LONG-TERM MARINE CORROSION OF WELDS ON STEEL PILING

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SUMMARY: Welds on mild and low alloy steels exposed to the marine environment are known to be prone to high levels of corrosion. Pitting usually is the critical form of attack. Quantification of the relative and absolute maximum pit depths that occur is important for predicting future and remaining structural life but longterm data is scarce. The present paper reports on a study of the statistical characterization of pit depths on longitudinally welded steel piling exposed for some 33 years in Newcastle harbour. The investigation is based on the hypotheses that the lack of homogeneity at the corrosion interface caused by differences in grain size, grain structure and the potential for pitting to occur preferentially along boundaries is responsible for the observed effects. The pit depth results obtained are compared with the results reported earlier for maximum pit depths measured on welded steel coupons exposed to similar Pacific Ocean 20°C seawaters for up to 3.5 years. It is shown that there is a reasonable degree of consistency between the two sets of results, adding confidence to the possibility of extrapolation of medium term data to the longer term.

Keywords: Mild Steel, Seawater, Corrosion, Pitting, Weld, Microstructure.

1. INTRODUCTION

The progress made in welding equipment and electrodes, the advancing art and science of designing for welding, and the growth in trust and acceptance of welding have combined to make welding a powerful implement for an expanding construction industry (Blodgett 1966). Such widespread recognition of welding as a safe means of making structural connections has come about after years of diligent practice and research effort and documentation of research findings. However, welded mild and low alloy welded steels when exposed to the marine environment are prone to corrosion, mainly in the form of pitting attack, which appears to be more severe in the so-called heat affected zone. This may have an important influence on the long-term safety of welded structures in marine environments.

Very few papers deal with the resistance of weldment to pitting, and there are some differences of opinion as to whether the weld metal is less resistant or more resistant relative to the parent metal. Generally, it can be assumed that the susceptibility of pitting will depend on differences in the composition and microstructure, caused by the high temperatures involved in the welding process and the subsequent cooling rate, these in turn being affected by the welding procedure used. Typically, the properties of the weld metal differ from those of the parent metal, even if of the same nominal composition. In the case of austenitic steels, the weld metal is in-homogeneous and usually contains ferrite not present in parent metal.

As is known (Smialowska 1986), austenitic steels heated in certain temperature ranges undergo sensitization and become prone to intergranular corrosion. A generally accepted explanation of sensitization assumes that at the sensitization temperature, chromium carbides precipitate at the grain boundaries, causing Cr impoverishment of the adjacent matrix. It is therefore expected that sensitized steels will be susceptible to both intergranular corrosion and pitting.

Similarly, carbon steels with electric resistance welded zones and exposed to seawater have been shown to be prone to selective corrosion attack on the weld (Kato et al. 1978). Scanning electron microscope examination indicated that pits initiated on MnS inclusions were concentrated in the weld. Pits developed into grooving corrosion as a result of the action of a macro-cell between the anodic weld and the cathodic base metal. Kato et al. (1978) assumed that the rapid heating and cooling, which occurs during electric resistance or induction welding, produced S-enriched zones in the matrix surrounding the inclusions. High corrosion rates at welds have also been shown (Eid 1989b) to be promoted by other factors, such as surface finish and variations in the grain structure between the weld metal, heat affected zone (HAZ) and parent metal.
For structural steels exposed to seawater immersion the maximum pit depth increases significantly after some initial period of exposure that lasts from months to years, depending on water temperature. This increase in maximum pit depth has been attributed, in part, to the development of anaerobic conditions at the surface (Melchers 2004, 2005) since anaerobic conditions are favourable to the occurrence of corrosion through the metabolism of sulphate-reducing bacteria (SRB) (Melchers 2005b). SRB-induced corrosion tends to be largely pitting corrosion that is initiated by the local attack of the metal surface by bacterial metabolites (Daumas et al. 1993). The principal metabolite generated by the SRB is H₂S and this is known to be the direct cause of localized corrosion (Melchers 2005b).

Corrosion in a marine environment overall is dependent on many different factors including material composition, seawater chemistry, pH, bio-fouling, microbiological organisms, pollution and fluid velocity characteristics, dissolved oxygen content, salinity and chloride concentration, galvanic interactions, temperature and environmental zone although not all these factors are of similar severity (Shifler 2004). Pitting usually is the critical form of attack.

Quantification of the relative and absolute maximum pit depths that occur in parent metal and in the weld zones is important for predicting future and remaining structural life. However, long term data is scarce, seldom reported in the literature and only anecdotally in corrosion handbooks. The present paper reports on a study of the statistical characterization of pit depths measures on longitudinally welded steel pipe piling exposed for some 33 years in Newcastle harbour. The pit depth results obtained for the 33 year old piling are compared with the results reported earlier (Chaves and Melchers 2010) for maximum pit depth measured on steel welded pipe coupons exposed to similar Pacific Ocean seawaters for up to 3.5 years.

Figure 1. Steel piling recently recovered from a tidally exposed mooring system in Newcastle harbour (left) and a close-up view of part of its cross-section (right) showing the weld cross section.

2. METALLURGICAL OVERVIEW OF PITTING

It is well-known that pitting corrosion is the result of in-homogeneities in alloy composition and that adjacent grains of slightly different composition may, in the presence of moisture, form galvanic couples (Eid, 1989a). Discontinuities, or grain boundaries, produce anodic and cathodic segregation and hence can lead to localized corrosion. In addition, localized heat treatments such as welding tend to cause a further level of discontinuity (Figure 2). Typically in a welded region, the grain size, element composition and crystal structure all vary across the weld. As a consequence such areas may suffer heavy corrosion attack.

The weld metal is a mixture of the melted composition from the rod or welding wire, and the base metal. Depending upon the criteria required for that weld, the rod and base metal may or may not be identical. In certain steel welds two crystal structures, ferrite and pearlite are produced by differential cooling-solidification rates after the heat strike has passed, where previously the base metal was fully austenitic. Figures 3 to 5 illustrate the difference in microstructure according to each of the zones. Attack on welds appears to selectively remove one phase or the other, but not both.
Figure 2. Welded pipeline cross-section sample after polishing and macro etching (left), with the boundaries between the Heat Affected Zone (HAZ), Weld Zone (WZ) and Parent Metal Zone (PMZ) marked (right).

Figure 3. 200x magnification of Weld Zone microstructure comprising of columnar grains of acicular ferrite (white) and pearlite (black) characterizing a Quenched steel producing a Martensitic microstructure.

Figure 4. 200x magnification HAZ microstructure displaying large grains of pearlite with Widmanstatten ferrite at the prior austenite grain boundaries (left) and a more finer grained region exhibiting equiaxed grains of ferrite and pearlite (right).
Figure 5. 200x magnification showing microstructure of the Parent Metal identifying equiaxed grains of ferrite and pearlite consistent with a hot rolled, medium carbon grade of steel.

3. RESULTS FOR PITTING CORROSION

Results of previous experiments carried out over a period of 3.5 years of exposure (Chaves and Melchers 2010) show that the deepest pits tend to occur in the HAZ throughout the exposure period. However, the difference in maximum pit depth between the zones varied considerably. Nevertheless, the relative magnitude of the respective pit depths in the three zones is generally consistent with the observations in the corrosion literature for corrosion pit depths in weldments and in welded pipelines.

The greater pit depths on the HAZ have been proposed to be the result of macro-structural differences and differences in steel composition (Eid 1989a). On the other hand, there is empirical support that small differences in composition can influence the depth of pitting for smaller individual coupons (Melchers 2006a) but this observation may not extend to long corrosion zones such as welds along pipelines and for the extended HAZ along these welds. Generally there is considerable difference in the chemical composition of the material in the three zones. However, for the welds considered previously (Chaves and Melchers 2010) there was essentially no difference in steel composition between the three zones (Table 1), so that the difference in pitting cannot be a result of composition differences. Nevertheless, as shown in Figures 3-5, there are differences in microstructure. This tends to provide support for the notion that differences in microstructure have an influence on pit depth (Eid 1989b).

The samples were analysed by optical emission spectrometry (direct sparking) at the Amdel - Bureau Veritas Laboratories in Cardiff, Newcastle. Samples were macro etched and the regions marked for analysis. Sparking was conducted on the cross section of the sample having individual sparks of approximately 5mm in diameter (as shown in Figure 6) meaning that variations in composition on a smaller scale are unlikely to be captured. The results are given in Table 1. The parent metal chemistry of the sample is consistent with a range of medium carbon grades of steel. The weld metal differs slightly from the parent metal steel; in particular in the weld the carbon content is lower and the silicon level higher. Silicon is often elevated in weld metal because the filter metal contains additional silicon as a deoxidiser.

Figure 6. Sample examined with macro etched on the left and prepared for chemical analysis on the right.
Table 1. Chemical composition

<table>
<thead>
<tr>
<th>Composition (weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample</strong></td>
</tr>
<tr>
<td><strong>Weld Zone</strong></td>
</tr>
<tr>
<td><strong>Heat Zone</strong></td>
</tr>
<tr>
<td><strong>Parent Metal</strong></td>
</tr>
</tbody>
</table>

3.1 Pit measurements results

The four steel pipe pilings used in this experiment, recovered from Newcastle harbour and provided by Newcastle Port Corporation were removed as part of maintenance and replacement of the supports of dolphins at the docking wharf. From each pipe three samples were cut with a conventional oxy torch. Care was taken to ensure that representative samples were cut from each of the zones, buried, immersed and tidal (Figure 7). Coupons were cut to a suitable size (250 x 250mm) with the weld in the centre of the sample to ensure that the heat generated by the process would not compromise the microstructure and/or the measurements of the data. The coupons were then macro etched so that the boundaries could be recognized by simple visual inspection (Figure 6). Each zone was then examined carefully for pitting and in particular for the location of the deepest pits. Figure 7 also shows the size adopted for each zone and a typical set of locations of the 10 deepest pits in each zone. Depths of the pits relative to the surrounding metal were measured using a dial gauge with 0.002mm sensibility.

![Figure 7. Retrieving sample from corroded surface of steel pipe (left) along with typical set of the 10 deepest pits in each zone (PM parent metal, HAZ heat affected zone and WZ weld zone).](image)

The measured pit depths are relative depths and need to be corrected to obtain estimates of total (or absolute) pit depth. This was done by assuming that the mass loss of the total coupon was roughly uniform all over, not preferential between zones and large enough that the error in neglecting the mass loss in the pits themselves could be ignored. This approach has been used in previous investigations of maximum pit depth. The corrected (absolute) pit depths as a function of time of exposure are shown in Figures 8-10. Results are shown for the 10 deepest pits in each zone, for each of the triplicate samples recovered from each pipe. In each case the data obtained in the earlier study (Chaves & Melchers 2010) for the period 0-3.5 years is shown also, together with the multi-linear trends through the average data.

As observed also in previous research, at some exposure periods of time there is a very considerable scatter both in the relative and in the absolute pit depths. This is consistent with findings earlier for coupons of mild steel, and is the results of variability in (a) the change in the governing corrosion process and (b) the possible influence of MIC in the corrosion process for longer exposures (Melchers 2006a). Also notice that the data obtained from the samples collected from the Newcastle Harbour steel piling only provides information for a single point in time, which in this case represents long-term 33 year exposure corrosion.
In the next set of Figures 11 to 13 data up to 3.5 years of exposure from previous investigation on maximum pit depth (Chaves and Melchers 2010) are plotted along with the results obtained herein.

Figure 8. Pit depth data for observed pits, mean and maximum trends for Parent Metal Zone. The data in the range 0-3.5 years is from the previous investigation (Chaves & Melchers 2010).

Figure 9. Pit depth data for observed pits, mean and maximum trends for Weld Zone. The data in the range 0-3.5 years is from the previous investigation (Chaves & Melchers 2010).

Figure 10. Pit depth data for observed pits, mean and maximum trends for Heat Affected Zone. The data in the range 0-3.5
years is from the previous investigation (Chaves & Melchers 2010).

Figure 11. Comparison between different maximum pit depth data for Parent Metal, HAZ and Weld Zone.

Figure 11 shows a comparison of data in the range 0-3.5 years from the previous investigation (Chaves & Melchers 2010) and the 33 year exposure period from Newcastle Harbour. It is seen that there is a high level of consistency between the maximum pits depth observed for the three zones.

3.2 Statistical Gumbel plot of the pitting measurements

Figures 12 to 14 show Gumbel plots for maximum pit depth data obtained for the 33 year exposure samples. As described above, nine mild steel coupons were retrieved from areas of the pilings exposed to buried, immersed and tidal marine conditions in Newcastle Harbour. Each Figure shows data and Gumbel lines for each of the three exposure zones.

Figure 12. Gumbel Plot for Maximum Pit depth data for observed pits in the Parent Metal Zone.
It may be observed that in each (33 year) data set the data does not fit a straight line particularly well, as would be expected if the data were Gumbel distributed. This could be, and usually is, dismissed as being the result of random variability and inherent error in limited observations. Figures 15-17 show the same data and linear plots together with the data and Gumbel lines for the observations at 1, 2 and 3 years exposure at Jervis Bay (Chaves & Melchers 2010). All these results are only for the immersion zone. Generally similar comparisons were found for the tidal and buried zones.
Figure 16. Comparison between extreme Gumbel plots for interpreted pit depth data for observed pits (Weld Zone).

Figure 17. Comparison between extreme Gumbel plots for interpreted pit depth data for observed pits (Heat Affected Zone).

It was noted that the majority of the deepest pits occur in the Heat Affected Zone, as might be expected from the observations given above. Table 2 provides an overview of the location and depths for the deepest pits observed.

Table 2. Maximum Pit Depth Observed (mm)

<table>
<thead>
<tr>
<th>Sample</th>
<th>B - 1</th>
<th>B - 2</th>
<th>B - 3</th>
<th>I - 1</th>
<th>I - 2</th>
<th>I - 3</th>
<th>T - 1</th>
<th>T - 2</th>
<th>T - 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>3.704</td>
<td>3.364</td>
<td>2.73</td>
<td>2.216</td>
<td>2.862</td>
<td>1.874</td>
<td>2.764</td>
<td>3.356</td>
<td>1.578</td>
</tr>
<tr>
<td>PMZ</td>
<td>2.896</td>
<td>3.128</td>
<td>1.376</td>
<td>2.252</td>
<td>8.11</td>
<td>1.458</td>
<td>3.16</td>
<td>2.022</td>
<td>1.678</td>
</tr>
</tbody>
</table>

* The abbreviations B, I and T stand for Buried, Immersed and Tidal zones respectfully.

4. DISCUSSION

The trend curves shown in Figures 8-10 are all similar to trends previously reported for pitting corrosion of individual small mild steel coupons without welds (Melchers 2004). That work proposed that there were successive changes in the corrosion process, including some for which there could be the involvement of hydrogen reduction and microbiologically influenced corrosion (Melchers 2006b). The present results generally are consistent with the earlier observations but the investigation of the potential influence of MIC for the present test series remains to be completed. Nevertheless, the influence of MIC has been observed for welds on stainless steels (Smialowska 1986) and thus might be expected also for welds on mild steels.
As for mild steel coupons without welds the present results also show a high degree of scatter in the data (see Figures 8 - 10). Again, as for coupon data, the scatter varies with exposure time. Further, the high degree of scatter for the longer exposure periods clearly is evident also in the Gumbel plots, Figures 12 to 14 indicated by the slope of the data set - this is a measure of the degree of scatter.

The Gumbel plots, Figures 15-17 show that the data for exposure periods less than about one year are approximately linear. Conventionally, this indicates that the data can be taken as Gumbel distributed. However, for the longer exposure periods, say after about 1.5 - 2 years, the data trends are distinctly non-linear. Extreme value analyses suggests that this implies that the data are not Gumbel distributed (Galambos 1987). Similar observations have been made earlier for the pitting of isolated small coupons without welds. These displayed a distinctly different trend for smaller pit depths and a further different distribution, proposed as Frechet distributed (Melchers 2006b). The latter is more conservative than the standard Gumbel plot in that it predicts greater pit depths for a given probability of occurrence. The present results indicate consistency with the earlier results for homogeneous coupons. However, when overall data trends for maximum pit depth in coupons without welds are compared with coupons with welds, considerable differences are seen. Figures 18-19 show how the data differ. Note that the mass losses for the samples with welds are for the whole sample with no distinction between the PMZ, HAZ or WZ. What is represented is the average mass loss of the triplicate samples at each given point in time.

![Figure 18](image1.png)

**Figure 18.** Comparison between different long term sets of maximum pit depth data (Parent Metal Zone). Taylor’s beach samples represent coupons without welds, while Jervis Bay samples represent parent metal zone of welded coupon readings.

![Figure 19](image2.png)

**Figure 19.** Comparison of different average corrosion loss between different long term sets of data. Taylor’s beach samples represent coupons without welds, while Jervis Bay samples represent welded coupon readings.

The differences in the trends shown in Figures 18 and 19 are unlikely to be the result of difference in micro-climate as these are very similar at Taylors beach (Melchers 2004a) and Jervis bay (Chaves & Melchers 2010). One possibility is the influence of MIC since the Taylors Beach site is somewhat removed from the Pacific Ocean. However, Jervis Bay is known to be subject to an annual inflow of offshore nutrients. Clearly these matters require further investigation.
From an industrial point of view, corrosion is accounted for during the design phase by means of a corrosion allowance. The present study shows evidence that corrosion observed in the Parent Metal is less than that in the Heat Affected Zone and this continues also long-term. This may mean that conventional corrosion allowances, if based on coupon tests without welds, could be inadequate. There also may be an implication for fatigue since pitting is known to increase proneness to fatigue cracking.

5. CONCLUSIONS

1- The present results from the 33 year-old steel piling appear to be consistent with the earlier results obtained under similar exposure conditions and also are consistent in a general sense with trends for maximum pit depth and for mass loss obtained earlier for coupons without welds. This consistency adds confidence to the possibility of extrapolation of medium term data to the longer term;
2- The slope of the fitted Gumbel plots for longer exposure periods indicates a much higher degree of scatter in the maximum pit depths for longer exposure periods. This may have important practical implications;
3- Detailed investigations remain to be completed regarding the reasons for the discrepancy between maximum pit depth of coupons without welds and the present results which tend to show much greater pit depths in the parent metal.

6. ACKNOWLEDGMENTS

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8. AUTHOR DETAILS

Igor A Chaves is a PhD research student at the University of Newcastle, Australia where he holds UNIPR Scholarship for studies in corrosion analysis and prediction. He initiated his studies on steel structures as a research trainee in 2004 at the Federal University of Vicosa, Brazil where he graduated in 2006. His interest for technological and scientific research lead him to the EESC University of Sao Paulo, Brazil, and as result of completing his Master’s degree in structural engineering in 2008, design guidelines for cold-formed composite steel and concrete beams were added to the Brazilian Standard of Steel Design.

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