Welding consumables for galvanizing kettles – assessment of long term exposure test coupons

K. B. Watson and B. G. Cannon

The selection of suitable welding consumables for the construction and repair of galvanizing kettles is an essential component in achieving a long and reliable kettle life. A test program was undertaken to investigate the performance of different welding consumables using short term laboratory exposures and also actual commercial production trials for up to 12 months. Based on these results, it is recommended that consumables with a silicon content up to 0.2% would generate welds capable of achieving satisfactory service. Conventional high silicon consumables (>0.3%) should never be used in the repair or manufacture of kettles.

Keywords

Welding, galvanizing, kettles, consumables

Introduction

The selection of welding consumables for galvanizing kettles has been made on their past performance. Whilst this has generally produced a satisfactory solution, it has not allowed advantage to be taken of newer, more productive advances in welding technology. The lack of a performance specification for welding consumables has made it very difficult to introduce better products. The design, specification and manufacture of galvanizing kettles is described elsewhere by Watson and Furphy[1].

Therefore, it was decided to investigate different candidate 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 was selected. They were initially compared by the welders for their weldability. Welded samples were then placed in different types of galvanizing baths to assess their resistance to corrosion by molten zinc. Watson et al[2] reported on the initial selection of welding consumables, laboratory testing and initial testing in production kettles. Welded samples which were immersed in a high throughput continuous galvanizing kettle and a general galvanizing kettle for 12 months have been examined. Based on this work, recommendations are made for welding consumables that will give a satisfactory performance matching those traditionally achieved.

Background

Zinc – iron metallurgy

When steel comes into contact with liquid zinc, a chemical reaction begins immediately between the two and a series of solid alloy layers begins to form[3], as summarized by Watson et al[2] and Bosman[4]. Briefly, two critical items dominate the rate of reaction and thus the life of the kettle:

- the operating temperature; and
- the silicon level.

Influence of temperature on rate of reaction

The rate of liquid zinc attack of an un-alloyed steel in the range of 440° to 480°C is parabolic with time. Iron mass loss as a function of temperature is shown in Figure 1. Departure from linearity in the range of about 480°-530°C is due to a change from parabolic to linear reaction kinetics. Above 530°C, the kinetics again follow a parabolic law, but reaction proceeds faster because of faster atomic diffusion at the higher temperatures. This effect is reflected in Figure 1 by the increase in the iron loss rate.

Role of silicon

Alloying elements in the steel can strongly influence the rate of zinc attack. Carbon, phosphorus and especially silicon can

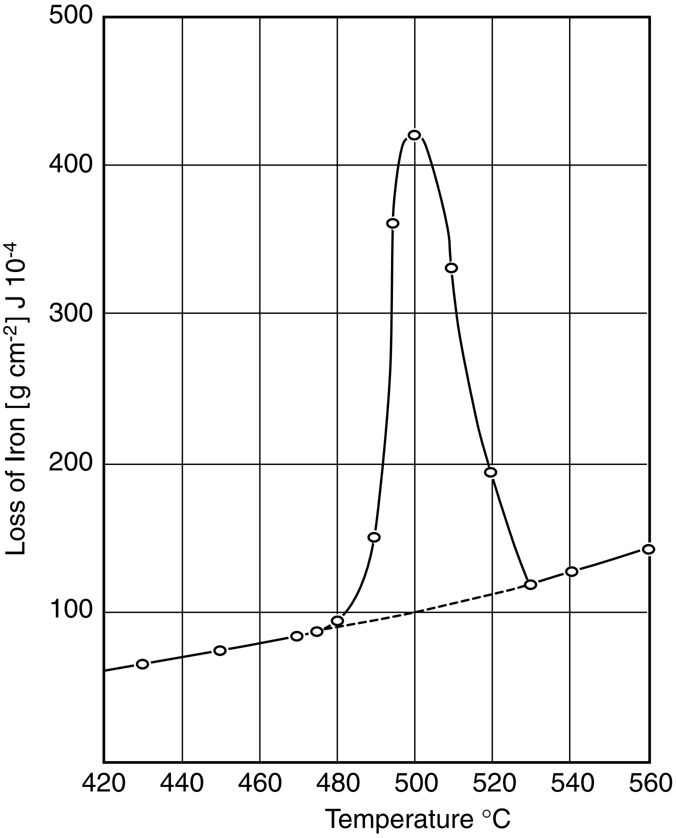

Figure 1. Iron loss versus bath temperature for an immersion time of 1 hour [5].

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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)[6]. Figure 2 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 %. Silicon contents in the base steel and the weld metal of 0.05% maximum are therefore traditionally preferred to prevent rapid corrosion of the kettle 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 silicon in the range 0.11 to 0.25%.

The control consumable MMAW-1 adopted in the test program is typical of that used in Australia and has a nominal composition of 0.13% Si. Galvanizing kettles 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 have similar silicon content and theoretically should also be suited for the end use.

Test methodology

Test Program

From concept, the planned test program was split into two phases. Phase I was a laboratory based rapid assessment program and with Phase II consisting of 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[7].

Phase II has been conducted in two commercial galvanizing plants. Samples were exposed to molten zinc for one month, three months and twelve months for each consumable type and then the rate and type of attack were assessed. Samples

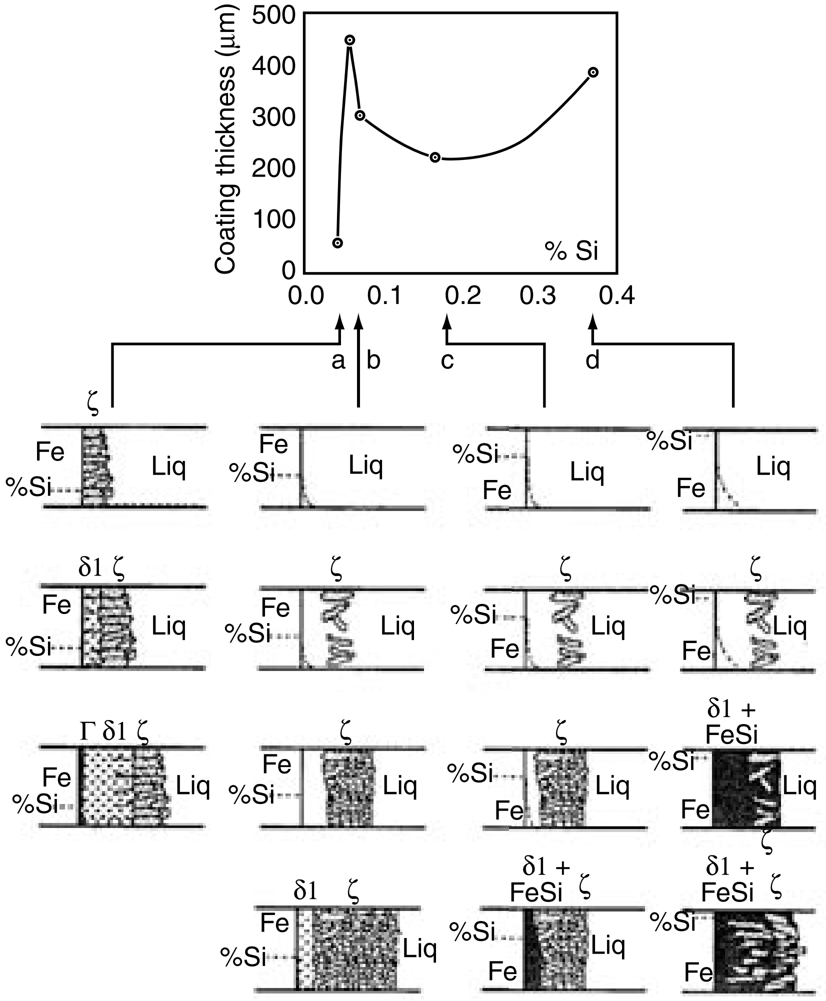

Figure 2. The Sandelin effect between 0.05 and 0.11 wt% silicon and the changes in the form of the alloy layer with increasing Si concentration[6].

exposed for one year were recently removed from a high productivity continuous wire galvanising kettle and a general galvanizing kettle. The results of these exposures are reported in this paper.

Selection of welding consumables

The consumable selection process which is described in detail in Watson et al[2], consisted of a number of steps. These were:

1. Consumables were grouped into their process types, then split into various sub-groups. The welding processes considered were Manual Metal Arc (MMAW), Flux Cored Arc (FCAW) and Gas Metal Arc (GMAW).
2. Two MMAW consumables were selected for testing, the primary control consumable (MMAW-1) which has been extensively used for kettle fabrication throughout Australia, and an off-the-shelf substitute (MMAW-2) with an identical classification (AWS E6020*).
3. FCAW consumables were divided into three groups - self-shielded, gas shielded - very low silicon and gas shielded - low silicon types. Those selected were a locally available self-shielded E70T-7 electrode (FCAW-1), an imported very low silicon AWS E71-T1 consumable (FCAW-2), and a gas shielded FCAW wire classified as an AWS E70T-G type (FCAW-3) with a nominal composition reported to be similar to the MMAW control consumable.
4. The final type of electrode for assessment was a conventional GMAW solid wire consumable used for welding conventional carbon and carbon-manganese steels (ER70-S6).

Flux cored consumables were of particular interest because of their potential to give significant productivity improvements during kettle manufacture. Additionally some of these were known to have been used successfully in South Africa and Australia in commercial kettle manufacture. All had nominally low silicon contents with the self-shielded variants also having a high aluminium content (normal for this type of consumable).

In the self-shielded category, a number of consumables had relatively high carbon contents (about 0.3%) which could potentially increase the risk of delayed weld metal cracking. In 1985, Jago and Lau[8] also expressed concern about the use of self-shielded consumables for this application due to the possible formation of embrittling grain boundary deposits of aluminium nitride at the service temperatures likely to be found in galvanizing kettles. Nevertheless, given the apparent success of these consumables[9], as well as anecdotal and other evidence[2] that kettle failures were rarely attributed to failure at or near the weld, it was decided to include a locally available higher carbon self-shielded consumable in the trial (FCAW-1).

The nominal silicon content of each of the welding consumables selected for the trial is shown in Table 1. Manufacturer's data sheets were used as a guide to the typical all-weld metal composition that can be expected when used within the manufacturer's qualification limits.

Table 1. 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 2. Chemical compositions of base steel and weld metals (wt%)

Element	Steel	FCAW-1	FCAW-2	FCAW-3	MMAW-1	MMAW-2	GMAW
C	0.050	0.29	0.055	0.020	0.115	0.070	0.065
P	0.010	0.016	0.011	0.004	0.017	0.013	0.013
Mn	0.22	0.29	0.81	1.66	0.28	0.77	1.26
Si	0.005	0.065	0.045	0.20	0.16	0.040	0.73
S	0.010	0.0035	0.008	0.005	0.012	0.009	0.007
Ni	0.016	0.019	0.016	0.009	0.015	0.018	0.013
Cr	0.014	0.033	0.024	0.029	0.017	0.027	0.014
Mo	<0.002	0.007	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	0.016	0.027	0.012	0.017	0.010	0.011	0.13
Al	0.027	1.6	0.004	0.012	<0.003	<0.003	<0.003
Sn	0.003	<0.002	<0.002	0.007	<0.002	0.005	<0.002
Nb	<0.001	<0.001	0.007	0.011	<0.001	0.003	<0.001
Ti	<0.003	<0.003	0.031	0.030	0.003	0.011	<0.003
V	<0.003	<0.003	0.014	0.019	0.005	0.017	<0.003
Btot	<0.0003	0.0005	0.0016	<0.0003	<0.0003	<0.0003	<0.0003
Ca	<0.0005	0.0009	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005

Note: Actual analysis of individual weld runs may vary from that shown due to weld procedure variations including dilution and location factors.

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* AWS consumable classifications are used in this paper on account of their general usage internationally and the fact that some of the consumables under test have not been classified under the Australian system.

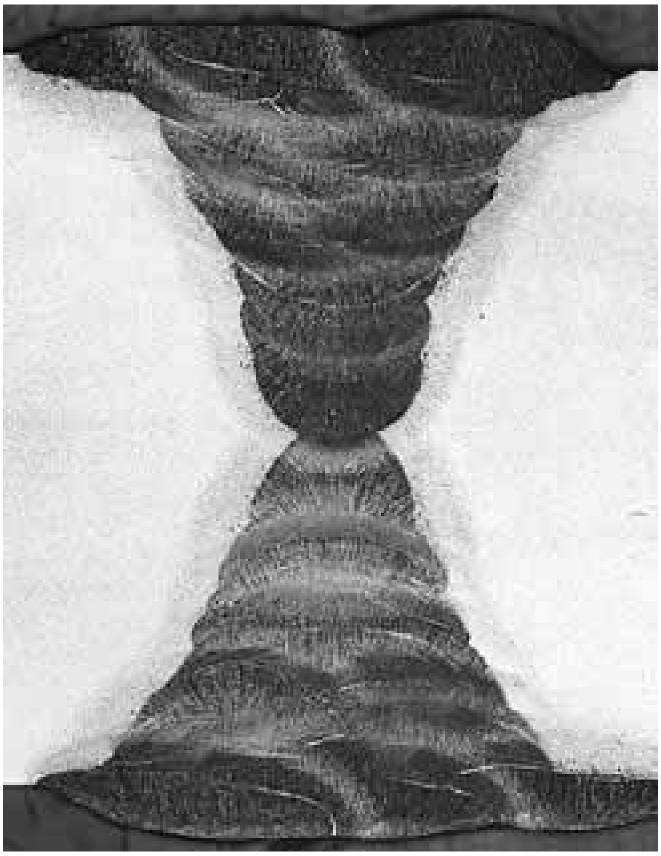

Figure 3. Macrograph of FCAW-1, 40mm plate thickness[10].

Results

Weldability

The deposited weld metal compositions and the base steel composition are shown in Table 2. The weld metal analyses (other than GMAW) are a direct analysis of weld beads within each test piece. Previous reported analyses[2,4] (including GMAW) were determined from all-weld metal samples taken from especially prepared weld pads and, as a consequence, variation is expected due to weld procedure variations.

The analysis of the steel is consistent with grade A1006 typical of that used in Australia for galvanizing kettle manufacture. The measured weld metal silicon contents are also consistent with the manufacturer's data sheets (Table 1) for all consumables.

Macro tests were taken 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.

FCAW-1 also showed white arching bands throughout all weld layers (see Figure 3). These bands were subsequently identified through electron probe micro-analysis[11] as being aluminium rich (>7% Al) ferrite layers originating from segregation effects occurring during the high temperature solidification of the weld metal (Figure 4). The likely cause of the segregation can be attributed to one of the following factors alone or in combination.

- Severity of mixing (i.e. turbulence in the weld pool).
- Original aluminium particle size.
- Cooling rate of the weld metal.

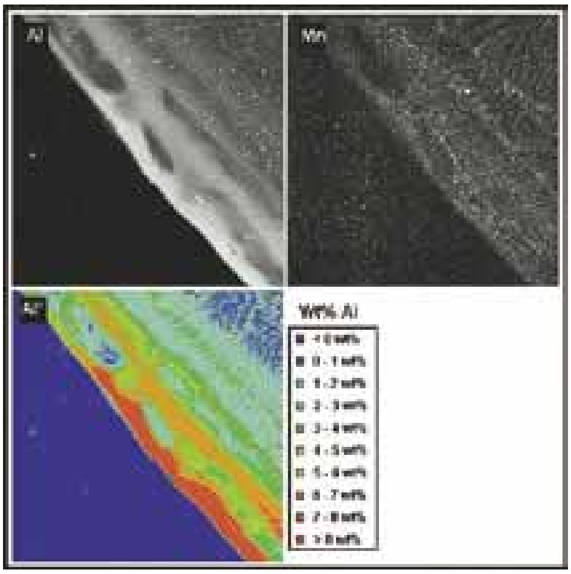

Figure 4. Electron probe micro-analysis image of a 512µm square region showing white aluminium-rich bands in FCAW-1[11].

Laboratory tests

The laboratory test results[4] were somewhat variable probably due to the small size of the laboratory melt pot used and the likelihood of iron saturation in the zinc solution (similar variations were encountered by Jago and Lau[8] who noted reaction rate instabilities for the first 21 hours of their tests).

However, based on weld metal loss at 500°C the consumables were ranked from lowest to highest loss as follows:

1. MMAW-1, MMAW-2 and FCAW-2
2. FCAW-1
3. FCAW-3
4. GMAW

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 also behaved in a similar way.

The GMAW consumable had a very high silicon content of 0.73% and the weld metal dissolved rapidly at 500°C, losing approximately 69% of the weld thickness in 24 hours of exposure. In contrast, the FCAW consumables typically showed a thickness loss of up to 17% at this temperature for the same time. The detailed results of this work are reported elsewhere[2, 4].

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 important to extrapolate these results to commercial kettles in a realistic manner.

Production kettle samples

Three samples per consumable from each 40mm thick weldment were placed in a high production continuous kettle and a general galvanizing kettle for varying periods. The continuous galvanizing kettle had a nominal operating temperature of 460°C and a throughput of 2500-3000 tonne per month, whilst the general galvanizing kettle had a nominal operating temperature of 450°C with a production of 200-300 tonne per month. The first set of samples was removed from

Figure 5. Liquid zinc attack on GMAW weld after 1 month.

Figure 6. Typical sample after 3 months exposure to liquid zinc.

Figure 7. Typical sample after 12 months exposure to liquid zinc.

Figure 8. Profile view of the long term test pieces from the continuous kettle, showing wasting.

the test bath after one month, the second set after three months and the remnant test set after one year.

As reported by Watson et al[2], after one month exposure in both kettles, 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 results confirm that conventional higher silicon type welding consumables are not suitable for use in the manufacture or repair of galvanizing 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 loss after one and three month exposure (Figure 6).

Long term continuous kettle samples

The welds in each sample were located at a uniform depth just below the liquid zinc surface of the continuous galvanizing kettle in a highly active melt region and subjected to an operational temperature of 460°C ± 10°C. Upon removing the test samples, kettle maintenance personnel[12] reported that the thickness loss experienced in the samples was also typical of that normally seen in the subsurface region of the bath. Over 30,000 tonnes of steel had been galvanized in the bath in the 12 months that the samples had been immersed in the molten zinc.

Once the one-year samples were removed from the bath, the zinc was removed from the samples, the samples measured then assessed for metal loss (Table 3). All samples showed some thinning in the weld region i.e. wasting, with the remnant weld reinforcement still sitting proud of the adjacent parent plate (Figure 7).

The variation in attack rate on the parent plate portion of each sample suggests that localised zinc turbulence and thus reaction rate instability was present. Comparing plate

Table 3. Metal thickness loss after 12 month exposure of test pieces – high production kettle.

Section	MMAW-1	MMAW-2	FCAW-1	FCAW-2	FCAW-3
Weld	7.6	8.4	8.9	8.2	7.1
Base plate near weld	7.4	8.2	8.0	7.9	7.2
Base plate deep in kettle	5.7	5.4	5.6	5.7	5.6
Weld Si (wt%)	0.16	0.040	0.065	0.045	0.20

Notes:
1. All loss units are in mm/year
2. Location of the test weld in the bath was set just below the liquid zinc surface where the rate of reaction was expected to be highest.

thickness loss in the region around each weld with that deeper in the bath showed a much slower rate of attack in the depths of the kettle where there is much less turbulence and greater process stability.

Whilst many of the weld samples emerged a little narrower at the weld compared with the balance of the parent plate, the weld did not seem to suffer any greater degree of attack than the parent plate. All welds continued to sit proud of adjacent parent material with no visible preferential attack at the weld toes. However, there did seem to be some minor preferential attack near the weld.

These results are comparable with those of Bosman[4] in his laboratory assessments other than his ranking for FCAW-3. Re-examination of those results would suggest that reaction instability was experienced, as reported by Jago and Lau[8] due to the short duration of the tests.

Excluding the GMAW sample, FCAW-1 (self-shielded) showed the highest rate of attack. Another interesting result was the industry standard, MMAW-1, was not the best performer. Table 3 shows that the performance of all samples was similar and the differences in weld metal loss are relatively small when compared to the rate of liquid zinc attack on the base A1006 test plate.

Long term general galvanizing kettle samples

Similar to the continuous galvanizing kettle, the welds in each sample were located at a uniform depth just below the liquid zinc surface of the general galvanizing kettle in the known active melt region and subjected to an operational temperature of 450°C ± 10°C. In this case about 2500 tonnes of steel were galvanized in the bath over the 12 months that the samples were immersed in the molten zinc i.e. about 10% of the throughput in the continuous kettle.

A sample of zinc coated base plate was sectioned from the MMAW-2 specimen for coating assessment[15], then the zinc coatings on all test pieces were removed, all samples measured and assessed for iron loss (Table 4). Considerably lower weld and parent metal loss was observed in these samples compared with those exposed in the continuous kettle.

Metal loss was reasonably consistent within each test piece with weld losses being typically similar to or less than parent plate losses. Whilst some minor wasting was noted (most likely associated with local turbulence observed in practice in all kettles), the results do indicate a more stable environment in terms of zinc flows within the top zone of the general galvanizing kettle. The lower operating temperature of this kettle would also contribute significantly to the much reduced losses and is consistent with the generally reported life expectancy for this type of kettle of about 10 years.

Metallography of zinc coatings

Samples exposed to molten zinc in the continuous galvanizing kettle for one month was removed in such a manner as to preserve their coating and then subjected to a sampling procedure that allowed the brittle zinc alloy layers to remain intact. The test pieces were then sectioned, the coatings examined and individual phases identified[13].

Assessment of zinc coatings commenced by referring to the Sandelin curve (Figure 2) and noting the location of the silicon content for each consumable. The base plate, MMAW-2 and FCAW-2 sit to the left of the Sandelin peak, with FCAW-2 at the peak (0.065% Si), MMAW-1 and FCAW-3 in the trough to the right of the peak, and assuming that the extrapolation of Sandelin's data can be justified, the silicon content of the GMAW weld is such that its reaction rate is more than three times that of the other welds. In reality, the dissolution of the GMAW weld metal was due to its high silicon content with the attack of other weld metals being marginal in comparison.

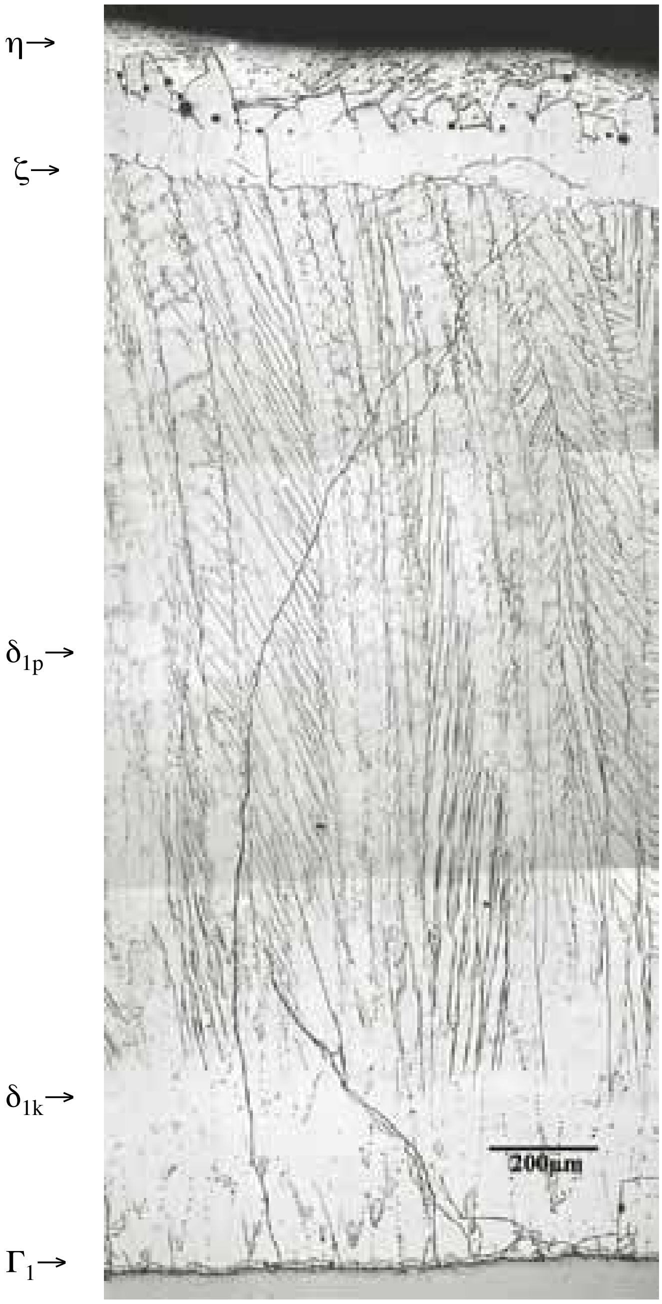

Figure 9. Typical zinc alloy phases after one month of immersion[13].

Normal zinc coatings on galvanized product consist of a series of alloy layers (Figure 2), the thickness of which will vary with composition of the base material, temperature of the bath, time the steel is held in the bath and the speed of withdrawal. The surface coatings within galvanizing kettles and thus the test samples are no different. They are present as a tiered structure (Figure 9) which generally consists of a thin gamma-one (Γ_1) layer, a "kompackt" (compact) delta-one k (δ_{1k}) layer, a "palisade" layer of delta-one p (δ_{1p}), a palisade layer of zeta phase (ζ) and an outer coating of eta (η) phase. It is this eta phase (essentially pure zinc) that galvanizers strive to obtain when galvanizing steel. As noted above, its thickness will largely depend on the speed of withdrawal of the steel

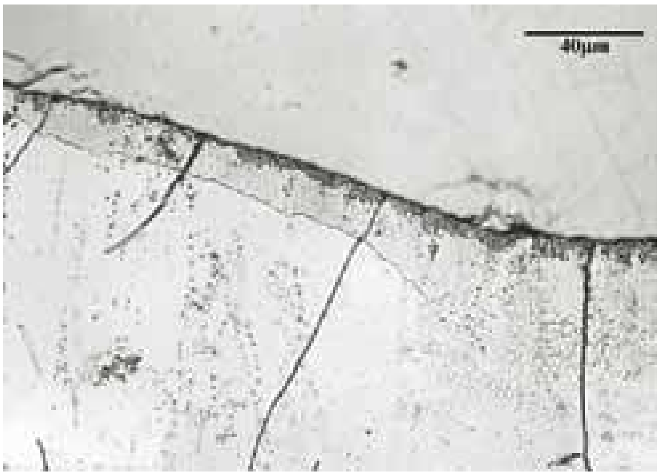

Figure 10. Photomicrograph of Zn rich layers on weld sample FCAW-3 (one month exposure)[13]. From top: steel substrate, gamma (thin dark layer); gamma-one (with outburst into delta-one k matrix); delta-one k.

from the bath, drainage of liquid zinc from the sample and how quickly it cools after withdrawal.

Occasionally another phase, a very thin gamma (Γ) layer (as distinct from Γ_1) is observed as one of the alloy layers but is normally unresolvable via optical metallographic techniques (especially in normal galvanized products). A thick gamma layer ($\approx$7μm) was observed on sample FCAW-3 (Figure 10), but was not detected optically on the other samples. Its development is not understood but has been postulated by Byron[14] in another case to relate to the presence of Ti.

A further observation was the enhanced development of the delta-one p phase (δ_{1p}) rather than zeta (ζ) or other phases as suggested by Figure 2. Zeta flaring, commonly observed in commercially galvanized samples with a composition around 0.065% silicon, was not observed in FCAW-1 which had a similar silicon content.

The significant loss of weld metal from the GMAW specimen (Figure 5) only occurred where filler metal was or had been present. When an alloy layer was observed adjacent to the weld metal on this sample, the zeta layer (ζ) was notably absent with the only evidence of its presence being the odd free floating grain. This is consistent with the concept that silicon in steel decreases the stability of ζ, reducing the lower limit of the temperature range for the linear reaction kinetics, typically in the temperature range 480°-530°C, for silicon-free steels.

It was also noted that the Γ_1 layer in the GMAW sample was approximately 170μm thick compared with 10μm in all other cases. This was possibly also a result of increased reactivity due to silicon, but may have also been enhanced by the valley shape formed which would have increased the surface area for the reaction.

Penetration of zinc into the grain boundaries of the steel substrate was commonly observed on all samples to a depth of about 20μm. It was also observed on the GMAW filler metal and to a much lesser extent on FCAW-2 and FCAW-3. Likewise "flares" or outbursts of gamma-one (Γ_1) into the overlying δ_{1k} layer (Figure 10) were commonly observed on the parent plate, remnant GMAW weld metal and to a lesser extent MMAW-1 and FCAW-3 weld metal. They were rare or non-existent on all other samples. The significance of these observations is not fully understood but is thought to relate to the rate of metal loss.

Table 4. Metal loss (mm) after 12 month exposure of test pieces – general kettle.

Section	**MMAW-1**	**MMAW-2**	**FCAW-1**	**FCAW-2**	**FCAW-3**
Weld	2.1	1.9	2.1	1.4	1.8
Base plate near weld	1.6	1.9	3.5	3.4	1.5
Base plate deep in kettle	2.3	2.6	3.1	3.2	2.3
Weld Si (wt%)	0.16	0.040	0.065	0.045	0.20

Notes: 1. All loss units are in mm/year
2. Location of the test weld in the bath was set just below the liquid zinc surface where the rate of reaction was expected to be highest.

Table 5. Comparison of phases present on A1006 plate [15]

	Mean thicknesses					
	1 month base plate			12 month base plate		
Phase	mm	SD (mm)	%	mm	SD (mm)	%
Gamma (Γ)	unresolved			0.7	(0.6)	<0.1
Gamma-one (Γ1)	12	(3)	0.5	19	(3)	0.4
Delta-one k (δ_{1k})	332	(136)	12.6	507	(400)	10.9
Delta-one p (δ_{1k})	1599	(547)	60.8	3965	(711)	85.2
Zeta (ζ)	172	(171)	6.5	116	(76)	2.5
Eta (η)	516	(1026)	19.6	47	(80)	1.0

Notes: 1. SD = Standard Deviation in microns. All figures are in parentheses.
2. % is proportion of mean thickness

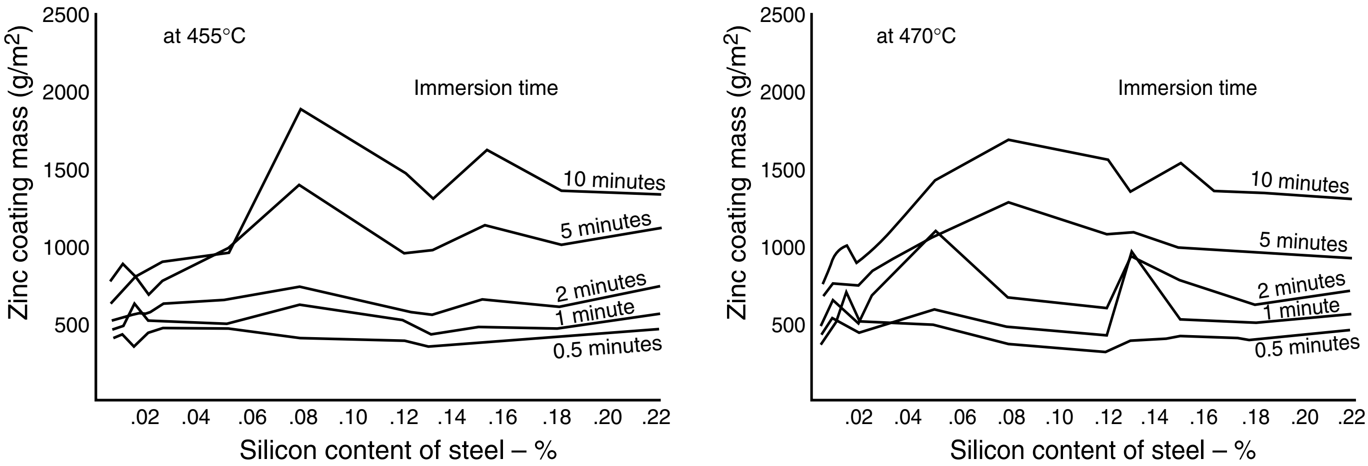

Figure 11. Variations in zinc coating mass with time, temperature and silicon content[16]

The MMAW-2 base plate sample immersed for one year in the general galvanizing kettle was also metallographically examined[15], in particular to compare the results with the detailed examinations carried out on the samples exposed for 1 month. Comparison of sections of the base steel in both cases yielded similar results except for the relative proportions of individual phases and a 75% increase in coating weight thickness with the greater exposure ($\approx$2700μm vs $\approx$4700μm)[15]. The relative proportions of phases detected are shown in Table 5.

The results show that the delta-one p (δ_{1p}) phase dominates and grows to a greater extent than other phases. It reinforces the view that whilst the zeta (ζ) phase predominates during short term liquid zinc immersion (i.e. normal galvanizing operations), it is the δ_{1p} phase that grows most rapidly with time and ultimately dominates the coating.

The relative differences in mean proportions of zeta (ζ) and eta (η) may not be significant due to the high values of the standard deviations compared to the mean values reported.

Another point to note is that the gamma phase became resolvable optically with time. The microstructure of the coating is similar to that of the one month exposed sample (Figure 9) and is thus not presented.

Features previously observed in the one month samples were also detected. Zinc penetration of the ferrite grain boundaries in the base plate was measured to a mean depth of 65μm which represents a 215% increase over that for the one month samples. Gamma-one (Γ_1) outbursts or "flares" (Figure 10) were also noted in the overlying delta-one k (δ_{1k}) layer and these penetrated about double the distance of those in the one month samples.

The parent plate microstructure had undergone some minor changes from the original ferrite/pearlite structure with some carbide coalescence and spheroidisation due to exposure to an elevated temperature around 450°C.

Discussion

Based on the results in Tables 3 and 4, it is evident that with the exception of the GMAW consumable, all consumables tested could be expected to give a good service life.

Whilst the results from Table 3 appear to indicate that FCAW-1 was slightly worse than the other consumables tested, these results are contradicted by those of Table 4 and thus serve to highlight the process instabilities encountered. There is also considerable anecdotal evidence that consumables with similar alloy design to FCAW-1 have been successfully used to manufacture general jobbing galvanizing kettles in both Australia and South Africa for many years. Jago and Lau[8] also reported that the rate of zinc attack on a self-shielded consumable similar to FCAW-1 was similar to that on the parent base steel which again adds weight to the above anecdotal evidence. Given the usage of these consumables, it is therefore likely that the potential embrittlement issues identified by Jago and Lau[8] may not be significant in this application and thus have not been reported in practice. In addition reference 9 suggests that the aluminium level in the self-shielded FCAW deposits may reduce the rate of liquid zinc attack. The manufacturer's consumable specification literature and Table 2 show that these consumables have a nominal silicon content similar to that quoted for the control consumable MMAW-1 and test consumable FCAW-3, all of which have silicon contents that sit to the right of the Sandelin peak in the trough range 0.11 to 0.25%. The relatively low silicon contents are likely to contribute to their successful application.

The higher carbon self-shielded flux cored consumables such as FCAW-1 (with carbon contents well above that of conventional consumables) may have an increased risk of delayed weld metal cracking. This form of cracking occurs shortly after the cessation of welding and hence is of concern only to the kettle manufacturer rather than the kettle purchaser. Whilst the authors are not aware of this form of cracking being observed in this application, it is an issue kettle manufacturers need to be aware of. Clearly, further work on the investigation of high aluminium bearing FCAW consumables in galvanizing kettle applications is warranted.

Finally, in conducting assessments of zinc coatings, it is worth revisiting the Sandelin curve (Figure 2) to gain an understanding of what it represents in practice. Sandelin's original methodology[16] was to immerse steel samples in molten zinc held at 455°C for 3 minutes and thence to assess the coatings. This practice has resulted in the simplification of the interpretation of the results over time and thus restricted their practical significance. Other investigations involving different exposure times and temperatures show considerable variations in coating mass with time, temperature and silicon content (Figure 11)[16]. Although this work has made it possible to define the composition range of silicon which has a strong influence on coating mass of normal galvanized product, it is worth noting that the expected trends are not always observed in practice[17]. Likewise, the test results show that the Sandelin peak at 0.065% silicon is not significant in the selection of welding consumables for the manufacture of galvanizing kettles which can be in service for up to 10 years.

Conclusions

With the exception of the GMAW consumable, all of the selected welding consumables performed satisfactorily during the testing programme.

The long term production kettle tests demonstrated that consumables with a silicon level up to 0.2% generate welds capable of achieving a satisfactory service life.

Conventional high silicon welding consumables (>0.3% Si) should never be used to repair, maintain or manufacture kettles as the results show clearly that a very short service life can be expected irrespective of the operating parameters used during galvanizing operations. As the consumable classification rarely restricts the silicon content to a level deemed suitable for use in a galvanizing kettle, reference should always be made to the consumable manufacturer to obtain appropriate guarantees of the composition e.g. test certificates, for that specific consumable prior to its use.

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