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A Simplified Maximum Pit Depth Model of Mild and Low Alloy Steels in Marine Immersion Environments

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Abstract: For mild and low-alloy structural steels under marine immersion conditions, the main influencing factors and the specific process of pitting corrosion were summarized in this paper.Based on the corresponding pitting corrosion mechanics and Melchers' pitting corrosion model, a simplified maximum pit depth model is proposed, which will be more concisely to predict the statistical characteristics of maximum macro-pit depth.Then the new model is applied to the analysis of various corrosion gauge data from some long term field investigations in China.Comparing with other pitting corrosion models,it is more reasonable to describe the maximum pit-depth curve of mild and low-alloy steels in marine immersion conditions as a Weibull function of exposure periods. Furthermore, the potential influences of some seawater environmental factors on model parameters are discussed,including seawater temperature, dissolved oxygen, salinity, PH, etc. Since the variations in the composition contents of mild and low-alloy steels will also make a full impact on maximum pit depth,comparative analyses of the effect of steel composition contents on pit depth and the model parameters are also carried out.

Key words: mild steel; low alloy steel; marine; immersion environments; pitting corrosion; corrosion model; maximum pit depth
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1 Introduction

Corrosion is one of the main reasons which causes structure failure and damage under marine environments.Several research programs have identified corrosion and fatigue as weakening the structures of aged bulk carriers[1-3]. Statistics for ship hulls show that around 90% of ship failures are attributed to corrosion, including corrosion fatigue[4]. It will be improperly to analyze the hull structure reliability within the life cycle without considering the weakening of mechanical properties caused by corrosion.

Due to the worldwide casualties of aging vessels during the last decade,the safety assessment of hull structures subjected to corrosion and fatigue has been of increasing interest since the 1990s.

Corrosion wastage in structure elements can reduce their ultimate strength. It is generally

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thought that the decline of structure ultimate strength caused by general corrosion (loss of thickness or "wastage") is more important. For general corrosion, which uniformly reduces plate thickness,the calculations of plate ultimate strength are typically carried out excluding the thickness loss due to corrosion.In most of the studies on time-dependent reliability of ship structures the effect of corrosion was represented by a linear or non-linear decrease of plate thickness with time (e.g. Refs.5-10).

For modern mild and low-alloy steels in marine immersion environment,pitting is only seldom a design-critical issue[11]. In part, this may reflect the fact that it has very little influence on the strength of reasonably well-maintained structures, such as ships.

However,according to some pitting observations for recent corrosion tests on mild steel coupons under saline immersion conditions, significant macro-pitting has been reported within one year of exposure[11]. In principle, serious pitting can cause perforation and this can be critical in containment situations, such as for ship tanks, sub sea pipelines, etc. Moreover, some scholars argue that the ultimate strength of plate element can be significantly decreased due to pitting corrosion as well as general corrosion[12].

Accordingly,the focus of the reliability analysis of ship structures considering marine corrosion has directed from the general corrosion to localized corrosion, especially, the pitting corrosion[13].

For pitting corrosion, the strength calculation procedure will be more complex, and for a simplified pessimistic treatment,the corroded plates have been idealized using an equivalent general corrosion. However, this method is not always relevant since it is not straightforward to define the "equivalent general corrosion thickness" properly.

The effect of pitting geometric parameters on ultimate strength of pitting structures, such as: pit depth, pit diameter, pit shape, etc., may change with loading condition of structure members.Extensive studies of the ultimate strength of plate element have been presented by Paik et al[12,14]. It was observed that the ultimate strength of a pitted plate element under axial compressive loads was governed by the smallest cross-sectional area, i.e., the most corroded (pitted) plate section of the plate[14]. In contrast, it has been realized that the ultimate strength of a plate element with pit corrosion and under edge shear is governed by the DOP (degree of pit corrosion intensity)[12].A serious of tensile/compressive buckling tests has been taken by Yamamoto[15] to investigate the effect of pitting corrosion on tensile strength/buckling behavior of hold frames of bulk carriers.It was pointed out that the reduction of the tensile strength of the members with pitting corrosion was larger than that of members with uniform thickness loss in terms of average thickness loss; while the compressive buckling strength of pitted members was smaller than or equal to that of members with uniform thickness loss in terms of average thickness loss.

Currently,there is still much controversy existing in the causes and the growth mechanism of pitting corrosion. In addition, there is also an extreme lack of detailed, integrated pitting database.So,the highest priority of the future work of the reliability analysis of ship structures considering corrosion may be developing the reasonable pitting corrosion model which can predict the statistical characteristics of corrosion wastage and can be expediently used in the reliability evaluations of ship structures[13].

Because of the practical significance above mentioned, the primary objective of the present paper is to develop a time-dependent model for the maximum pit depth of mild and low-alloy steels under marine immersion conditions,based on the fundamental corrosion mechanisms and various pitting gauge data from some long term field investigations in China.

As mentioned in the earlier studies, the environmental factors of seawater, including average temperature, dissolved oxygen, salinity, PH, have some potential influences on pitting corrosion behavior. The corresponding discussion is also given in this paper.

Furthermore,small changes in the composition of mild and low alloy steels can affect their immersion corrosion behavior[16]. It can be expected that the metal composition will make a full impact on maximum pit depth, too. Comparative analysis of the effect of steel composition contents on pit depth and the model parameters are reported.

2 Review of previous studies

2.1 Traditional model

The growth of pits with time is often represented by a relationship,typically the power function[11,23]:

$$d(t)=C_1\cdot(t-t_i)^{C_2} \qquad t\geq t_i \tag{1}$$

where $d(t)$ is the pit depth, t is the exposure periods, t_i is the time to pit initiation, C_1 and C_2 are constants obtained from curve fitting Eq.(1) to the experimental pitting data.

The validity of this traditional model has been proved by laboratory observations and short term seawater immersion tests. However, it is unaccepted to infer metal corrosion law of long exposed cycle by laboratory observations or short term seawater immersion tests.Melchers indicated that long term pitting behavior appears to be associated with anaerobic conditions and is therefore not well represented by models of the type $C_1\cdot t^{C_2}$ which are commonly fitted to short-term observations[11]. For realistic risk assessments the traditional model based on short-term laboratory observations is of limited use[17].

2.2 Linear model

Paik et al[18] considered all longitudinal strength members from a database of thickness measurements consisting of 7 503 data points from 44 bulk carriers. By statistical analysis, a linear corrosion model is derived, namely

$$t_r=c_1(T-T_c) \qquad T\geq T_c \tag{2}$$

where t_r is corrosion depth in mm; T is the age of vessel in years; T_c is the life of coating in years, usually assumed to follow a log-normal distribution[19,20]; coefficient C_1 is in part indicative of the annual corrosion rate in mm/year.The probability density function of C_1 is considered to follow a Weibull distribution.

Because the corrosion wastage measurements above mentioned have been collected for both types of corrosion, Paik believes that the linear model (2) is suitable for localized corrosion as well as general corrosion[20].

2.3 Melchers' model

According to field observations of mild and low alloy steels under marine immersion conditions from a range of international sources, Melchers[11] developed a time-dependent model for maximum depth of pitting based on the multi-phase phenomenological model[21] of general corrosion (weigth loss).

It represents pitting corrosion under marine immersion as consisting of a number of successive phases.Fig.1 shows that model to account for the observations of micro-pitting in Phases 0 and 1 and macro-pitting since Phase 2.

Phase 0 represents the effect of very short-term behavior due to water velocity and surface finish effects. Phase 1 is the "kinetic" phase in which corrosion is primarily under "concentration control," which is limited by the rate of oxygen diffusion through the water adjacent to the corroding surface.Corrosion in Phase 2 is controlled by the rate of oxygen supply through the increasing thickness of the corrosion product.Phases 3 and 4 describe periods of rapid and approximately steady-state corrosion, respectively, both under predominantly anaerobic conditions. Their precise mechanics is not fully understood but they are consistent with long-term corrosion data[11].

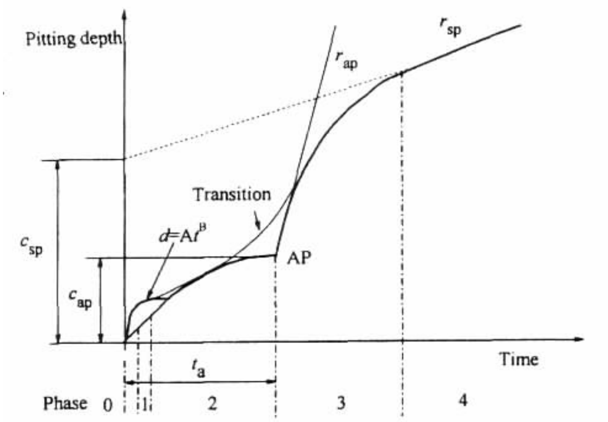


Fig.1 Phenomenological pit depth-exposure time model and its parameterization[11,22]

This new interpretation of pit depth as a multiphase function of time is based on a representation of fundamental corrosion mechanisms. The various test result, obtained from a variety of sources, showed that the multiphase model is appropriate for longer exposure periods in seawater immersion conditions, at least for mild and low alloy steels[11].

However, the model includes a number of phases, while each phase has its own different parameters. It will be difficult to ascertain those parameters respectively in engineering application. Therefore, there are still some difficulties and inconvenience to apply this model to reliability analysis of ship structures directly.

3 The new time-dependent model of pit depth

3.1 Pitting process of mild steel

The maximum pit depth of mild steel coupons (carbon content 0.052%) under saline immersion conditions are shown in Fig.2[11].The coupons were commenced on November 4, 1997 and May 3, 1999 individually,at Taylors Beach, Australia. In both cases, the coupons were 100mm by 50mm by 3mm thick and were prepared,recovered, cleaned, and weighed to ASTM corrosion testing standards G1 and G52[11]. It provides observations for micro-pitting at monthly exposure intervals and an overview of whole corrosion behaviors of mild steel under long time exposure.

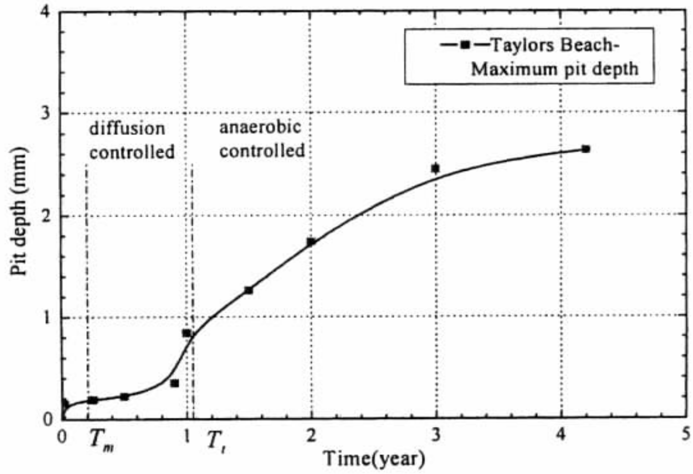


Fig.2 Maximum pit depth of coupons exposed at Taylors Beach, Australia[11]

Combining the observations above mentioned and basic pitting mechanisims, the pitting process of mild steel under immersion conditions can be summarized and inferred as follows:

Laboratory experiments with normal carbon steels show that micro-pits of only a few microns in size appears to form immediately after immersion, and quickly reach 100 microns to 200 microns in diameter with similar depths[23].During the short initial period corresponding to "activation controlled" corrosion, the corrosion loss-time behavior is highly non-linear[24].

It is generally thought that pitting of mild steel under saline immersion conditions tends to be initiated at sulfide inclusions, principally manganese sulfide inclusions.The areas immediately adjacent to the sulfide inclusions become anodic and thus subject to attack. After minutes to hours of exposure,the sulfide inclusions tend to become undermined and fall away. The associated micro-pit then grows at a much reduced rate[23].

The process of pitting corrosion then comes into the "diffusion controlled" phase which is controlled by the rate of oxygen supply through the increasing thickness of the corrosion product.For the increasing of the area exposed to corrosive medium, pits grow smoothly with enhancing corrosive rate. While the growth of corrosion rate decrease gradually.

The pitting corrosion enters into the "anaerobic controlled" phase after the corrosion rate reaches its maximum.This phase describes the period of approximately steady state corrosion with declining corrosion rate under predominantly anaerobic conditions.

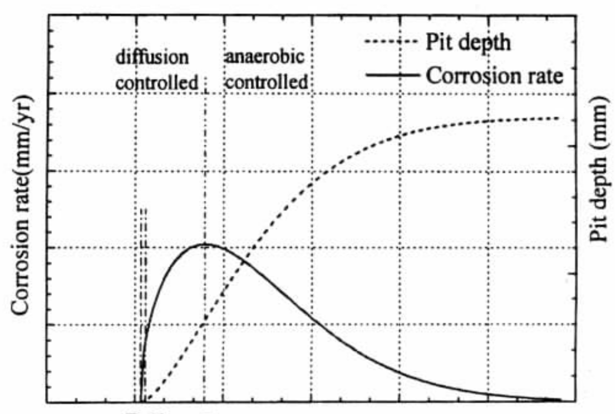


Fig.3 The time-dependent model of pit-depth and pitting-corrosion rate

In sum,the whole pitting corrosion under marine immersion conditions can be roughly divided into three phases, as below:

(1) No corrosion, $t\in[0, T_i]$;

(2) The formation and growth of micro-pits, $t\in[T_i, T_m]$. In this phase, the pitting corrosion behavior is highly non-linear, the corrosion rate increases and decreases drastically;

(3) The formation and development of macro-pits, $t\in[T_m, T_l]$. The phase of pits growing steadily can be further divided into two stages: the corrosion accelerating, $t\in[T_m, T_t]$ and the corrosion decelerating, $t\in[T_t, T_l]$.

Where T_i is the time of micro-pits emerged; T_m is the time of macro-pits generally formed; T_t is the transition moment of corrosion-rate trend; T_l is the life of structure or the time at which repair and maintenance takes place.

The time-dependent model of pit-depth and pitting-corrosion rate is shown in Fig.3.

3.2 The mathematical model of maximum pit depth

For simplicity,a Weibull function is adopted to describe the growth of macro-pits with exposure time, namely

$$d(t)=d_m\{1-\exp[-[\alpha(t-T_i)]^m]\} \tag{3}$$

The corresponding pitting corrosion rate is also given here:

$$\dot{d}(t)=d_m\cdot m\alpha^m(t-T_i)^{m-1}\exp\{-[\alpha(t-T_i)]^m\} \tag{4}$$

where T_i, d_m, α, m are model parameters to be determined.

The deficiency existed in traditional model is that the corrosion rate exists a sudden jump at the initial time and then declining monotonically. The existed models aforementioned are unable to reflect the acceleration and deceleration stages of the pits depth growth,and inconsistencies with pitting observations of some corrosion tests on steel coupons under immersion conditions.

But the new Weibull function model can fully reflect the special processes while $m>1$. The corrosion rate reaches its maximum at $T_t=T_i+\sqrt[m]{(1-1/m)}/\alpha$.

The new model fitting for all maximum pit depth data of mild steel coupons at Taylors beach is shown in Fig.4a. Benefited from the fine fitting performance of Weibull function, the fitting effect for this data group is satisfactory, especially the macro-pits. But, the data point of micro-pits cannot be well described by this new model for the highly non-linear phenomena in this stage.

Strictly speaking, the new model is only suitable for the phase of macro-pits. Because of the non-linear particularity in the preliminary stage, it seems to be unrealistic to describe the entire pitting process by a single function.

For the assessment of time-dependent reliability of ship structures,it is essential to inspect the weakening of structural bearing capacity in the long term. Therefore, the influence of micro-pits may be neglected in the meaning of engineering practice.

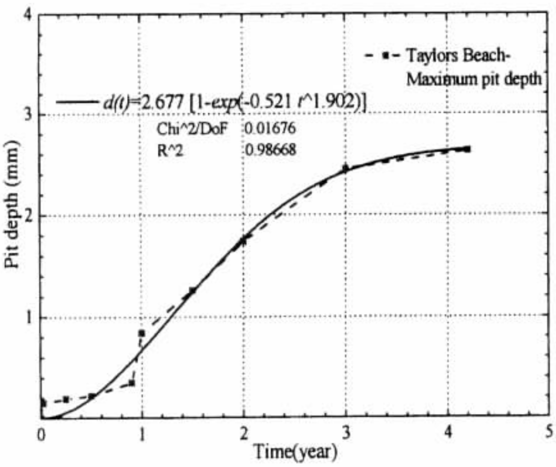


Fig.4a The new model fitting for all maximum pit depth data at Taylors beach, Australia

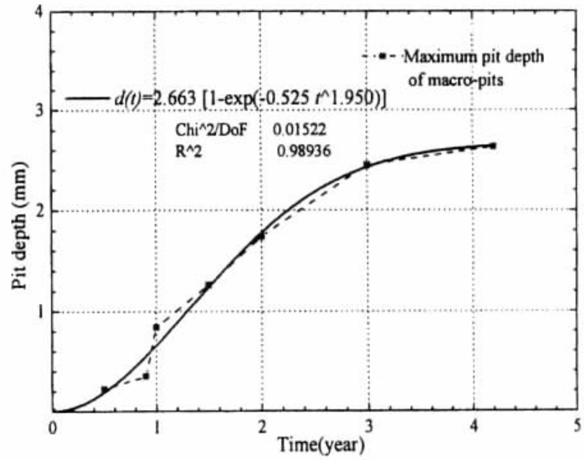


Fig.4b The new model fitting for maximum pit depth data of macro-pits at Taylors beach, Australia

Using the least-squares method, the regression analysis on the pit depth of macro-pits is given in Fig.4b. Compared to Fig.4a, the fitted value of model parameters and the corresponding correlation coefficient R^2, chi-square test of goodness of fit are extremely close. The corrosion rate transition time T_t are 1.297 year, 1.317 year respectively, with the corresponding depth in 1.010mm, 1.027mm. While the extreme value of corrosion rate are 1.159mm/yr and 1.180mm/yr respectively. All the errors are less than 1.5%.

Therefore, the above mentioned deficiency of the new model does not affect its engineering applicability.

3.3 The model parameters analyses

For simplicity, a Weibull function is adopted to describe the growth of macro-pits with exposure time. The influence of parameters d_m, α, m on the new pitting corrosion model is shown in Fig.5a, 5b, 5c respectively.

T_i is the position parameter, which means the time pits emerged. For the carbon steel

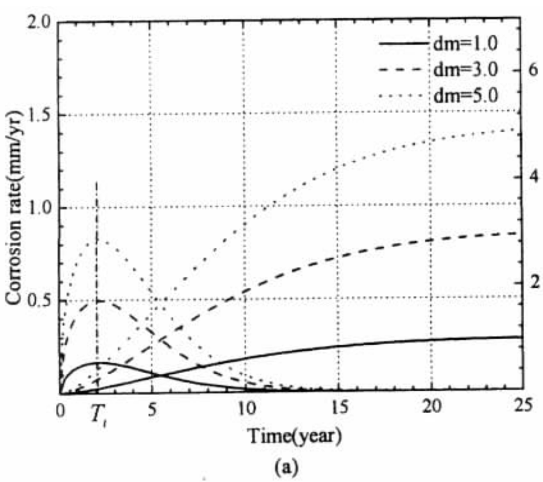


Fig.5a Influence of the long-term corrosion pit depth on the new pitting corrosion model

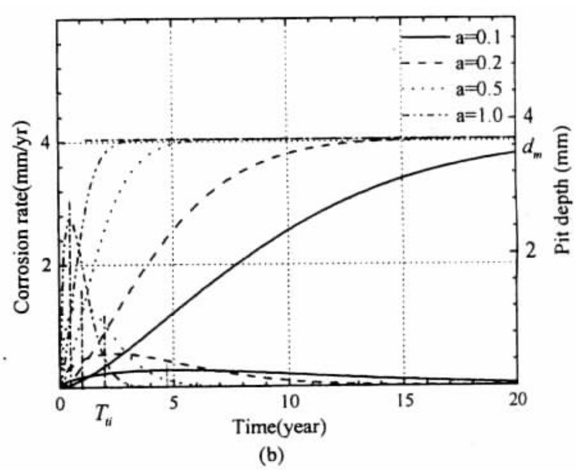


Fig.5b Influence of the scale parameter on the new pitting corrosion model

coupons without any CPS (Corrosion Protection system),it is reasonable to assume T_i =0 because of micro-pits appears to form immediately after immersion.d_m is the long-term depth of pits which attributes the medium and long-term anticorrosion performance of steels. α is the scale parameter, determines the model corrosion curve gradient,as well as the transformation time of corrosion-rate tendency (while m>1). m is the shape parameter which determines the trend of corrosion rate.When m>1.0, there is a period of corrosion acceleration and a period of corrosion moderating; when m<1.0, the corrosion rate is decreases monotonically.

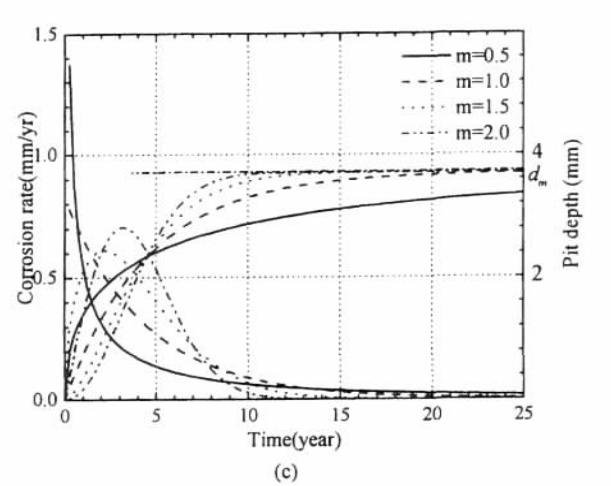


Fig.5c Influence of the shape parameter on the new pitting corrosion model

3.4 Comparison of the goodness of fit between several models

The max pit depth-exposure time curves of mild steel (A3), manganese steel (16Mn) and chromium steel (921) was given in Figs.6~8. Each date group was fitted by traditional model, linear model and the new Weibull model respectively.

The coupons were exposed under marine immersion conditions at Qingdao area,China; 200mm by 1 000mm by 6~8mm thick and were tested to China corrosion testing standards GB5776-86[25,26]. The main compositions of steels were listed in Tab.A1.

According to the correlation coefficient R^2 listed in Figs.6~8,the linear correlation degree is in turn the Weibull function model, the traditional model, the linear function model. The chi-square test proved that the Weibull function model has the higher fitting precision.

In the pitting observations for long-term exposition (>4 years) under marine immersion conditions, the pit depth of manganese steels and carbon steels are close, while chromium steel is deep than carbon steels[26]. The order of model parameter d_m in Figs.6~8 conforms to the observation.

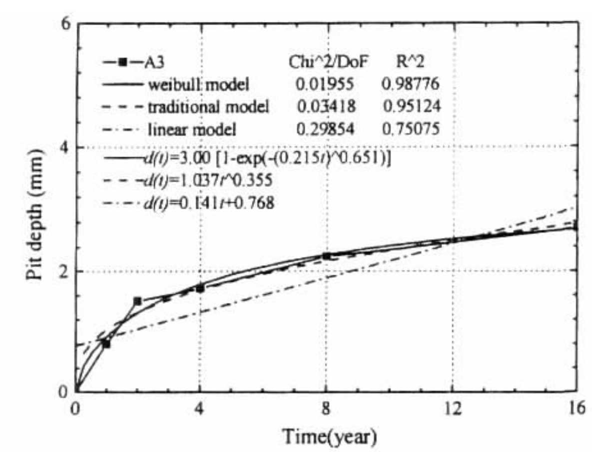


Fig.6 The max pit depth-exposure time curves of mild steel (A3) under marine immersion conditions at Qingdao, China

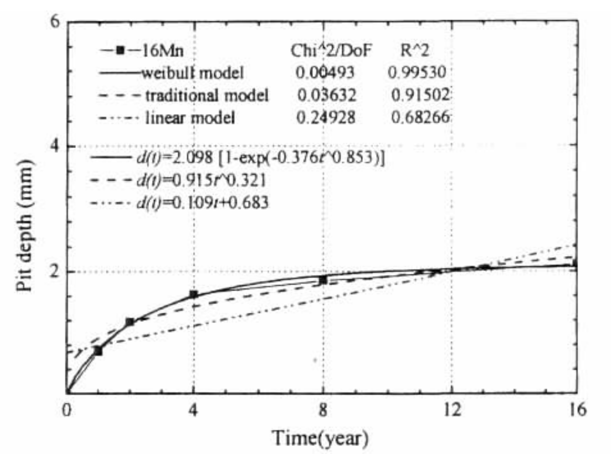


Fig.7 The max pit depth-exposure time curves of manganese steel (16Mn) under marine immersion conditions at Qingdao, China

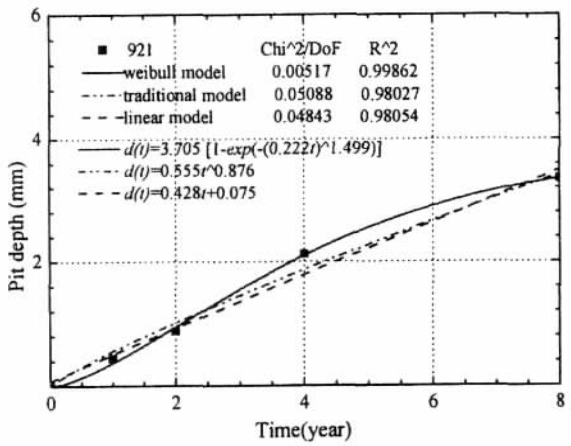


Fig.8 The max pit depth–exposure time curves of chromium steel (921) under marine immersion conditions at Qingdao, China

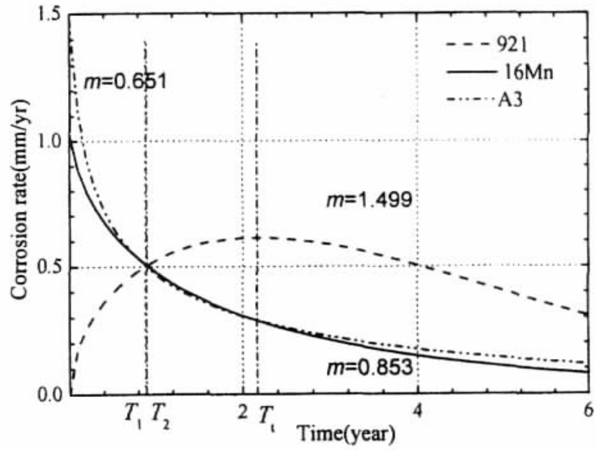


Fig.9 The corrosion rate curves of mild and low–alloy steels

Furthermore, the so-called "corrosion resistance reverse" of chromium steels can be reflected by the new model perfectly, as shown in Fig.9.

Based on the above discussions, it can be concluded that the new model has its superiority in the goodness of fit and the characterization of some special phenomenon existed in corrosion process.It will be more reasonable to describe the maximum pit-depth curve of mild and low-alloy steel in marine immersion conditions.

4 Effects of seawater environmental factors on model parameters

Some seawater environmental factors have the potential influences on corrosion behaviors including seawater temperature, dissolved oxygen, salinity, PH, etc.

The maximum pit depth of A3 steel exposed at Qingdao,Xiamen and Yulin areas under marine immersion conditions[27] are studied here through the least-square method, based on the proposed new model, as shown in Fig.10. The seawater environmental factors of each test area are listed in Tab.A2.

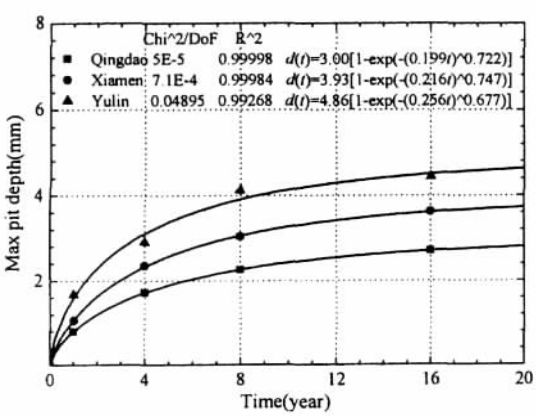


Fig.10 The max pit depth–exposure time curves of mild steel (A3) in full immersion zone at various test sites and the corresponding model parameters

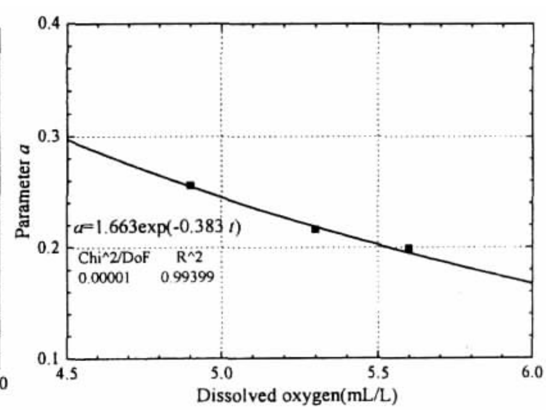


Fig.11 α as a function of seawater dissolved oxygen

4.1 Annual seawater dissolved oxygen

On carbon steels, as water dissolved oxygen concentration increased,the long- term depth of pits d_m and scale parameter α show a downward trend. Fig.11 shows α as an index function of seawater dissolved oxygen.

4.2 Annual average seawater temperature

With the increasing of annual average seawater temperature,d_m and α show an upward trend. The corresponding functions are listed in Fig.12a, 12b.

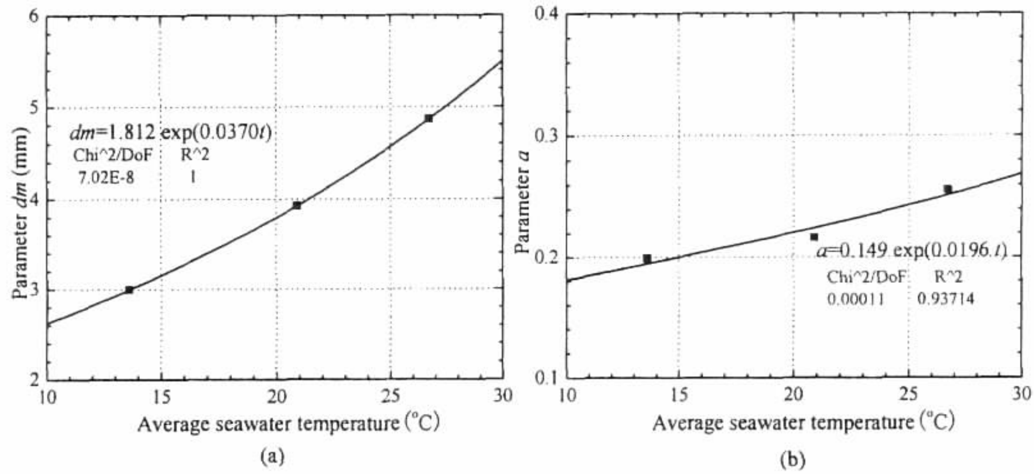


Fig.12 (a) The long-term pit depth d_m as a function of average seawater temperature (b) The scale parameter α as a function of average mean seawater temperature

4.3 Other factors

According to Fig.10 and Tab.A2,the long- term depth of pits d_m and scale parameter α are in direct proportion to the PH value of seawater while the shape parameter is in inverse proportion to seawater salinity.

5 Effects of steel compositions on model parameters

Similar to the external environmental conditions, the variations in the composition contents will make a full impact on the corrosion behavior of mild and low- alloy steels under saline immersion conditions also. Therefore, it is necessary to make a comparative analysis of the effect of steel- composition contents on pit depth and the model parameters,with the attempt to found the main influencing elements and their respective effects.

Fig.13 shows the maximum pit depth of several mild steels coupons under saline immersion conditions exposed at Qingdao, China[25,26]. And each data groups are fitted by the new Weibull model respectively.The corresponding fitted model parameters were listed in Fig.13, too. The main compositions of steels were listed in Tab.A1.

To study the sensitivity of the variations in the composition contents,the multiple linear regression analysis of the fitted model parameters shown in Fig.13 is given here:

$$Y=B_0+B_1 X_1+B_2 X_2+\cdots+B_k X_k \quad (5)$$

where Y is the corrosion model parameter; X_i (i=1,k) are the composition contents of steels (wt%); B_i(i=1,k) are the regression coefficients, shown in Tab.1.

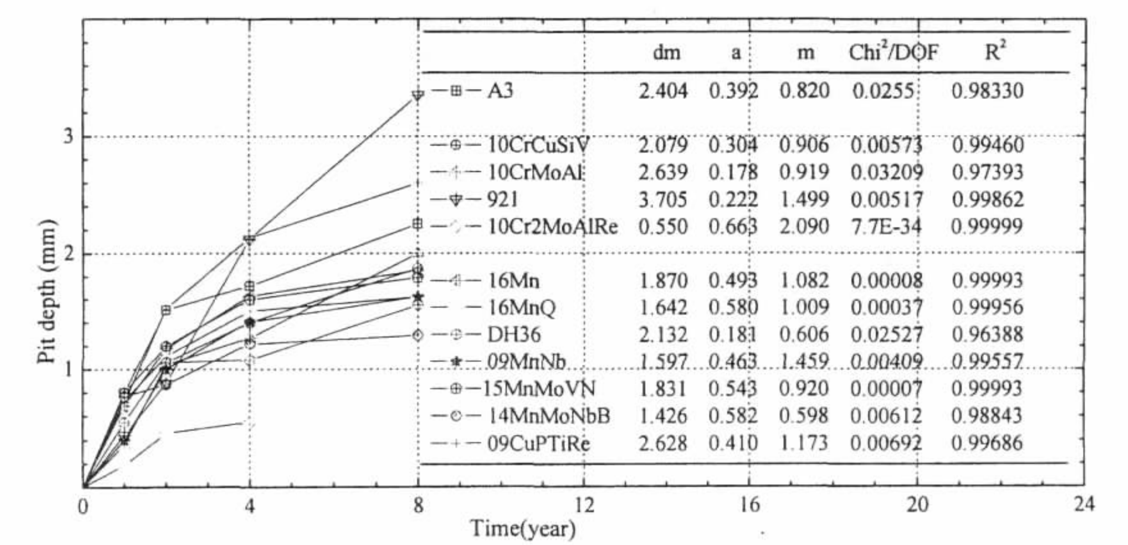


Fig.13 Maximum pit depth of coupons exposed at Qingdao, China and the corresponding fitted results

Tab.1 The multivariate linear regression coefficients of alloying elements with the model parameters

	Regression parameters									
	B_0	B_C	B_{Mn}	B_{Cr}	B_S	B_{Mo}	B_P	B_{Si}	R-Square	F-Statistic
d_m	5.681	-7.991	-2.041	-1.420	55.468	1.305	-24.131	-1.674	0.862 79	3.593 05
α	-0.386	2.263	0.304	0.253	-4.951	-0.062	5.928	0.184	0.516 41	0.610 22
m	0.824	-2.383	0.189	0.551	14.860	-0.421	2.597	-0.133	0.720 91	1.476 07

As the external corrosion environment of tested coupons, such as water temperature, velocity, salinity, sea organisms, sediment, etc., basically the same, the difference between the model parameters of these steels can be seen from its variations in the composition contents.

The effects of carbon, sulfur, phosphorus and silicon, manganese, chromium, molybdenum, copper, aluminum, et al on model parameters are displayed in Fig.14 to Fig.19.

5.1 Carbon

Changes in the carbon content of mild and low alloy steel have a significant impact on its model parameters. With the increase in carbon content, the shape parameter m of the mild and low alloy steels with similar sulfur contents, show a downward trend, as shown in Fig.14c.

The effect of carbon content on the long-term depth of pits d_m is too complicated.If the effect of chromium was neglected,then d_m declines gradually with the increase in carbon content when S>0.01%, as shown in Fig.14a.

5.2 Sulfur

Sulfur content have a great impact on the model parameters of low-alloy steels,and which effect is very closely related to the level of carbon contents.

Fig.15a, 15b show the relationship between sulfur content and d_m, α, m respectively.

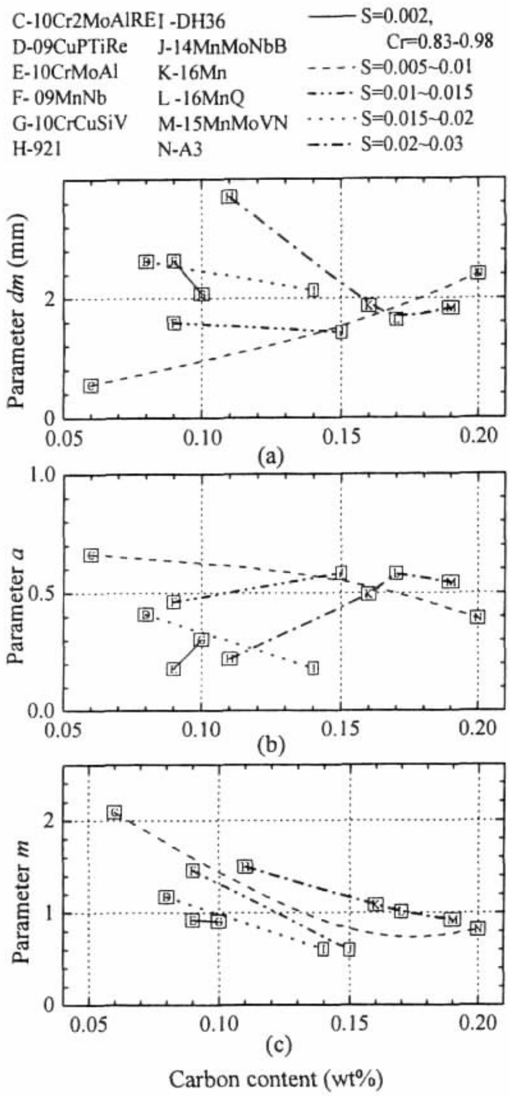


Fig.14 Effect of carbon content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

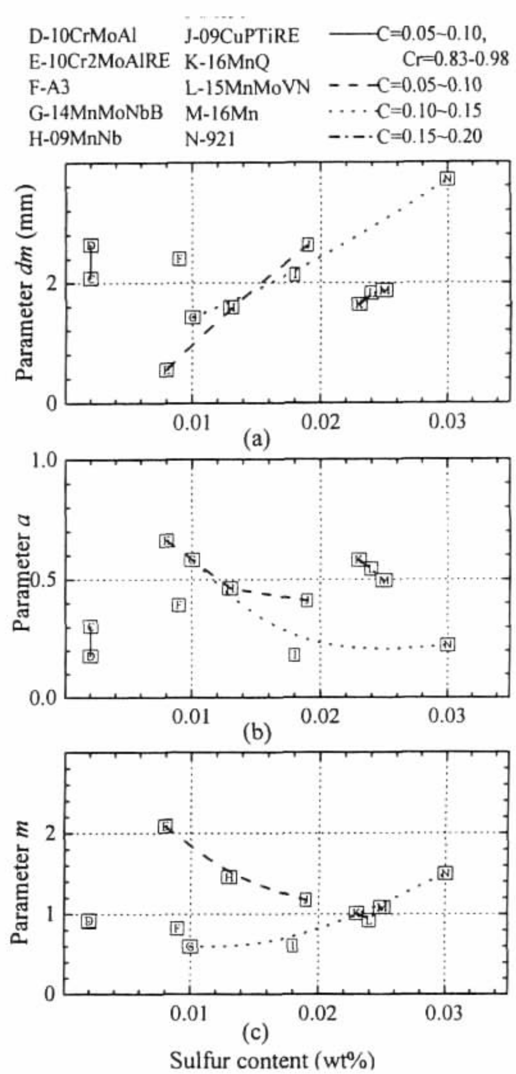


Fig.15 Effect of sulfur content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

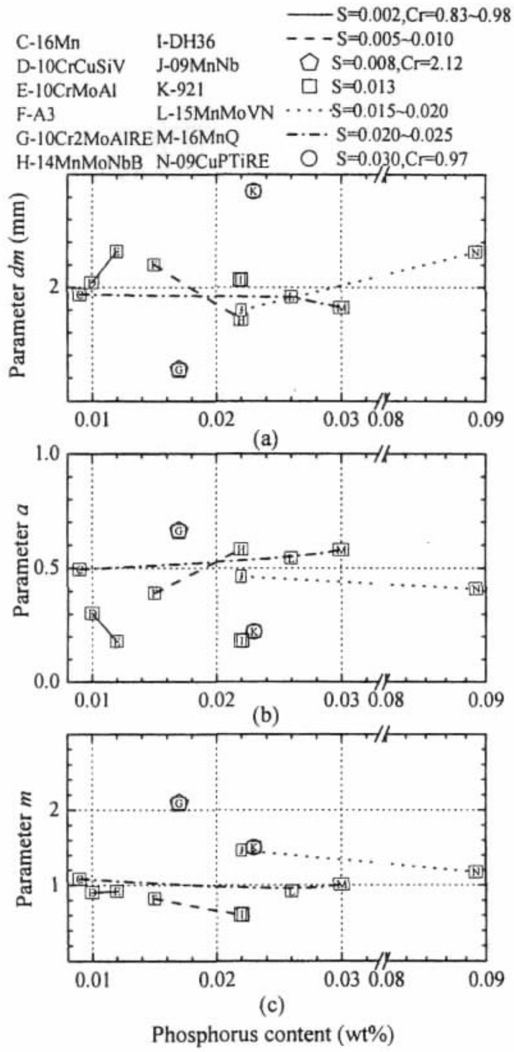
5.3 Phosphorus

Fig.16c suggests that the effect of phosphorus content on the shape parameter m may be negligible. Excluding the effect of chromium on it, m declines slightly with the increase in phosphorus content.

5.4 Silicon

The effects of silicon on model parameters seem to be minimal. Besides, the effects are closely related to the sulfur contents of steels.The model parameters change slightly with the variation of silicon content, while the sulfur content S<0.005%.

If one neglects the influences of manganese, molybdenum and nickel, d_m and the silicon content are in reverse proportion; When S<0.015%, m is directly proportional to silicon content approximately; S>0.015%, inversely proportion. As indicated in Fig.17a, Fig.17c.



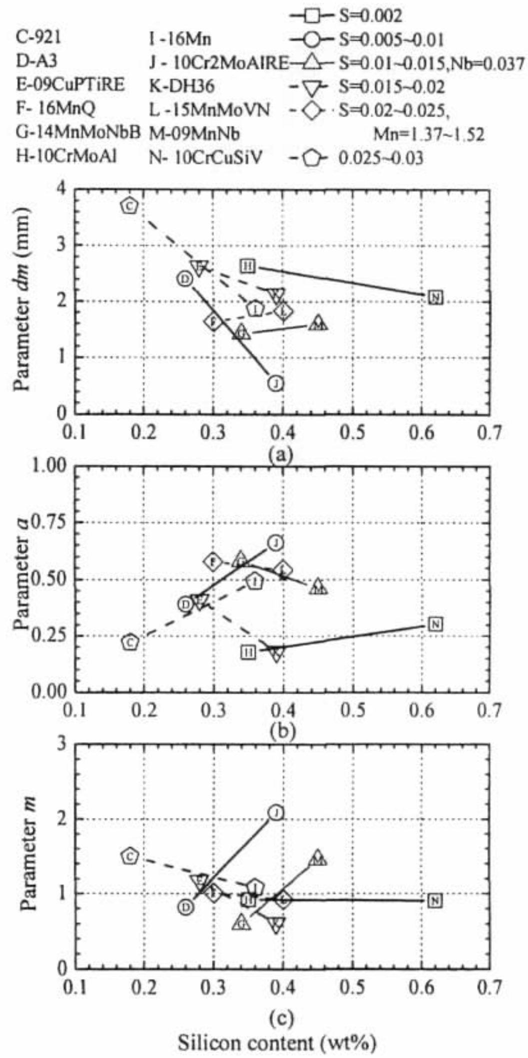


Fig.16 Effect of phosphorous content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

Fig.17 Effect of silicon content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

5.5 Manganese

As previously noted, pitting of mild steel tends to be initiated at sulfide inclusions, principally manganese sulfide (MnS) inclusions. It is evident that the manganese content is also one of important influence parameters.

If the effect of chromium was separated, the rule can be shown by Fig.18a, Fig.18b: Along with the increasing of manganese content, d_m drops, α rises approximately.

5.6 Chromium

The useful data to assess the effect of chromium is limited. According to the related data points shown in Fig.15a, Fig.15b, Fig.16a, Fig.16b, d_m is directly proportional to chromium content; α is inversely proportional to chromium content (Cr<2.12%).

5.7 Molybdenum

Evidently, there is some interactive effect between molybdenum and chromium.Figs.19a~19c show the effect of molybdenum content on model parameters of steels.

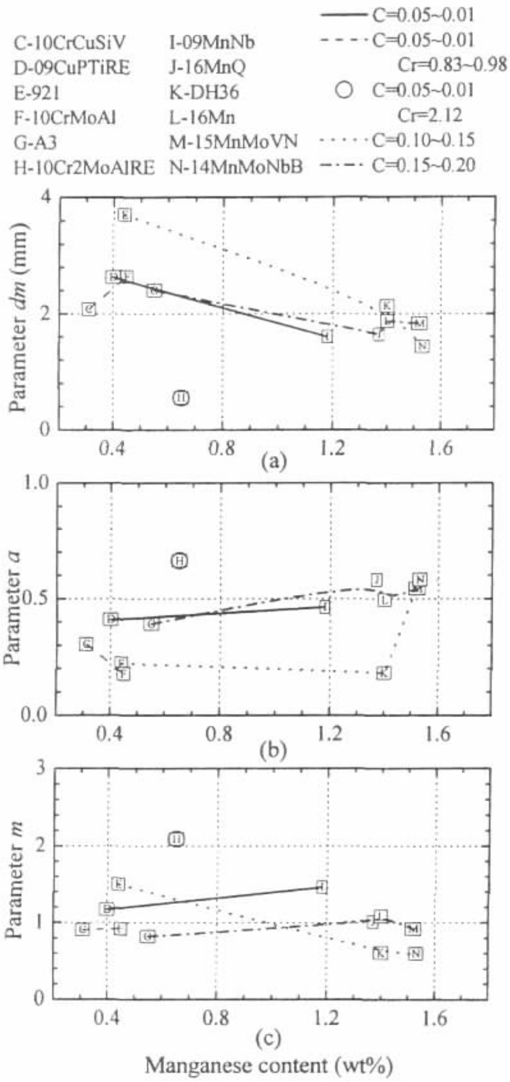


Fig.18 Effect of manganese content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

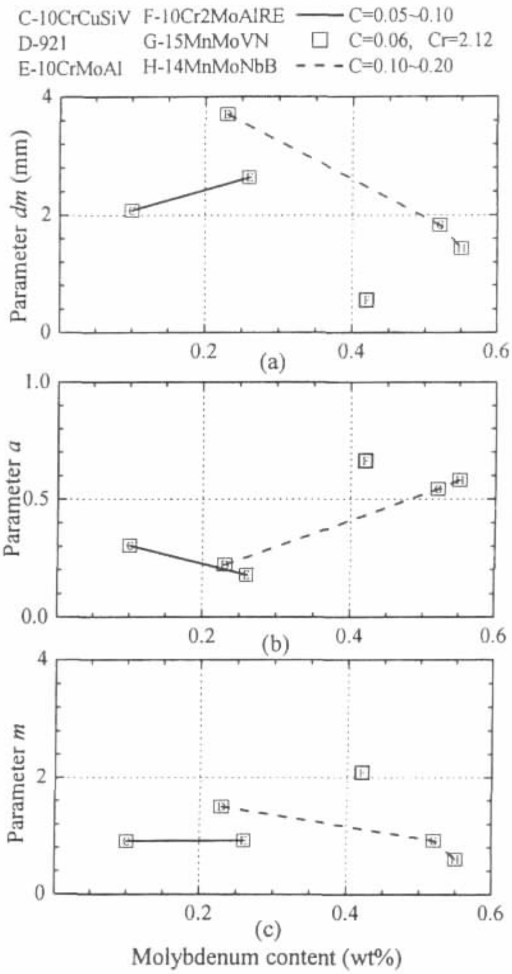


Fig.19 Effect of molybdenum content (wt%) on corrosion model parameters (a) d_m, (b) α, (c) m

6 Summary

For mild and low-alloy structural steels under marine immersion conditions, the main influencing factors and the specific process of pitting corrosion were summarized in this paper, according to the pitting corrosion mechanics and various corrosion gauge data from some long term field investigations in China.

Based on the pitting corrosion mechanics and Melchers' pitting corrosion model with its corresponding corrosion date, a simplified maximum pit depth model has been proposed here, which will be more concisely to predict the statistical characteristics of maximum macro-pit depth.

Then the new model has been applied to the analyses of various corrosion gauge data from some long term field investigations in Qingdao, China. Comparing with other pitting corrosion models, it will be more reasonable to describe the maximum pit-depth curve of mild and low-alloy steel in marine immersion conditions.

Furthermore,the potential influences of some seawater environmental factors on model parameters were discussed herein, including seawater temperature, dissolved oxygen, salinity, PH,etc,according the pitting corrosion data from long term field investigations in Qingdao, Xiamen and Yulin.

Since the variations in the composition contents of mild and low-alloy steels will also make a full impact on maximum pit depth, comparative analyses of the effect of steel composition contents on pit depth and the model parameters were also briefly discussed.

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Appendix:

Tab.A1 Main composition (wt%) of steels

	C	Mn	Cr	S	Mo	P	Si	Nb	Cu	Al
Mild steel										
A3	0.2	0.55	-	0.009	-	0.015	0.26	-	-	-
Chromium steel										
10CrCuSiV	0.1	0.31	0.83	0.002	0.1	0.01	0.62	-	0.25	-
10CrMoAl	0.09	0.45	0.98	0.002	0.26	0.012	0.35	-	-	0.57
921	0.11	0.44	0.97	0.03	0.23	0.023	0.18	-	-	-
10Cr2MoAlRE	0.06	0.65	2.12	0.008	0.42	0.017	0.39	-	-	0.86
Manganese steel										
16Mn	0.16	1.40	-	0.025	-	0.009	0.36	-	-	-
16Mn (Q)	0.17	1.37	-	0.023	-	0.03	0.3	-	0.07	-
DH36	0.14	1.40	-	0.018	-	0.022	0.39	0.03	-	0.025
09MnNb	0.09	1.18	-	0.013	-	0.022	0.45	0.037	0.07	-
15MnMoVN	0.19	1.52	-	0.024	0.52	0.026	0.4	-	-	-
14MnMoNbB	0.15	1.53	-	0.01	0.55	0.022	0.34	0.037	-	-
09CuPTiRe	0.08	0.40	-	0.019	-	0.089	0.28	-	0.29	-

Tab.A2 Enviromental factors (annual average) of seawater at various test area

	Dissolved oxygen mL/L	Seawater T/℃	Salinity ‰	PH
Qingdao	5.57	13.6	3.2	8.16
Xiamen	5.3	20.9	2.7	8.17
Yulin	4.9	26.7	3.4	8.3

碳钢、低合金钢全浸没海洋环境下最大点蚀深度简化模型

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摘要: 腐蚀是导致老龄船舶结构失效的主要原因之一。结合基本点蚀原理, 文章对碳钢、低合金钢海水全浸没点蚀的主要影响因素、具体点蚀进程做了简要解释与评述。基于 Melchers 点蚀深度模型及其相关实验数据, 文中提出一种简化形式的新型点蚀最大深度模型, 并采用该模型对三组我国船舶结构常用碳钢、低合金钢的青岛海域全浸没点蚀试验观测数据进行分析。通过对比验证, 证明采用 Weibull 函数表示点蚀最大深度随时间变化关系是合适的。此外, 依据青岛、厦门、榆林海域碳钢试验数据, 文中还对海水环境因素, 如: 溶解氧浓度、平均温度、盐度、PH 值等, 以及钢材成分变化对新型最大点蚀深度模型各参数的影响进行了初步探讨, 得出了相应的函数关系式及相关结论。

关键词: 碳钢; 低合金钢; 海洋环境; 全浸带; 点蚀; 腐蚀模型; 最大点蚀深度
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