluminum has on the mechanical integrity of arc stud welds. However, to the knowledge of the authors, there is no published research on the subject. The objective of this investigation is to establish the effect of Al tip of carbon steel arc stud welds on the weldability, mechanical properties, and microstructure of the weld metal of shear connectors used in the construction of typical composite metal deck concrete floors.

Experimental Procedure

The experiments were conducted using ¾-in. (19-mm) arc studs, which is a typical size used for metal deck construction. The geometry and material of the studs were in accordance with EN ISO 13918 (Ref. 8). The chemical composition and mechanical properties of the base material, stud, and aluminum tip material are given in Table 1. Aluminum tips in spherical form were used as inserts into the holes stamped onto the flat faces of the studs. The masses of Al tip inserts ranged in five levels from 0 to 0.64 g — Fig. 3.

M. GHOLAM BARGANI and F. MALEK GHAINI (fmalek@modares.ac.ir) are with the Department of Material Science and Engineering, Tarbiat Modares University, Iran. A. MAZROI is with the Department of Civil Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran.
maximum amount was equivalent to four times the weight of an Al tip that the manufacturer of the stud used in standard production. The samples were accordingly denoted: X0, X0.5, X1 (ordinary production), X2, and X4 Al.

Figure 4 shows the schematic of the welding setup for the experiments. The equipment used for arc stud welding was model BTH PRO-D 2200. The stud welds were made with the following process parameters: lift 5.5 mm (the height that the stud is lifted from the workpiece to create the arc opening) and plunge 3.5 mm (the length that the stud is plunged).

The arc time and arc current for the first set of the tests were taken directly from the guide given by the manufacturer of the welding machine. For the 19-mm stud, it was 1650 A and 650 ms, respectively. This first series of tests was nominated PT (preliminary tests). However, visual examination of the resulting stud welds, according to EN ISO 14555, showed there was insufficient fillet weld reinforcement and most of the welds did not pass visual examination (Table 2).

The first sets of stud welds were examined for weld metal aluminum contents by optical emission spectroscopy. However, to go through the whole assessment tests, a second set of welds were made with slightly higher arc currents (1750 A) and arc times (800 ms) (Table 3). With each weld parameter, two sets of tests were made — one for macro examination and one for the bend test.
The welds were visually inspected and then the weld cross sections were prepared for chemical analysis and macro examination. Cross sections of welded studs were polished and etched by 2% Nital (2% HNO₃) for optical microscopy. Scanning electron microscope (SEM) with energy-dispersive spectrometer (EDS) were used to investigate the weld microstructure of the specimens. The Vickers microhardness test with a 50-g load was performed on the representative weld metals, and the results were reported (average of five points). The bend test was performed by a hydraulic bend test machine, as shown in Fig. 5. Also, SEM was used to investigate the fracture surfaces after the bend test.

**Results and Discussion**

As shown in Table 3, all samples of the second set of stud welds, made with higher arc current and arc time, passed the visual inspection, i.e., there was an acceptable fillet around the joint with no sign of excessive undercut or spatter. However, examination of macro sections showed the stud welds made with no Al tip had many porosities (in a crushed form) — Fig. 6. On the other hand, the samples from 0.5 to 4 times the ordinary level were internally free from gas porosity.

Formation of gas porosity in the arc stud without an Al tip is believed to be due to gas metal reactions involving carbon in the liquid steel with the oxygen from the air or other sources such as iron oxides. The carbon monoxide/dioxide gas bubbles can form in the liquid weld pool and become trapped during solidification when the weld pool is sluggish, and finally the gas pores are crushed at the time of plunge. This form of crushed weld porosity can be considered unique to arc stud welding process — Fig. 6A.

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**Fig. 5** — Bend testing of stud welds. A — The bend test machine; B — schematic of the bend test procedure.

**Fig. 6** — Macro sections of arc stud welds with no Al tip and with the normal amount. A — Sample X0Al (no Al tip); B — sample X1Al (0.16 g Al).

**Fig. 7** — Schematic of the reaction in the weld pool.

**Fig. 8** — Aluminum content of the weld metals of the stud welds with various amounts of Al tip for weld metal by high and low current and time welding.
Figure 7 shows a schematic of the reactions in the weld pool. However, by addition of aluminum, which is a strong deoxidizer, the oxygen forms aluminum oxide as in slag or inclusions. Thus, at the time of solidification, the weld pool is deprived of much of its dissolved oxygen. In this regard, the chemical activity of oxygen in the weld pool is reduced to a level that carbon can no longer react with to form carbon monoxide gas bubbles.

Figure 8 shows the results of chemical analysis for the Al content of weld metals of arc studs with various Al tip masses. By cross checking with results of macro examinations in Table 3, it can be seen that aluminum at 0.1 wt-% has been sufficient to deoxidize the weld metal to the extent needed to prevent formation of gas porosity.

Figure 8 also shows the aluminum content of weld metals of stud welds made with the lower levels of arc current and arc times (preliminary tests) is 30% higher. This is due to the fact that at higher arc current and times, more masses of the stud body and base metal are melted, causing the actual concentration of Al in weld metal to decrease. In addition, the figure shows the relative recovery of Al increases as its concentration passes the 0.2 wt-% level. This can be due to the fact that the entrapped volume of oxygen and oxides in the stud weld cavity is limited, and once that oxygen reacts with the Al to form slag, the rest of the Al becomes free to be recovered in the weld metal.

The bend test was performed on the stud welds in accordance with the EN ISO 14555 standard (Ref. 9), which requires that after a number of 30-deg reversal bending (as shown in Fig. 5), the connection breaks outside of the weld zone. As can be seen from Table 3, the samples with no Al tip and those with twice and four times the ordinary level failed the bend test, i.e., they broke through the weld metal.

Figure 9 shows the appearance of some of the welded connections after the bend test. It was clear that the stud welds made with no Al tip had failed in the weld zone due to the high volume of trapped porosities, which weakened the weld — Fig. 9A and B. The region marked B and C in Fig. 9A shows fracture in the weld metal is associated with gas porosity. The SEM of the fractured faces of the samples that passed the bend test (i.e., X0.5 and X1 Al), showed they had a ductile appearance — Fig. 9C and D. Dimples and microvoid regions as marked by A and Á in Fig. 9A, C shows the appearance of ductile fracture. The region marked D in Fig. 9E shows cleavage fracture. However, fractured faces of those samples that failed the bend test due to }

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**Table 2 — The First Set of Arc Stud Weld Tests (PT)**

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight of Al Tip (g)</th>
<th>I (A)</th>
<th>T (ms)</th>
<th>Result of Visual Test</th>
<th>WM Al (wt-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0 Al</td>
<td>0</td>
<td>1650</td>
<td>650</td>
<td>Not sufficient fillet</td>
<td>0.02</td>
</tr>
<tr>
<td>X1/2Al</td>
<td>0.08</td>
<td>1650</td>
<td>650</td>
<td>Not sufficient fillet</td>
<td>0.08</td>
</tr>
<tr>
<td>X1 Al</td>
<td>0.16</td>
<td>1650</td>
<td>650</td>
<td>Acceptable</td>
<td>0.33</td>
</tr>
<tr>
<td>X2 Al</td>
<td>0.32</td>
<td>1650</td>
<td>650</td>
<td>Not sufficient fillet</td>
<td>0.71</td>
</tr>
<tr>
<td>X4 Al</td>
<td>0.64</td>
<td>1650</td>
<td>650</td>
<td>Not sufficient fillet</td>
<td>1.01</td>
</tr>
</tbody>
</table>
high Al (i.e., X2 Al and X4 Al) showed more signs of a cleavage mode of fracture — Fig. 9E and F. The region marked D in Fig. 9E shows cleavage fracture. The evidence suggests it is wise to keep the aluminum content of the arc stud weld metal below an approximate figure of 0.5 wt-%. This would also give a safeguard against improper setting of arc stud weld parameters, which may lead to an accidental increase of Al content of the weld metal.

The microstructures of weld metals of specimens with different levels of Al were studied by optical microscopy and SEM — Fig. 10. Widmanstätten ferrite (WF), acicular ferrite (AF), polygonal ferrite (PF), and grain boundary ferrite (GF) were identified in the microstructure of welds with up to 0.4 wt-% Al (X0, X0.5, and X1 Al studs) — Fig. 10A–C.

However, at 0.95 wt-% Al (X2 Al stud), some δ-ferrite (more than 50% according to MIP 4 software) were identifiable — Fig. 9D. At 1.35 wt-% Al (X4 aluminum levels), the microstructure was completely different and δ-ferrite and coarse grain ferrite were the main phases present — Fig. 10E.

In SEM studies, using energy-dispersive spectroscopy (EDS), it was attempted to identify the inclusions in the weld metals at various levels of aluminum content. It was found that the inclusions in the weld metals made with studs that had an aluminum tip were rich in Al (Fig. 10B–D), whereas the inclusions in the weld metal made with the stud that had no aluminum tip was rich in Fe (Fig. 10A). Conventional EDS cannot identify oxygen or nitrogen (as they are light elements), so these inclusions can be either nitrides or oxides or combinations of the two. However, based on the appearance of the inclusions and considering other studies, they should be mainly aluminum and iron oxides of Al2O3 and Fe2O3 types, respectively (Ref. 10).

The above change in the weld metal microstructure can be supported qualitatively by referring to the phase diagrams shown in Fig. 11A and B. Figure

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight of Al tip (g)</th>
<th>I (A)</th>
<th>T (s)</th>
<th>Result of Visual Inspection</th>
<th>WM Al (wt-%)</th>
<th>Hardness (HV)</th>
<th>Bend test</th>
<th>Fracture Appearance</th>
<th>Macro Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0 Al</td>
<td>0</td>
<td>1750</td>
<td>800</td>
<td>Acceptable</td>
<td>0.03</td>
<td>520</td>
<td>Failed</td>
<td>Ductile</td>
<td>Failed</td>
</tr>
<tr>
<td>X1/2Al</td>
<td>0.08</td>
<td>1750</td>
<td>800</td>
<td>Acceptable</td>
<td>0.13</td>
<td>415</td>
<td>Accept</td>
<td>Ductile</td>
<td>Accept</td>
</tr>
<tr>
<td>X1Al</td>
<td>0.16</td>
<td>1750</td>
<td>800</td>
<td>Acceptable</td>
<td>0.40</td>
<td>410</td>
<td>Accept</td>
<td>Ductile</td>
<td>Accept</td>
</tr>
<tr>
<td>X2 Al</td>
<td>0.32</td>
<td>1750</td>
<td>800</td>
<td>Acceptable</td>
<td>0.95</td>
<td>430</td>
<td>Failed</td>
<td>Brittle</td>
<td>Accept</td>
</tr>
<tr>
<td>X4 Al</td>
<td>0.64</td>
<td>1750</td>
<td>800</td>
<td>Acceptable</td>
<td>1.33</td>
<td>800</td>
<td>Failed</td>
<td>Brittle</td>
<td>Accept</td>
</tr>
</tbody>
</table>
11A shows the iron-rich part of the binary Fe-Al phase diagram. Figure 11B, which has been calculated by Thermo-Calc and used previously to explain the effect of the aluminum addition in a FCAW consumable, also takes into account the effect of the presence of carbon in the weld metal (Refs. 7, 11).

The phase diagrams indicate that at low Al levels, δ-ferrite is the first phase to form in solidification. Transformation of δ-ferrite to austenite occurs in cooling and finally transforms to α-ferrite at temperatures lower than 900°C. However, at aluminum contents higher than 1%, only partial transformation of δ-ferrite to austenite can occur, so instead of α-ferrite, one would find δ-ferrite in the weld metal microstructure.

Finally, the result of hardness tests on the weld metal as a function of aluminum content is shown in Fig. 12. It can be seen that even at 0.95 wt-% Al, the hardness is still in the 400 HV window, but at 1.33 wt-% Al, it jumps to 800 HV. The high hardness at 1.35 wt-% Al is attributed to the formation of WF in the coarse grain δ-ferrite (Refs. 7, 12), as indicated in Fig. 10E.

It is interesting to note the drop in hardness in cooling and finally transforms to α-ferrite at temperatures lower than 900°C. However, at aluminum contents higher than 1%, only partial transformation of δ-ferrite to austenite can occur, so instead of α-ferrite, one would find δ-ferrite in the weld metal microstructure.

Conclusion

The effect of Al tips in arc stud welding, which function as shear connectors in the fabrication of composite metal deck concrete floors, is significant. If no Al tip is used, due to reactions of oxygen with carbon, the resulting weld becomes porous to the extent that the connection does not pass the required bend test.

Aluminum at concentrations as low as 0.13 wt-% were found to act as an effective deoxidizer and prevent gas porosity in the weld zone. However, at 0.95 wt-% Al concentrations, due to the formation of δ-ferrite, the stud weld connection does not pass the bend test. But it is at 1.35 wt-% Al that the hardness of the weld metal increases from the 400 to the 800 HV window. The aluminum content of the weld metal is not only a function of the Al tip weight, but also the arc stud welding parameters. A 19-mm carbon steel stud with an aluminum tip weighing 0.16 g would result in an arc stud weld metal with around 0.40 wt-% Al concentration, which would satisfactorily pass the mechanical tests.

This study shows that it is not adequate to rely only on visual inspection of arc stud welds. It is crucial (as required by most steel structural work standards such as AWS D1.1, Structural Welding Code — Steel) to conduct the start of shift bend testing along with visual inspection.

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References