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Review Article

Time Dependent Development of Aluminium Pitting Corrosion

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Aluminium alloys have excellent corrosion resistance to a wide variety of exposure conditions. Usually they corrode by pitting rather than by uniform corrosion. For infrastructure applications long-term corrosion behaviour is of interest. The relatively limited long-term pitting data that is available shows that maximum and average pit depths do not follow the power law function as conventionally assumed but tend to follow a bimodal trend with exposure time. This is consistent with the bimodal trends observed previously for corrosion mass loss of aluminium alloys. Most likely it is the result of the accumulation of corrosion products over the pit mouths, leading to the gradual development of localised anoxic conditions within pits. In turn this permits the development within the pits of anoxic autocatalytic conditions, consistent with established theory for pitting corrosion of aluminium. It also is consistent with observations of hydrogen evolution from pits. The implications of this for practical applications are discussed.

1. Introduction

Aluminium and its alloys usually have excellent corrosion resistance. Particularly for atmospheric exposures they show almost no pitting and very limited general corrosion [1, 2]. This has been attributed to the development of thin protective oxide films, which can be formed only in environments containing sufficient oxygen [3]. Close examination of corroded surfaces shows that the main corrosion phenomena are pitting and sometimes intergranular corrosion [4]. In immersion and in wet and in marine conditions aluminium alloys corrode relatively more, largely by pitting but it is still modest [5, 6]. In consequence, aluminium and its alloys are widely used in the aerospace, defence, and marine industries. They also increasingly are being used in structural and other commercial infrastructures. They are used for pipelines, tanks, pressure vessels, shields, and other structures for which containment is a design and operational criterion. For these applications the prediction of the likely future long-term pitting behaviour and hence the probability of perforation is particularly important. In other cases perforation may be simply unsightly or undesirable. In all cases the development of the maximum depth pit with increased time of exposure needs to be predicated.

It is conventional in corrosion studies to assume that corrosion $c(t)$ as a function of time t follows a power law function:

$$c(t) = At^{B}, \qquad (1)$$

where A and B are constants obtained from fitting the function to data. With some exceptions, much of the quantitative information about the corrosion of aluminium and its alloys is for short-term exposures (a few hours, days, or weeks) and for these the power law appears to be a reasonable approximation. However, it also has been applied to data from a number of long-term exposure studies (up to 20 years) and for these deviations from (1) have been noted. Usually these deviations have been dismissed as the result of experimental or recording error (see Ailor [7] for a summary).

Much of the information about corrosion of aluminium and its alloys is presented in terms of mass loss and most of it is for atmospheric corrosion. Such data has been used to estimate the constants A and B in (1). However, experience shows that there are wide variations in the values obtained for these "constants" between different sites or exposure conditions or by investigators, with, for example, B varying between 0.33 and 1.0 or more (e.g., [8]). Taken together with

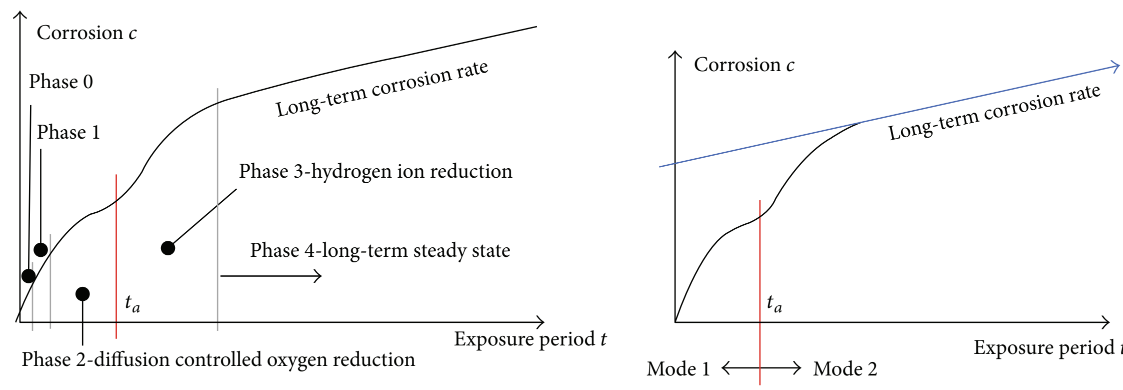

Figure 1: Schematic bimodal model for long-term corrosion loss and pit depth in marine environments showing brief descriptions for each of the phases involved and the linear idealization for long-term corrosion. The change from mode 1 with predominantly oxic corrosion conditions to mode 2 with predominantly anoxic conditions occurs at t_a.

the deviations from (1) noted above, this suggests that (1) is not a good model for longer-term corrosion trends.

The power law also has been used for depth of pits. Using short-term (36 weeks) laboratory experiments on a wide variety of aluminium alloys in freshwater and other water Aziz and Godard [9] found $B = 1/3$ to be a consistently good fit to the data. On the other hand, de la Fuente et al. [10] noted that maximum pit depth appeared to increase quickly in the early exposure period but decreased to a low corrosion rate after about 2 years. This was based on their own covering of some 14 years of exposure and also on atmospheric corrosion field data for various aluminium alloys [1, 8]. Using these data they proposed that for aluminium alloys in atmospheric exposures the maximum pit penetration $p(t)$ can be expressed as a function of the exposure time t by the empirical relationship

$$p(t) = a \log t + b, \tag{2}$$

where a is a constant obtained from calibration to data and b is the year-1 maximum pit depth. Both depend on the alloy type and the atmospheric exposure conditions.

A recent extensive review of published detailed longer-term mass loss data for different atmospheric exposure conditions for marine immersion and coastal zone exposures demonstrated that the bimodal corrosion model shown schematically in Figure 1 was much more consistent with the data than the power law model (1) [11]. In that analysis, most attention was given to corrosion as measured by mass loss per unit surface area as a proxy for uniform corrosion. There were two data sets for pitting corrosion. These also showed evidence of bimodal behaviour. This should not be surprising, as the bimodal trend has been observed also for both uniform and pitting corrosion of low carbon steels, weathering steels, and cast irons [11]. The bimodal model, like the power law, has a scientific basis. However, only the bimodal model recognizes that the mechanics of corrosion can change as the corrosion process progresses [12].

The intent of the present paper is to examine in more detail whether the bimodal model is applicable to pitting corrosion of aluminium alloys, using data sets for longer-term corrosion reported in the literature. As will be seen, there is only a modest amount of detailed data available for the longer-term pitting of aluminium alloys, that is, data with sufficient points in the region corresponding to the transition from mode 2 to mode 3 (Figure 1). Many experimental programs in the past were designed on the assumption that the power law is applicable, with the result that the time period between observations of corrosion mass loss and maximum pit depth increases as the experiment progresses and thus may miss the critical changeover region around t_a (Figure 1).

An extensive review of data for longer-term corrosion of aluminium from field study sites under realistic exposure conditions was given earlier [11]. As noted, that study used mass loss as a proxy for general corrosion even though it obviously includes the mass of material lost in pitting corrosion. Because the corrosion of aluminium and many of its alloys tends to be low and also mainly confined to pitting corrosion [4], other proxies such as loss of tensile strength have been used. Herein the emphasis is on the *maximum* depth of corrosion pits, recognizing that in the past pit depth has been difficult to measure particularly for small or shallow pits and that in longer-term exposure programs staff and hence the fine detail of techniques and procedures used may change. One important aspect for pitting corrosion is identification or reconstruction of the original surface as reference for the depth of pits. The possibility exists also that there may have been measurement, transcription and/or recording errors, although these usually are rare. These factors add a degree of uncertainty to the veracity of the reports of observed data that should be considered in the interpretation of reported data, noting that a high degree of internal consistency should be expected for corrosion observations under generally similar conditions and with similar materials. There is no evidence of significant "jump" changes in general corrosion and pitting behaviour (cf. [3–6]).

In the next section published data for long-term pitting corrosion of a range of aluminium alloys under (mainly) field exposure conditions are used to examine the applicability

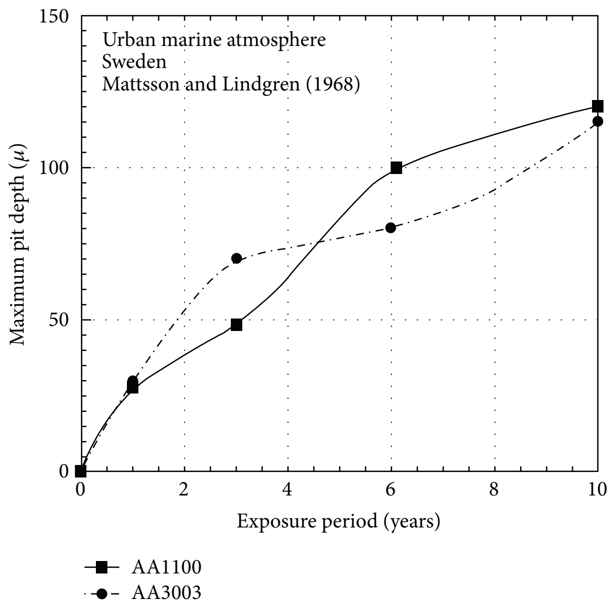

FIGURE 2: Data for maximum pit depth of AA1100 aluminium exposed in urban marine atmospheric environment showing the trends for pit depth are bimodal. The changeover to mode 2 occurs at about 3 and 7 years of exposure for AA1100 and AA3003, respectively. Data from Mattsson and Lindgren [13].

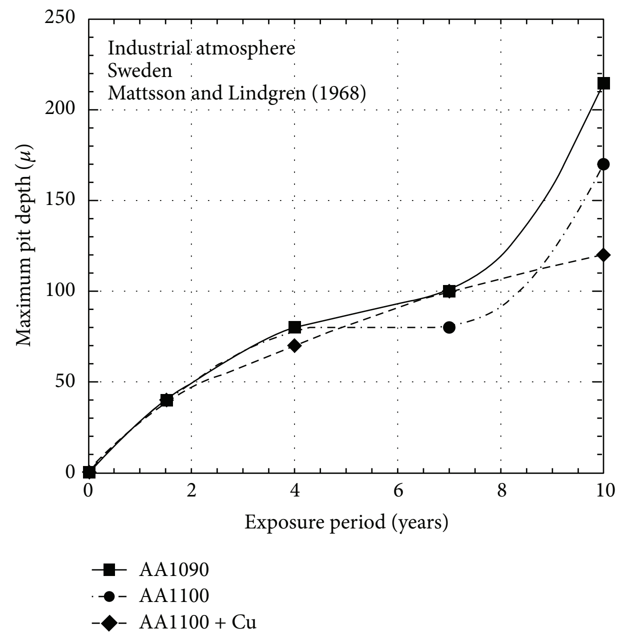

FIGURE 3: Data for maximum pit depth of aluminium alloys AA1090, AA1100 alloyed with Cu exposed in an industrial atmospheric environment showing the trends for pit depth are bimodal. The changeover to mode 2 occurs at about 7 years of exposure. Data from Mattsson and Lindgren [13].

of the bimodal model functional form for maximum pit depth. It is shown, by inference, that sufficiently detailed data are, largely, consistent with the bimodal trend, although in some cases it is necessary to make some allowance for inconsistencies in the data as reported. In all cases the data in the experimental programs for a particular aluminium alloy were obtained from separate coupons, exposed for different periods of time. None of the experimental programs traced the actual temporal development of an individual pit even in a laboratory setting that still remains a very difficult task without interfering with the actual mechanisms controlling the pitting processes. In the data sets available usually only the deepest pit(s) at any point in time is reported. As a result, the trends given, for the experimental observations or for the power law or the bimodal function, refer to the locus of such maximum pit depths. The subsequent section explores possible reasons for the bimodal corrosion characteristic for aluminium alloys, the possible development with time of the pitting process, and also the implications for practical application and extrapolation. There is no attempt herein to calibrate the parameters of the bimodal model to field data: the diversity in range of aluminium alloys is too great compared to the data sets currently available.

2. Atmospheric Pitting Corrosion

Longer-term data for pitting of aluminium alloys in atmospheric conditions reported by Mattsson and Lindgren [13] is shown in Figure 2 for urban marine atmospheric exposure and for industrial atmospheric exposures in Figures 3 and 4. In each case a smooth best-fit trend has been drawn through the data points using the Stineman smoothing function [14].

In Figure 4 one data point has been ignored. Although there is usually some variability in pit depth between different samples, the large difference in pit depths shown is considered unlikely to have arisen from such natural variability but is more likely the result of an error in recording or measurement. Coupled with the fact that for any individual pit the maximum depth cannot decrease with increased exposure time and the subsequent maximum pit depths are less, it suggests that the point shown is in error. Ignoring the data point leaves a trend consistent with bimodal behaviour. Apart from this case, no interpretation was necessary for any of the data sets to obtain the bimodal trend for the progression of maximum pit depth with time. Although not stated in the source material it may be assumed that the data shown were the average values of the maximum pit depth measured on two or three replicate coupons. This is standard procedure for corrosion experiments [2].

For aluminium exposed in an aggressive marine exposure site at Alicante (Spain), Otero et al. [15] report pit depth observations at 1, 2, 4, and 10 years of exposure. These are insufficient in number to obtain sufficiently discerning trends, except in a few cases. Figure 5 shows a number of these.

Maximum pit depth data for 3 different grades of aluminium exposed for 20 years in unspecified marine atmosphere conditions were summarized by Vargel [4] (Figure 6). Each trend through the data, if carefully considered, shows

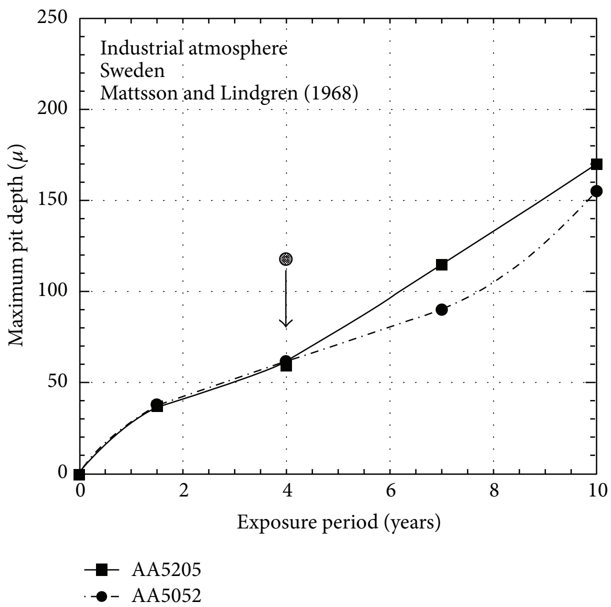

Figure 4: Data for maximum pit depth of aluminium alloys AA5205 and AA5052 exposed in an industrial atmospheric environment showing the trends for pit depth are bimodal. In this case the changeover to mode 2 occurs at about 5 years of exposure. Data from Mattsson and Lindgren [13].

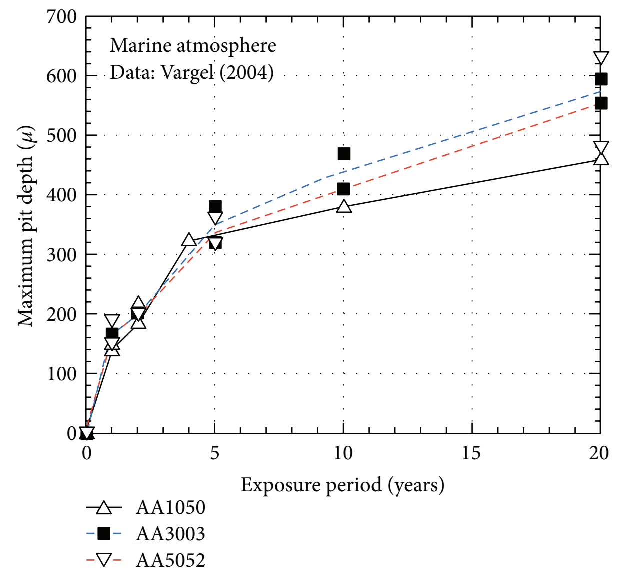

Figure 6: Data for maximum pit depth of aluminium alloys AA1050, AA3003, and AA5052 exposed in unspecified marine atmospheres for up to 20 years. The trends for maximum pit depth are shown and are bimodal. The changeover to mode 2 occurs at about 2-year exposure. Data from Vargel [4].

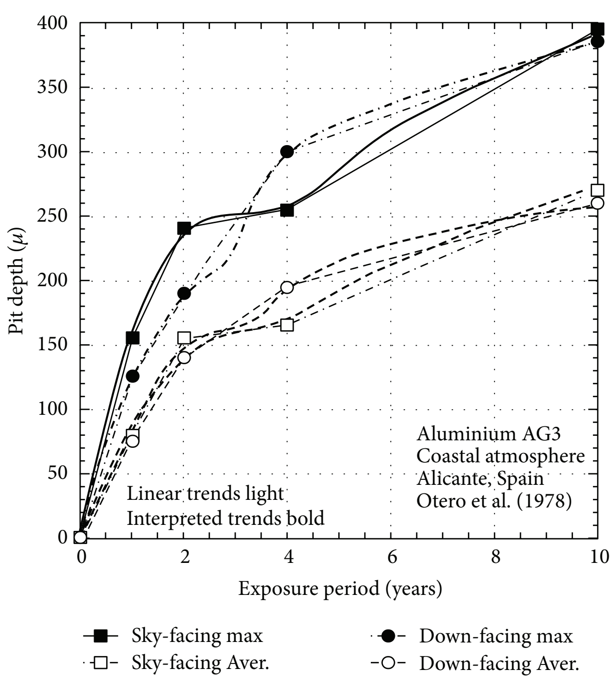

Figure 5: Data for maximum pit depth of aluminium alloy AG3 exposed in a coastal atmospheric environment at Alicante, Spain. The trends for pit depth are clearly bimodal or can be interpreted easily as such. The downward facing coupons show more aggressive pitting. In this case the changeover to mode 2 occurs at about 3-4 years of exposure. Data from Otero et al. [15].

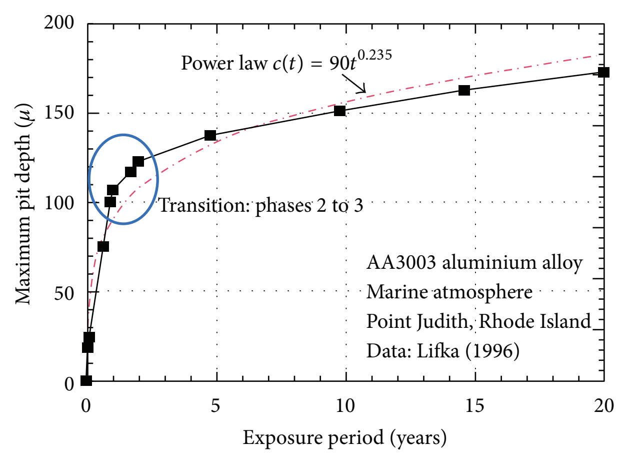

Figure 7: Data for maximum pit depth of aluminium alloy AA3003 exposed in the marine atmosphere at Rhode Island, NJ, for up to 20 years. The trend for maximum pit depth is shown. The location where the changeover from mode 2 to mode 3 is expected to occur is shown circled, at about 2 years of exposure. Data from Lifka [29].

bimodal behaviour in the early stages, with the change from mode 2 to mode 3 (Figure 1) at about 2 years.

The transition from mode 1 to mode 2 (or from phase 2 to phase 3) in Figure 1 can be quite subtle. This is evident in Figure 6. It is even more subtle in Figure 7. There is a very clear change in trend at around 2 years of exposure and this timing corresponds to that in Figure 6 for similar exposure conditions and that in Figure 2 for alloy AA3003.

3. Marine Pitting Corrosion

As part of a larger and very comprehensive corrosion program, coupons of AA1100 and AA6061-T each 230 × 230 × 6 mm (nominal) in size were exposed in the Panama Canal Zone (PCZ) for up to 16 years in water at 27°C on average [2]. The seawater exposures were at Fort Amador and the freshwater exposures in Gatun Lake, part of the Panama Canal Zone system. The coupons were recovered periodically in duplicate, cleaned, and weighed for mass loss determination. The depths of the 20 deepest pits over all the coupon faces were determined and the average value is reported. Also, the maximum of each of those 20 deepest pits was reported. It is not clear from the original source material how the original surface of the coupons was determined after corrosion had occurred and whether the same procedures for this were used throughout the 16 years of the experimental program. The chance of error in procedure is much less for the mass loss determination as it uses the difference between the original mass of a coupon and the mass of the same after corrosion. There is no record of the way the coupons were identified but there are reasonable standard methods for doing so and because of the scale and importance of the whole project these are almost certain to have been followed. This indicates that errors are much less likely to have been made for mass loss, except that occasionally the total mass loss rather than the mass loss per side appears to have been reported [11].

For aluminium alloy AA1100 Figures 8–10 show the reported data for the maximum pit depths, for the 20 deepest pits, and for mass loss exposed for up to 16 years to seawater immersion, seawater midtide, and soft freshwater conditions [2]. Trend lines shown are drawn through the data using a standard smooth curve fitting routine employing the Stineman function [14]. The data in Figures 8 and 9 show obvious bimodal trends for all three data sets. In Figure 9 the data for maximum pit depth and for the 20 deepest pits at 8-year exposure appear to be considerably in error, for the reason noted above that it is extremely unlikely that maximum pit depths decrease in depth, even on different coupons, as much as is shown. However, there can be errors and natural variability in measurement, including that of establishing the original surface, as appears to have been the approach used [2]. For this reason these two data points were ignored in constructing the best-fit curves shown. Both of these are bimodal. In Figure 10 subjective interpretation of the pattern of the trend lines around the changeover from mode 1 to mode 2 is shown. However, the longer-term trend is not affected.

For aluminium alloy AA6061-T the data for marine immersion and for freshwater immersion show a clear bimodal trend even though the pit depths in the first few years for seawater immersion are very shallow (Figure 11). The trend for mass loss (×10) is shown for comparison. For midtide exposures the maximum pit depths were observed to be very shallow and showed considerable variability. These data and any trends are not considered herein. By comparison, pitting in soft freshwater is much more severe. Those data show a very clear set of bimodal trends (Figure 12).

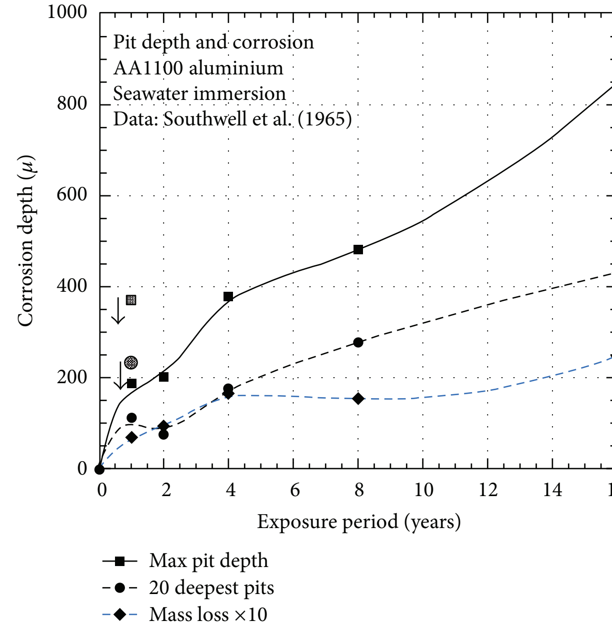

Figure 8: Data and fitted trends for AA1100 exposed to marine immersion conditions. The changeover to mode 2 occurs at about 3 years of exposure. Data from Southwell et al. [2].

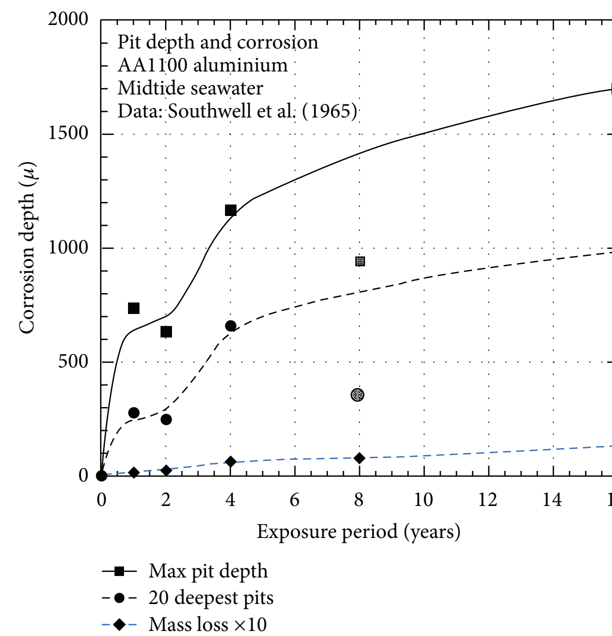

Figure 9: Data and fitted trends for AA1100 exposed to midtide marine conditions. The changeover to mode 2 occurs at about 3 years of exposure. Data from Southwell et al. [2].

Extensive data for maximum pit depth was reported by Godard et al. [16, 17] but only for observations at 1, 2, 5, and 10 years, which, for most data sets, is insufficient to show sufficiently discerning trends. The exceptions are a few data sets with quite deep pitting. A selection is shown in Figures 13 and 14 for different exposure trials with 6xxx series aluminium alloys. In both figures one of the data sets has been

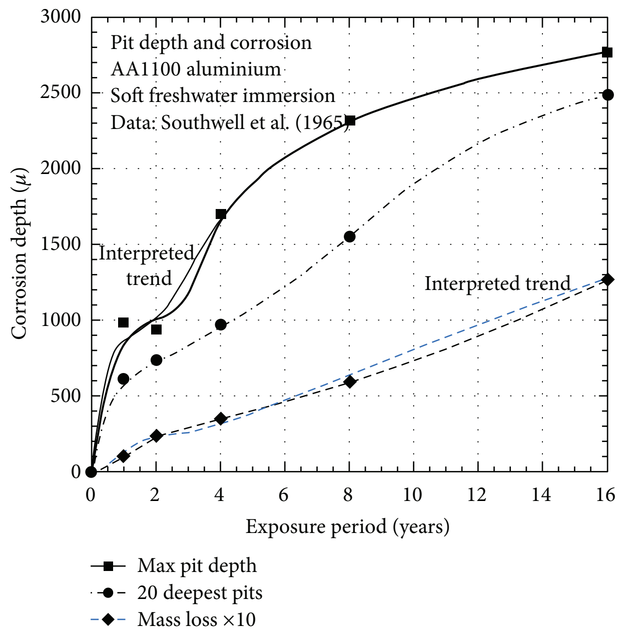

Figure 10: Data and fitted trends for AA1100 exposed to freshwater immersion conditions (Gatun Lake, PCZ). The changeover to mode 2 occurs at about 3 years of exposure. Data from Southwell et al. [2].

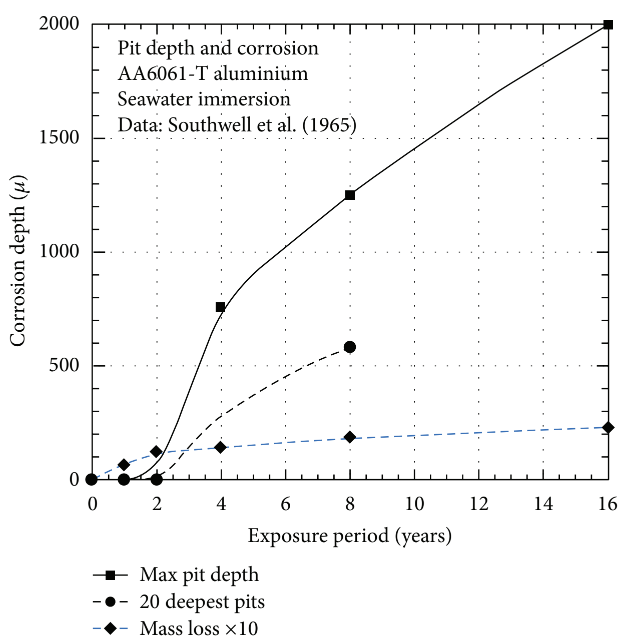

Figure 11: Data and fitted trends for AA6061-T exposed to seawater immersion conditions in the PCZ. The changeover to mode 2 occurs at about 3 years of exposure. Data from Southwell et al. [2].

interpreted as showing bimodal behaviour. The others show it directly when the data is fitted using the Stineman algorithm [14].

4. Accelerated Freshwater Exposures

As noted, aluminium alloys tend to be protected from corrosion by the aluminium oxide layer and therefore show little measurable pitting corrosion in atmospheric conditions. To counter this effect, Aziz and Godard [9] adopted a procedure in which the original oxide film was removed by immersion in 85% phosphoric acid for 2 minutes at 70°C, followed by 5 minutes of rinsing and then immediate immersion in slowly changing 25°C Kingston tap water for the duration of the test. Kingston tap water is "fairly hard" at about 127 ppm total hardness. After exposure the number of pits per unit area was counted using a low power microscope and the pit depths are estimated using the focusing technique. A typical set of results is shown in Figure 15. Only the trend for the 1.25%wt Mn alloyed material has been interpreted, slightly, as shown with the bold broken line. The other trends were obtained using the Stineman algorithm [14]. It shows that the changeover from mode 1 to mode 2 occurs after about 3-4 months, a shorter time than observed for the cases shown above.

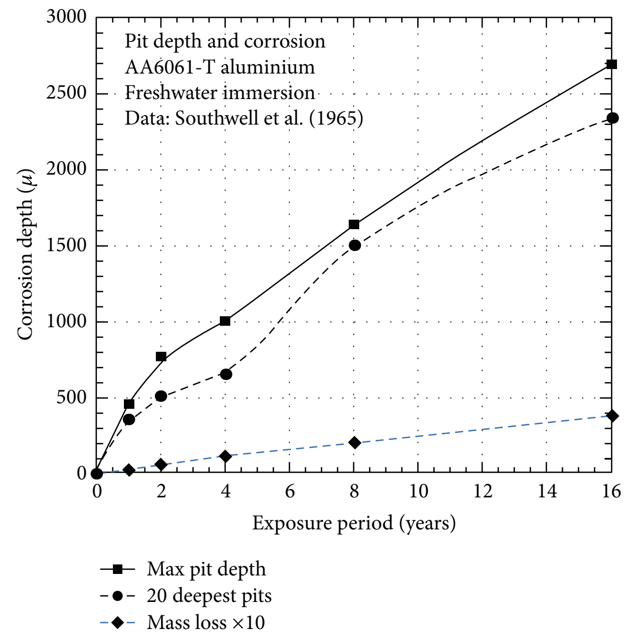

Figure 12: Data and fitted trends for AA6061-T exposed to freshwater immersion conditions (Gatun Lake, PCZ). The changeover to mode 2 occurs at around 4 years of exposure. Data from Southwell et al. [2].

5. Discussion

Despite the wide variation in the sources from which the above data were obtained and the wide variation in exposure conditions, the data and trends obtained for them provide strong evidence that pitting of aluminium alloys follows, for long-term exposures, the bimodal trend idealized in Figure 1. For short-term exposures, however, the very early part of the bimodal model, consisting of phases 0 and 1 in Figure 1, may be considered similar in trend development to the classical power law, provided that the period of exposure is much less than t_a. This can explain the claim, particularly for short-term laboratory and other short-term experiments, that aluminium alloy pit depth data are consistent with

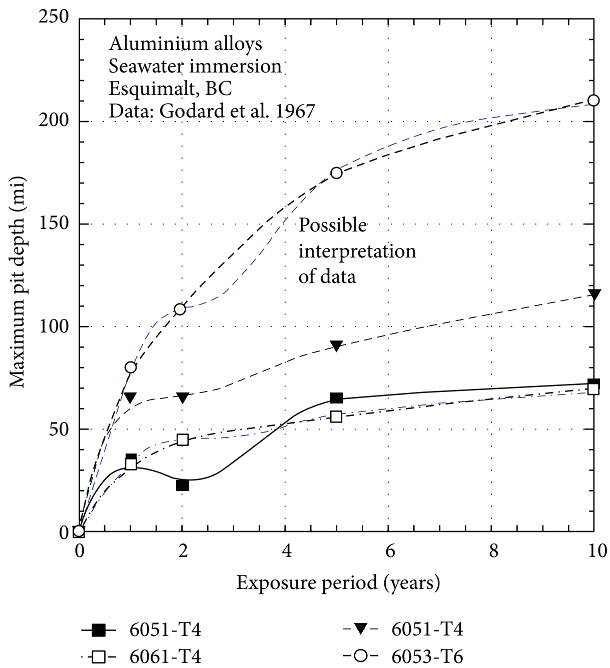

Figure 13: Data and fitted trends for several 6xxx series aluminium alloys exposed to seawater immersion conditions at Esquimalt, BC, Canada. The changeover to mode 2 occurs at around 2-3 years of exposure. Data from Godard et al. [16].

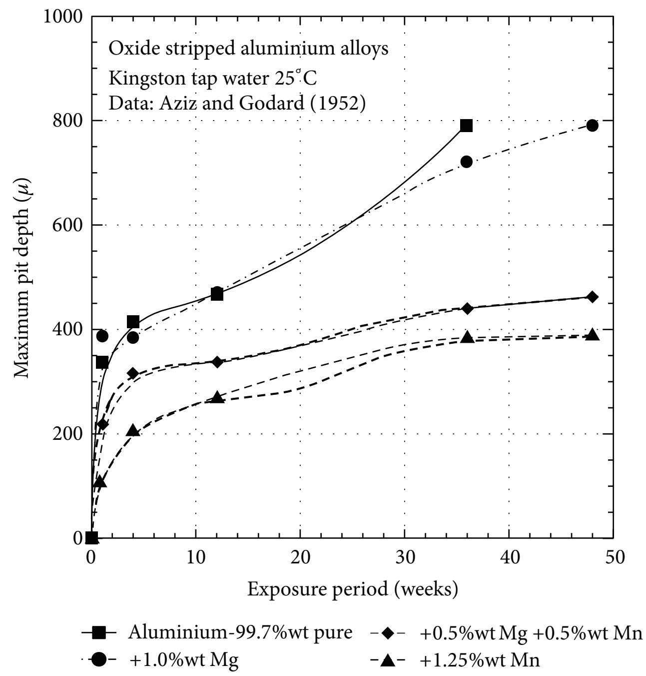

Figure 15: Maximum pit depth trends for low alloy aluminium alloys with oxide stripped off prior to exposure in hard freshwater. Note: horizontal axis is weeks (data from Aziz and Godard [9]).

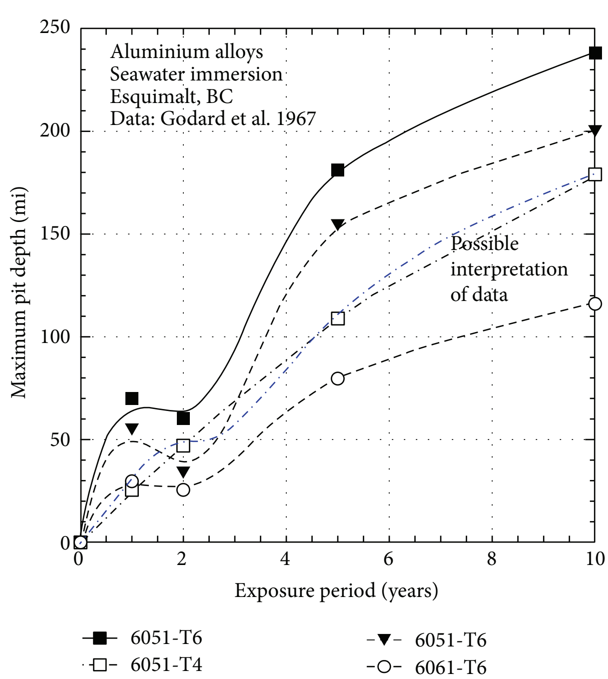

Figure 14: Data and fitted trends for several 6xxx series aluminium alloys exposed to seawater immersion conditions at Esquimalt, BC, Canada. These are different sets of data to those in Figure 13. The changeover to mode 2 occurs at around 2-3 years of exposure. Data from Godard et al. [16].

the power law (e.g., [18]). The power law can be derived mathematically (and with some simplifications) from considering the buildup of corrosion product and its effect in reducing access of oxygen to the corroding interfaces [11]. This applies to phase 2 in Figure 1, but the earlier phases (0-1) are governed by different mechanisms and the power law can be considered only an approximation for them. This was recognized earlier [10] and also is recognized in the division of the different corrosion mechanisms by phases (0–2) in the bimodal model. However, the bimodal model also recognizes that eventually the buildup of corrosion products can cause further changes in the governing corrosion mechanisms, represented by the corrosion process entering into phase 3, at the commencement of the second mode. For steels the mechanisms for this have been discussed [12] and are likely to be similar to aluminium alloys. In both cases eventually the corrosion processes develop into phase 4, representing long-term, steady state corrosion. The latter is clear in observations for long-term corrosion (e.g., [2]).

It has been proposed [12] that the electrochemical mechanisms operating in the early part of phase 3 of the model (Figure 1) are similar to those involved in the autocatalytic, low pH process for crevice and pitting corrosion and follow mechanisms first proposed by Wranglen both for steel [19] and for aluminium [20]. This requires an aggressive ion, for steel usually either chlorides or sulfides or both [21], even though neither need play a direct role in the chemical reactions. They provide the potential drop that governs the depth of the crevice or pit. This has support in computational modelling and has been calibrated against actual laboratory studies [22, 23]. However, the proposal for its application to longer-term pitting corrosion and to describe the development of the bimodal model (Figure 4) is recent [12].

For aluminium alloys the development of the bimodal trend can be related directly to the relevant corrosion reactions. On first exposure to the atmosphere aluminium quickly develops a thin, compact, and highly corrosion resistant oxide (passive) film. It consists, at ambient temperatures, mainly of γ-alumina and quickly hydrolyses, in the presence of water or moisture, to a thin (2-3 nm) layer of boehmite and other oxides in a complex mix of corrosion products. When chlorides are present the corrosion products also may include $AlCl_3$, $Al(OH)Cl_2$, and $Al(OH)_2Cl$. These have all been identified in practice and are considered to be associated with highly acidic solutions. This immediately suggests pitting as the principal form of corrosion for aluminium, as indeed commonly is observed [3, 10]. The topography of the corroding surface becomes, at the microlevel, increasingly more nonuniform and more nonhomogenous as corrosion progresses. As a result, the built-up thickness and properties of corrosion product also become increasingly more nonuniform and nonhomogenous. Localized regions with very low oxygen concentration levels may then develop, along with differential aeration cells being established over the corroding surface. Superficially these will be randomly distributed. This also establishes conditions sufficient for the initiation and progression of crevice and pitting corrosion under anoxic conditions [24]. Together, these may be considered the scenario applicable to corrosion at time $t < t_a$ in Figure 1. Further corrosion is likely to occur predominantly under localized anoxic conditions, with the cathodic reaction changing to the dissociation of water. In turn this will cause the release of gaseous hydrogen, earlier proposed as being, initially at least, the corrosion rate controlling reaction [12, 20]. It is consistent with reports of hydrogen evolution from pits in aluminium and being identified as from the pitting process as opposed to other possibilities [25]. This change in corrosion behaviour accounts for the step change in corrosion rate as the corrosion processes change from mode 1 to mode 2 at time t_a (Figure 1).

Hydrogen evolution is very unlikely to remain the rate limiting step for any extended time period since its effusion is fast, owing to its small molecular size and soon other, larger molecular corrosion products can be expected to be limited by their rate effusion. It is likely that the outward effusion and perhaps eventual diffusion of a soluble aluminium corrosion product such as $AlCl_2$ will become rate limiting. However, this proposition, as well as some of the other aspects of the above, remains for detailed investigation.

More generally, the cases given herein for aluminium alloys show that the conventional assumption of the applicability of the power law is limited in validity to very short exposure periods or as only a considerable approximation to long-term pitting corrosion. They all show the power law or any other unimodal function does not accord with the available evidence, closely and carefully examined. This observation has important implications in practice for extrapolating and prediction. This can be illustrated using the data for immersion exposure of AA1100 in freshwater (Figure 10). Using the same data and trends as in Figure 10,

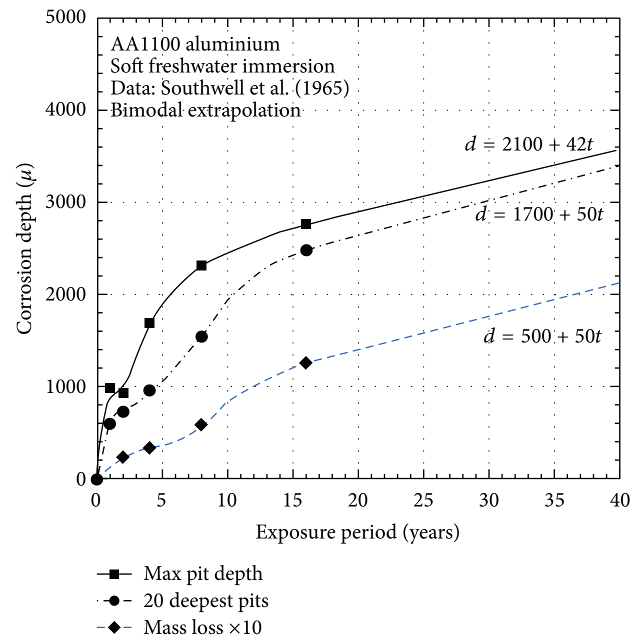

Figure 16: Data and trends for AA1100 in freshwater shown in Figure 10 with the trend curves extrapolated to 40 years, based on the tangent at 16 years and the long-term trend consistent with Figure 1.

the trend curves extrapolated to 40 years are shown in Figure 16. In contrast, Figure 17 shows the power law fitted to the complete data set for 16 years and extrapolated to 40 years. As expected, there are some differences between the pit depths and corrosion at 40 years, but they are not large. In part this can be attributed to the power law being dominated by the trend in the longer-term data. The situation changes if the data base is shorter. This is shown by the power law pitted to the data for 0–8 years only and extrapolated (Figure 18). The calibration constants A and B are considerably different from those in Figure 17. The extrapolated trends also are very different.

For engineering applications it is likely that the differences in the extrapolations of maximum pit depth and average pit depth shown in Figures 16–18 are important. Comparison of the trends in Figures 17 and 18 raises the important issue of the length of data required to obtain reasonable estimates. In a different way this also arises from Figure 16 since the accuracy of the long-term trend depends much on the data for phase 4 of the bimodal model (Figure 1). For the power law and for the bimodal function short-term data has small value in development of long-term trends. However, there is an important difference in the philosophy underlying the bimodal function. The bimodal model divorces the corrosion mechanisms and processes that occur soon after corrosion commences from those that govern longer-term behaviour. This immediately draws attention to the likelihood that parameters and influences relevant to corrosion in the early stages (modes 0-1) are different from those relevant to longer-term corrosion. This in itself may explain some of the difficulties of correlating many of

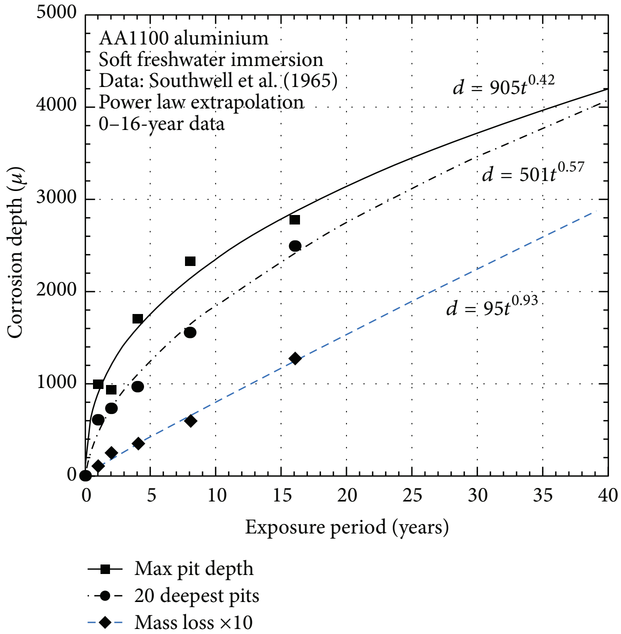

Figure 17: Data for AA1100 in freshwater shown in Figure 10 with a power law fitted to data for 0–16 years extrapolated to 40 years. The expressions for each fitted power law function are shown.

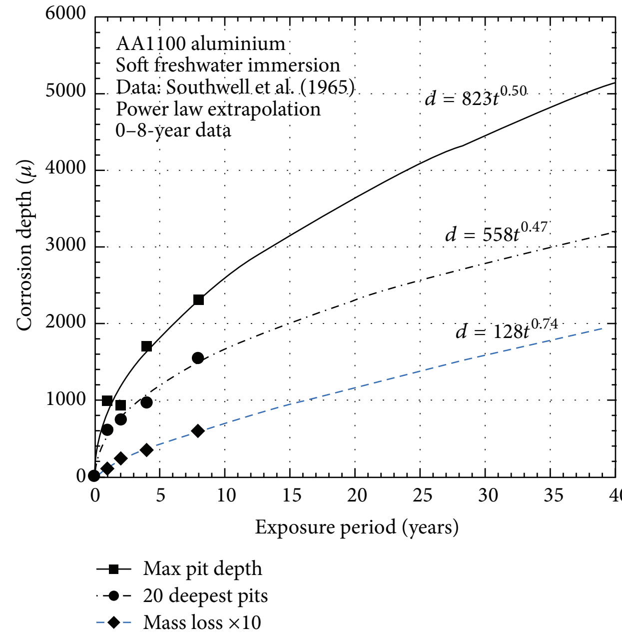

Figure 18: Data for AA1100 in freshwater shown in Figure 10 with a power law fitted to data for only the period 0–8 years and then extrapolated to 40 years. The expressions for each fitted power law function are shown. Note change in vertical axis compared with Figures 16 and 17.

the conventional influences for corrosion identified in laboratory (electrochemical) experiments with actual field experience (e.g., [26]).

For steel it is possible that part of the reason for the bimodal characteristic corrosion is the influence of microbiologically influenced corrosion (MIC), particularly in phases 3 and 4 [12]. However, this is unlikely to be the case for aluminium alloys since, apart from some specialized cases involving algae, microbiological corrosion of aluminium appears not to have been observed [4, 27, 28]. Clearly, a number of aspects arise from these observations that require further investigation.

6. Conclusion

This study of the progression with time of the maximum depth of corrosion pits for aluminium alloys has drawn on pit depth measurements obtained in a number of independent studies for a variety of exposure conditions and for a number of different aluminium alloys. The following conclusions may be drawn:

(1) The empirical data shows that the long-term trend for the maximum pit depth caused by corrosion of aluminium is more consistent with a bimodal function than with the classical power law function. This was demonstrated for cases of aluminium alloys exposed to seawater and freshwater immersion and also for exposures to marine, industrial, urban, and combined environments.

(2) The bimodal behaviour is consistent with the buildup of corrosion products causing changes in the corrosion process from one initially governed by oxygen reduction to one controlled later initially by hydrogen ion reduction. The mechanisms involved are consistent with well-established theory for the corrosion of aluminium including pitting corrosion. The eventual long-term corrosion rate is likely rate-controlled by other processes, such as steady state metal ion diffusion. The available evidence supports long-term corrosion being modelled as a linear function.

(3) The bimodal behaviour indicates that the set of parameters controlling short-term or laboratory observations is not the set of parameters governing long-term corrosion. It is demonstrated that this may have implications for the ability to predict longer-term corrosion behaviour from shorter-term test results.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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