Welding consumables for galvanizing kettles

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The galvanizing kettle, used to contain the molten zinc, is an essential item in the operation of a galvanizing company. Since premature failure of a kettle causes major financial disruption of business, conservative specification of welding consumables has been observed in vessel fabrication, in order to ensure acceptable performance. Very little information has been published on welding of galvanizing kettles.

As the low silicon welding consumables traditionally used in Australia for vessel fabrication constitute a relatively small market, some manufacturers have withdrawn or limited their availability to end-users prepared to purchase them in batch lots. It was therefore decided to investigate potential alternative welding consumables and processes. After reviewing the literature on the chemical reactivity between molten zinc and different types of steel, a number of representative welding consumables were selected and trialed.

Accelerated laboratory immersion tests confirmed the adverse effect of high Si content on the rate of liquid Zn corrosion of weldments in steel plate used to fabricate galvanizing kettles. These tests and on-going trials in commercial zinc baths indicate that low silicon FCAW and MMAW electrodes are available which show acceptable resistance to Zn attack, and will therefore provide satisfactory alternatives to the traditional MMAW consumables.

Keywords

Welding, galvanizing, kettles, consumables, liquid metal corrosion

Introduction

The galvanizing kettle is a key component in the batch galvanizing process. Premature failure of a kettle causes major financial disruption of business and conservative specification of welding consumables has been traditional in vessel fabrication, in order to ensure acceptable performance. Very little information has been published on welding of galvanizing kettles.

Kettles are typically constructed from 50mm thick steel plates and welding represents the major variable cost. Watson and Furphy[1] have discussed the method of construction and operational requirements of galvanizing kettles. Vessels usually range from 2 m to 13 m in length and weigh from 2 to 50 tonne. A typical vessel shape is shown in Figure 1. The largest known kettle is 25m long, 3.15m wide and 3.76m deep.

The low silicon welding consumables traditionally used in Australia for vessel fabrication constitute a relatively small market and recently some manufacturers have either withdrawn their consumables from the market or restricted their availability to end-users prepared to purchase them in batch lots. In addition to finding a solution to this problem, kettle fabricators need to increase efficiency by using more productive welding processes and consumables. Therefore, it was decided to investigate different candidate welding consumables and processes. After reviewing the literature on the chemical reactivity of between molten zinc and different types of steel, a number of representative welding consumables were selected. They were initially compared by the welders for their weldability and the rate of production. Welded samples were then placed in different types of galvanizing baths to assess their resistance to corrosion by molten zinc.

Background

Premature failure of kettles

Kettles have a finite life due to corrosion of the steel by zinc attack. This varies depending on the throughput, for example a kettle for a continuous galvanizer would be expected to last for 6 months before requiring repairs or replacement. For a high throughput general galvanizer, a kettle would be expected to last 3-5 years. For a small batch plant a kettle would be expected to last over 10 years.

There are very few documented cases of kettle failure in the literature. Due to the high costs incurred if a kettle is out of service, problems are often fixed before an investigation can be carried out. In addition, operators are reluctant to discuss the failure of a kettle which has resulted from bad operating practices. Tunney, Konecny, Balliett and Cigan[2] discussed the

Figure 1. Typical shape of a galvanizing kettle.

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failure of over 6 kettles in America. They concluded that some of the kettles had been over-heated. The primary failure was due to over-stressing the plate by having a thinner base plate than that used in the wall. In addition no props were provided to support the walls, resulting in the base plate fracturing at the centre of the long side.

A study[3] of other failures in Australasia and South East Asia is summarised in Table 1.

Operational criteria

Zinc melts at 420°C and the corrosion of the tank accelerates at about 480°C. Therefore the bath has a relatively narrow operating range of say 440°C to 460°C with a target of 450°C. This requires a good furnace design linked with good control mechanisms. The key temperature for the life of the kettle is the temperature at the steel-zinc interface. Trained operators are needed who understand the consequences of operating outside the 440-460°C range.

A good furnace design provides a bath of uniform temperature with no significant hot spots. The adoption of diagonally opposed burners provides a relatively uniform temperature in the furnace and therefore the bath. Single burner furnaces, typical in older installations, have been shown to have a higher potential for the development of hot spots.

Heavy dross along the wall of the kettle forms an insulating layer and therefore the temperature at the steel zinc interface can enter the dangerous zone. Therefore it is important to regularly check the bath for dross and remove it when required. A rapid increase in the amount of dross is a good indicator of increased corrosion of the kettle.

Zinc – iron metallurgy

When steel comes into contact with liquid zinc, zinc atoms begin immediately to diffuse into the steel, iron atoms diffuse outwards and a series of solid alloy layers begins to form[4]. Some uncertainty still remains about the zinc-rich end of the binary phase equilibrium diagram[5,6], but there is general agreement that the three intermetallic compounds: Γ (Fe_3Zn_{10}, 20-27wt% Fe); δ ($FeZn_{10}$, 7-11wt% Fe); and ζ ($FeZn_{13}$, 5.7-6.3 wt% Fe) form with increasing zinc concentration[7]. During the service life of a galvanizing vessel a Zn gradient exists between the molten zinc and the steel substrate. Therefore, equilibrium is not attained and the Fe-Zn phase equilibrium diagram only offers guidance as to the sequence of phases likely to be present at the bath temperature as a function of Zn composition. At a typical bath temperature of 460°C, the sequence of phases extending towards the steel is liquid Zn (with minor concentrations of Fe, and possibly Pb and Al), ζ, δ, Γ and α -ferrite (containing Zn in solid solution).

The rate of liquid zinc attack of an un-alloyed steel in the range of 440 to 490°C is parabolic with time, determined by the rate of solid state diffusion of zinc and iron atoms through the alloy layers[4]. The Γ layer is a strong barrier to diffusion of the zinc and iron atoms and therefore diffusion through this phase is generally considered to be rate-controlling[8]. The mass loss m (in grams of iron per cm^2) is given by the equation $m = at^{1/2}$, where t is exposure time (min) and a is a temperature dependent rate constant with units of $g.cm^{-2}.min^{-1/2}$. Iron mass loss as a function of temperature is shown in Figure 2.

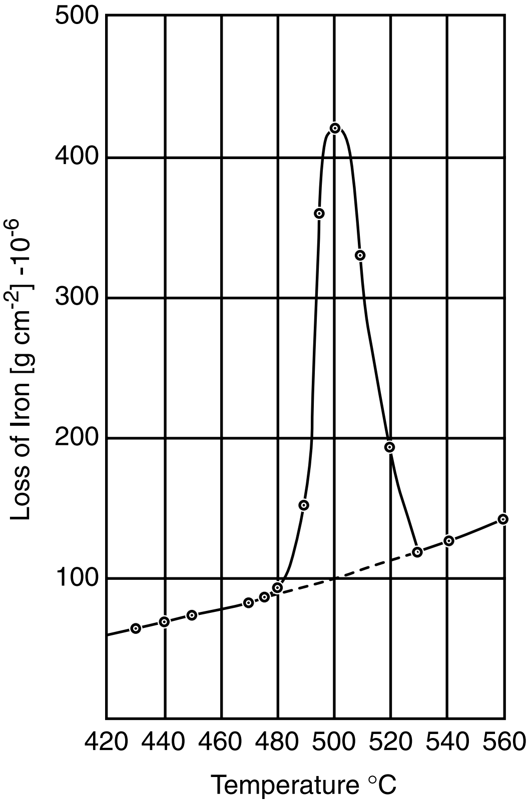

Figure 2. Iron loss versus bath temperature for an immersion time of 1 hour (Reference 9).

Departure from linearity in the range of about 480-530°C is due to a change from parabolic to linear corrosion kinetics. In this range $m = bt$ where b is a rate constant with units of $g.cm^{-2}.min^{-1}$. This dramatic change in the rate of attack is believed to originate as follows. For bath temperatures above about 495°C the morphology of the ζ phase changes, forming as large irregular idiomorphic crystals rather than in the more compact form characteristic of lower temperatures. As a result, the liquid zinc can more easily penetrate to the underlying δ layer, which starts to show cracking possibly due to intergranular penetration of Zn along the columnar

Table 1. A summary of kettle failures and causes.

Kettle No	Failure	Cause
1	Worm holes in steel plate at steel / lead interface level	Hot spots due to heating system and poor temperature control
2&3	Holes in steel plate at dross level	Hot spots due to dross being allowed to form on walls
4	Fracture at heat affected zone of weld at kettle base	Overheating of kettle and overstressing of the steel resulting from no propping
5	Fracture through heat affected zone and weld at wall to floor (at end of kettles life)	Inadequate weld size
6	Worm holes through kettle	Over heating of kettle
7	Weld locally eaten out	Weld repaired using incorrect consumable

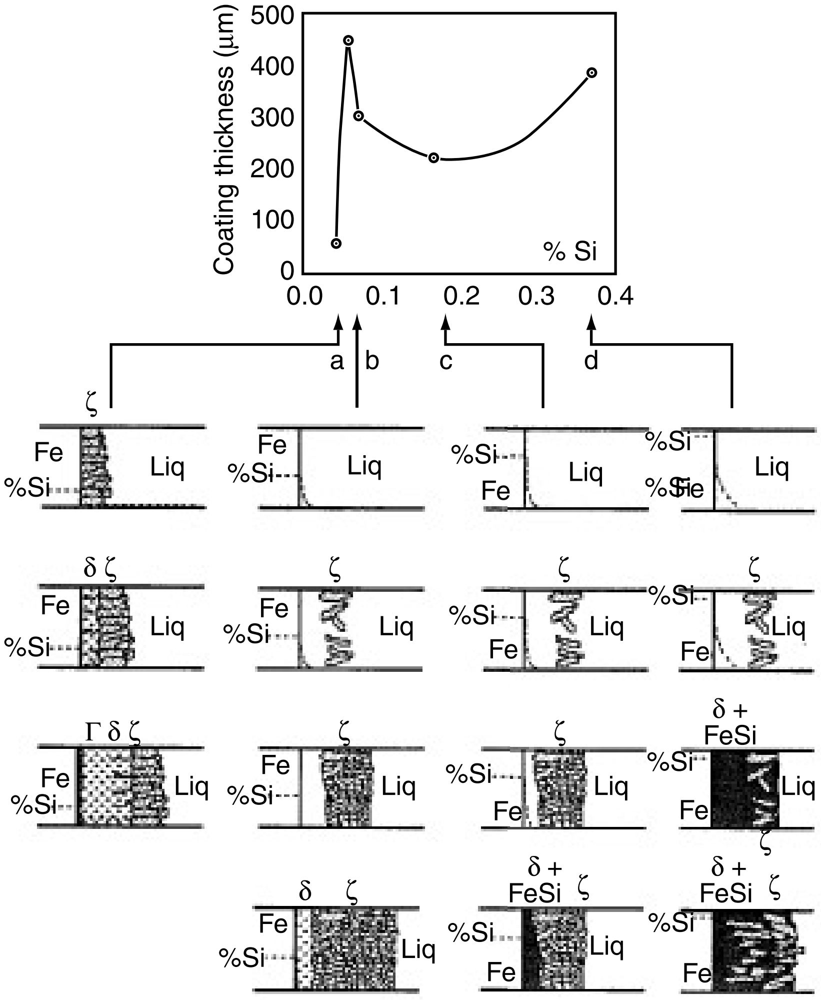

Figure 3. The Sandelin effect between 0.05 and 0.11 wt% silicon and the changes in the form of the alloy layer with increasing Si concentration (Reference 11).

grain boundaries. This allows direct contact of liquid zinc with either Γ phase or the steel itself^{10}, producing more rapid attack on the steel. Above 530°C, a thin, closed δ layer re-forms, restricting access of liquid Zn and the rate of corrosion again becomes controlled by solid state diffusion. Although the kinetics follow a parabolic law, corrosion proceeds faster because of faster atomic diffusion at the higher temperatures. This effect is reflected in Figure 2 by the increase in the iron loss rate.

Alloying elements in the steel can strongly influence the rate of zinc corrosion. Carbon, phosphorus and especially silicon can widen the temperature range of rapid linear attack. Silicon bearing steels are characterised by the development of thick alloy layers, particularly over the range 0.05-0.11 wt% Si (the Sandelin range) in which ζ phase formation dominates^{11}. Figure 3 illustrates the variation in alloy layer thickness with Si content, showing the peak in the Sandelin range, and rapid thickening as Si increases above 0.3 %. In the latter case, a thick mixed layer of δ and FeSi underlie the ζ layer. Silicon contents in the base steel and the weld metal of 0.05% maximum are therefore preferred to prevent rapid corrosion of the vessel steel. As welding consumables with such low silicon contents are both difficult to obtain commercially, and are typically considered by welders as not being user friendly, it is more common to find typical weld metal compositions for welding consumables designed for galvanising applications with weld metal silicon in the range 0.11 to 0.25.

The control consumable MMAW-1 is typical of this with a nominal composition of 0.13% Si. Galvanising baths manufactured using this consumable have been known to perform well for many decades and it has therefore been the consumable of choice for specifiers and fabricators alike. Some of the alternative consumables under consideration for this application also exploit this range and theoretically should also be suited for the end use.

Test methodology

Testing program

From concept, the planned test programme was split into two phases. Phase I was to be a laboratory based rapid assessment type programme and Phase II to be confirmatory trials conducted in commercial galvanizing baths.

Phase I was conducted at the University of Wollongong, and involved tests on 10mm thick slices of double-vee welds of 40mm thick A1006 steel plate. The samples were submerged for 24 hours in molten zinc in a small stainless steel crucible heated to either 485°C or 500°C. These temperatures were chosen because 485°C is at the typical lower range of the commencement of rapid attack by molten zinc on steel and

500°C is the temperature generally accepted to be that at which the reaction rate is maximised and promotes rapid dissolution of parent steel. The onset of rapid attack is known to vary with silicon content but for lower silicon steels (and weld metals) it is reported in the literature to vary between 480 and 490°C [9]. These accelerated tests were therefore based on raising the temperature of the molten zinc above the normal industrial operating range (440 - 460˚C).

Phase II is currently being conducted in a number of commercial galvanizing plants including a spinning kettle type plant, a structural steel jobbing galvanising kettle and a high productivity continuous wire galvanising kettle. 40 mm thick samples are being exposed for one month, three months and twelve months for each consumable type with the rate and type of attack to be assessed.

Selection of welding consumables

Prior to commencement of the research program, an international search had been conducted on the availability of low silicon consumables deemed suitable for use in the manufacture of galvanizing kettles. At the time of formulation of the research proposal, availability of potential consumables was confirmed with the various consumable manufacturers. Additionally, a search for published support information was conducted in the open literature but none was found.

The consumables were firstly grouped into their process types and were then split into various sub groups. The processes considered were MMAW, FCAW, GMAW and SAW.

Potential suitable MMAW consumables were readily available from at least three sources. In addition to a control MMAW consumable (MMAW-1) which has been extensively used for kettle fabrication, an off-the-shelf substitute was selected and included in the trial (MMAW-2). Its classification (AWS E6020[1]) was identical to that of the control consumable. A number of cellulosic consumables (AWS E6010) were also noted to be potentially suitable for use in this application but were not included in the trial.

FCAW consumables were divided into three groups: self-shielded, gas shielded; very low silicon, gas shielded; and low silicon types. At least five self-shielded FCAW consumables (AWS E70T-7 and E70T-4 types) were considered to be suitable for trial, some of which were known to have been used successfully in South Africa and Australia in commercial baths. All had nominally low silicon contents and high aluminium contents (normal for this type of consumable). However, a number also had high carbon contents of ≈0.3% which gave rise to concern by the authors at the potential risk of delayed weld metal cracking. In 1985, Jago and Lau[12] also expressed concern about the use of self shielded consumables in this application due to the possible formation of embrittling grain boundary deposits of aluminium nitride at the service temperatures likely in galvanizing kettles. Nevertheless, given the successful use of these consumables, as well as anecdotal evidence that kettle failures were rarely attributed to failure at or near the weld, it was decided to include a locally available self-shielded E70T-7 electrode in the trial (FCAW-1).

In the very low silicon gas shielded FCAW consumable category, one imported AWS E71-T1 consumable was located that was being promoted in Australia at the time as being especially designed for galvanising baths. It was selected for trial due to its nominal chemistry being very close to that of the parent plate and to provide the opportunity to assess its handling characteristics and relative productivity (FCAW-2).

The final FCAW type considered was a gas shielded FCAW wire (AWS E70T-G type) with a nominal composition reported to be similar to the control MMAW consumable. Whilst not currently readily available in Australia, it is known that it is used in South Africa for the manufacture of galvanizing kettles. Given the claim of good running characteristics and its usage elsewhere, this consumable was of strong interest to the fabricator for trial (FCAW-3).

The final type of electrode for assessment was a conventional continuous wire consumable used for welding mild steels. Both solid GMAW wires and gas shielded FCAW wires were considered, and a common ER70-S6 GMAW wire was selected for use due to the fact that the fabricator had sufficient stock available for the trial.

The nominal silicon content of each of the welding consumables selected for the trial is shown in Table 2. Data were generally sourced from the manufacturer's data sheets and are provided as a guide to the typical all-weld metal composition that can be expected when used within the manufacturer's qualification limits.

In the latter stages of the formulation of this project, the authors were notified of the availability of a potentially suitable SAW wire and flux combination meeting the low silicon requirements of the end use but were unable to include it in the assessment program due to insufficient flux being available in Australia at the time.

Table 2. Nominal silicon contents of base steel and welding consumables (wt%)

	Steel	FCAW-1	FCAW-2	FCAW-3	MMAW-1	MMAW-2	GMAW
Nominal Si	0.010	0.09	0.013	0.13	0.13	0.08	0.53

Table 3. Welder comments on performance of welding consumables

Welding Consumable	Welder Rating (out of 10)	Amount of visible fume	Relative Rate of Production	Comments
FCAW-1	8	Very high	1.5	easy to use
FCAW-2	3	Medium	1.0	hard to use
FCAW-3	8	Medium	1.3	easy to use can be used with high amps low splatter
MMAW-1	8	Medium	1.0	good in all positions
MMAW-2	4	Medium	1.0	fluid requires a lot of clean up
GMAW	9	Low	1.3	easy to use

Results

Weldability

During the preparation of the test plates, the welders were asked to rank each of the consumables and to comment on deposition characteristics (see Table 3). The rate of production has been based on welding of a one metre long test plate. Semi-automatic welding processes were used for the preparation of the samples FCAW-1, FCAW-2, FCAW-3 and GMAW. Longer term tests are planned with fully automatic processes with higher heat inputs to increase rates of production. Table 3 confirms that the welders prefer a consumable that runs well and gives a low level of defects with little spatter.

The all-weld metal composition of the welding consumables under test plus the base steel plate is shown in Table 4. The analysis of the steel is consistent with grade A1006 typical of that used in Australia for galvanising kettle manufacture. The measured silicon contents are also consistent with the manufacturer's data sheets (Table 2) for all consumables. Since the base steel Si content is very low, the diluted weld metals are likely to have lower Si levels than those listed in Table 4.

Macrographs (see Figure 4) were prepared and assessed for all test plates. The examination showed some minor porosity was present in all FCAW and GMAW samples with more extensive porosity being evident in MMAW-1 (control sample) and MMAW-2.

Immersion tests

The laboratory test results[13] were somewhat variable, probably due to the small size of the laboratory melt pot used and variable amounts of iron dissolution in the molten zinc. However, based on the measured loss in weld metal thickness (originally 10 mm) at 500˚C and visual examination, the consumables were ranked from lowest to highest loss as follows:

1. MMAW-1, MMAW-2 (0.2 mm loss) and FCAW-2 (1.3 mm loss)
2. FCAW-1 (qualitative ranking)
3. FCAW-3 (1.7 mm loss)
4. GMAW (6.9 mm loss)

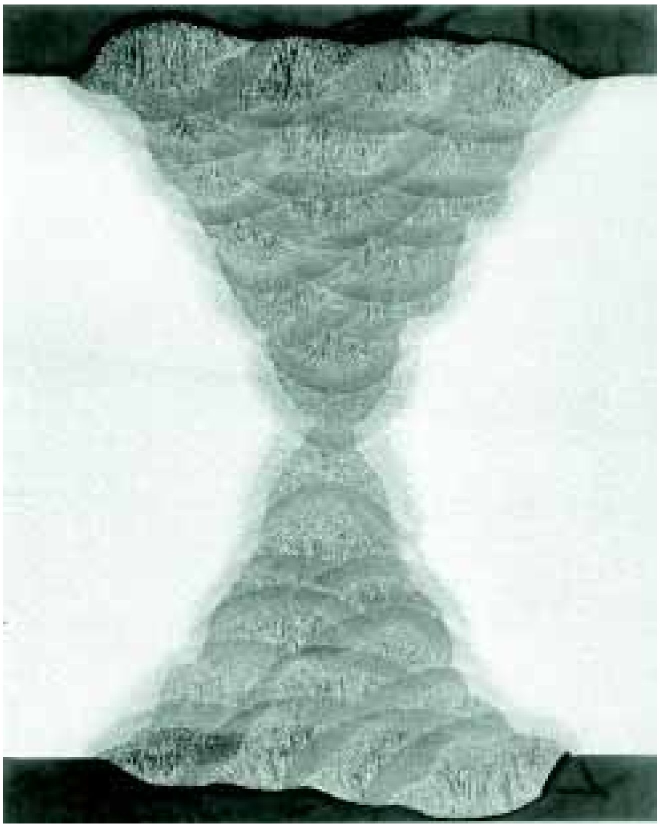

Figure 4. Typical macrostructure of double vee welded 40 mm thick plate

The rankings overall are consistent with the effect of increasing Si content, with the lowest Si consumables performing better under the test conditions. MMAW-2 performed in a similar manner to the control consumable MMAW-1. Consumable FCAW-2 had a composition similar to the base steel and behaved in a similar way.

Table 4. Chemical compositions of base steel and welding consumables (wt%)

	Steel	FCAW-1	FCAW-2	FCAW-3	MMAW-1	MMAW-2	GMAW
C	0.055	0.30	0.040	0.021	0.12	0.075	0.065
P	0.010	0.011	0.009	0.004	0.017	0.014	0.013
Mn	0.22	0.28	0.57	1.45	0.19	0.70	1.26
Si	0.005	0.07	0.03	0.17	0.085	0.04	0.73
S	0.011	0.004	0.009	0.005	0.012	0.013	0.007
Ni	0.016	0.016	0.011	0.009	0.016	0.013	0.013
Cr	0.014	0.033	0.015	0.029	0.014	0.025	0.014
Mo	<0.002	0.007	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	0.016	0.024	0.013	0.016	0.009	0.007	0.13
Al	0.027	1.6	0.006	0.01	<0.003	<0.003	<0.003
Sn	0.003	<0.002	<0.002	0.006	<0.002	0.004	<0.002
Nb	<0.001	<0.001	0.004	0.011	<0.001	0.002	<0.001
Ti	<0.003	<0.003	0.022	0.029	0.004	0.009	<0.003
V	<0.003	<0.003	0.012	0.022	0.004	0.016	<0.003
B_{tot}	<0.0003	0.0006	0.0009	<0.0003	<0.0003	<0.0003	<0.0003
Ca	<0.0005	0.0015	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005

Notes: 1. MMAW - 1 consumable is control sample
2. All analyses conducted using Atomic Emission Spectroscopy

Figure 5. Liquid zinc attack on GMAW weld

The GMAW consumable had a very high silicon content of 0.73% and dissolved rapidly at 500°C, losing approximately 69% of the weld metal thickness in 24 hours of exposure. In contrast, the FCAW consumables typically showed a weld metal thickness loss of less than 17% at this temperature for the same time. The two low Si MMAW electrodes also showed good resistance to liquid metal corrosion. The detailed results of this work are reported elsewhere[13].

Given that the tests were conducted in the temperature range corresponding to rapid "linear" corrosion kinetics, they also serve as a useful guide as to the estimated time that a kettle will survive a local hot-spot which typically occurs either when dross builds up and is not removed or when non-uniform heating takes place in the kettle.

Since these tests were conducted in the "linear attack range" rather than the much slower "parabolic attack range", typical of normal galvanizing at 450 - 460°C, it is clearly important to extrapolate these results to commercial kettles in a realistic manner. Accordingly a series of 40mm thick weldments are currently being exposed for up to one year in various types of production kettles.

At the time of preparation, samples had been received for visual examination after one and three months exposure to molten zinc held at ≈460°C in a kettle with a throughput of approximately 3000-4000t/month.

After one month exposure, the weld metal on all GMAW welded test pieces had all but dissolved and all specimens were removed from the trial at this point. Figure 5 is typical of what remained of the test piece. Needless to say, these preliminary results confirm that conventional higher silicon type welding consumables are not suitable for use in the manufacture or repair of galvanising kettles since they are likely to fail rapidly after a short exposure time even without hot spots being considered.

Visually, all other samples had little (if any) noticeable weld metal iron loss after one and three month exposure (Figure 6). More accurate determinations will be made as part of the assessment programme in the coming months.

It is expected that after one year of molten zinc exposure in the high throughput kettle, a reasonable guide will be available to the industry to advise on the suitability of alternative consumables to the control MMAW consumable which is now proving difficult to source. Given the conservatism within the galvanizing industry (due to the high consequential costs if the wrong consumable is used), this is important as it will give the kettle end users some confidence to specify alternatives for their kettle manufacture without exposing any of the stake holders to perceived high risk choices. It should also provide some guidance to researchers as to where future research can be undertaken so as to give the kettle end users confidence in the final recommendations.

Figure 6. Sample typical of FCAW and MMAW welds after 1 month exposure to liquid zinc

Conclusions

Accelerated laboratory immersion tests have confirmed the adverse effect of high Si content on the rate of liquid Zn corrosion of weldments in steel plate used to fabricate galvanizing kettles. These tests and on-going trials in commercial zinc baths indicate that low silicon FCAW and MMAW electrodes are available which show acceptable resistance to Zn attack, and will therefore provide satisfactory alternatives to the traditional MMAW consumables. The welding characteristics of these alternative consumables will also be important in the selection of suitable consumables for the weld fabrication of galvanizing vessels.

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