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RELIABILITY OF CORROSION DEPTH DATABASE FOR ALLOYS EXPOSED TO THE MARINE ENVIRONMENT

POUZDANOST BAZE PODATAKA O DUBINI KOROZIJE U LEGURAMA IZLOŽENIM DEJSTVU MORSKE SREDINE

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- fitovanje raspodele
- pouzdanost

Abstract

The importance of studying corrosive processes is evident. However, researchers are often faced with the lack of sufficient empirical data, especially in the application of advanced modelling techniques in the field of artificial intelligence. In this paper, we applied the technique of inserting synthetic data into empirical databases based on measuring corrosion depth caused by three different marine environments over samples of three different alloys after 12 and 18 months of exposure to the environment. Empirical and extended databases are further used to analyse a linear model of corrosion depth based on the assumption that corrosion processes occur immediately after exposure to the effects of the marine environment. In each observed database, the best two-parameter, three-parameter, and multiparameter continuous distributions are selected by fitting. After a comparative presentation of the obtained results, the influence of the inserted synthetic data is detected. Although an empirical density function can be defined for corrosion data, the practice has shown that the most favourable way to analyse system failure data is to determine a distribution that follows empirical data well and then to calculate other functions from the reliability domain based on the determined probability density function. Based on this fact, starting from the detected most favourable continuous distributions that adequately describe corrosive behaviour of observed alloys in seawater environment, this paper also provides analyses of observed alloys from the standpoint of reliability.

Izvod

Značaj ispitivanja korozivnih procesa je više nego evidentan. Međutim, istraživači su često suočeni sa problemom nedostatka dovoljne količine empirijskih podataka, naročito u slučaju primene naprednih tehnika modeliranja u oblasti veštačke inteligencije. U ovom radu je prikazana tehnika ubacivanja sintetičkih podataka u empirijsku bazu na osnovu merenja dubine korozije prouzrokovane dejstvom tri različite morske sredine na tri različite legure nakon 12 i 18 meseci izloženosti. Empirijska i proširena baza podataka su zatim upotrebljene za analiziranje linearnog modela dubine korozije zasnovanog na pretpostavci da korozivni procesi kreću da se odvijaju odmah nakon izlaganja dejstvu morskih sredina. U svakoj posmatranoj bazi podataka su fitovanjem odabrane najbolje dvo-parametarske, tro-parametarske i višeparametarske neprekidne raspodele. Nakon uporedne analize dobijenih rezultata, uočen je uticaj ubačenih sintetičkih podataka. Iako je empirijsku gustinu funkcije moguće definisati za podatke o koroziji, praksa je pokazala da je najpovoljniji način za analiziranje sistema podataka o otkazu određivanje raspodele koja dobro prati empirijske podatke uz naknadno računanje drugih funkcija iz domena pouzdanosti na osnovu određene forme funkcije gustine verovatnoće. Na osnovu ove činjenice, počevši od utvrđivanja najpovoljnije neprekidne raspodele koja na adekvatan način opisuje ponašanje odabranih legura pri koroziji u morskim sredinama, ovaj rad takođe prikazuje i analizu posmatranih legura sa stanovišta pouzdanosti.

INTRODUCTION

Since the appearance of metallic materials in various industries, corrosion has emerged as the dominant degradation factor. Corrosion occurs in various physical forms such as general corrosion, pitting corrosion, fretting corrosion, galvanic or two-metal corrosion, crevice corrosion, intergranular corrosion, selective leaching or parting, erosion-corrosion, stress corrosion, etc., which affect the change in chemical composition of metals and degradation of their technical-technological and exploiting conditions /1/. Previous research has shown that damage caused by corrosion of all types of material is about 3-4% of the Gross National Income of developed countries, /2, 3/.

Due to different forms of corrosion and its large harmful effect on various metallic and non-metallic materials, numerous studies are conducted to discover the cause, corrosion intensity, and harmful consequences.

Although a number of authors believes corrosion is unstable, time-dependent and of constant velocity that can be expressed linearly, a nonlinear model is more realistic in terms of describing the process /4/. For these reasons, numerous studies show that in different environmental conditions, taking a significant number of influential parameters that affect the course of corrosion over time can be described as linear or nonlinear models /5/. These models describe the loss of base metal thickness (in mm) of wear, or as a percentage of wear concerning the built-in value /6, 7/, or loss of mass /8/.

Special attention to the research of corrosion is paid to the influence it has on new materials such as smart materials. These materials can change shape, position, stiffness, natural frequency, and other mechanical characteristics when they expand to temperature, stress, moisture, pH, electric or magnetic fields. Among various smart materials as piezoelectric, self-healing, chromogenic, etc., shape memory alloys (SMA) are more attractive for different industrial applications. The main characteristic of SMAs is the shape memory effect (SME), i.e. to remember their original shape when returning to the pre-deformed shape upon heating related to the solid-state transformation of martensite to austenite, and vice versa /9, 10/. Furthermore, superelasticity, high damping capacity, and double shape memory effect are also discovered thermomechanical properties of SMA /11, 12/.

Since their discovery in 1932, numerous research has been carried out to find better technical and technological characteristics of alloys and their application in various branches of industry. Specific thermomechanical characteristics of SMA have enabled application of these materials in various industries, such as automotive, railway, aircraft, maritime industries, medicine and robotics, /13-17/.

The application of SMA in the marine environment has a special challenge for many researchers, both due to the application of new materials and due to specific environmental conditions in which SMA are applied /18/. Numerous SMA applications occur in the maritime industry, both on vessels, fixed platforms, or in deep sea /19/.

From its inception until today, numerous SMA families have appeared based on Au, Al, Cu, Ni, and Ti. These are mainly alloys with two or three elements, although there are also families of alloys with more than three elements. So far, Ni-Ti, Cu-Al-Ni, Cu-Zn-Al, and Fe have been the most widely used. Ni-Ti-based alloys have proven to be the most functional but expensive. Cu-based alloys have shown excellent shape memory characteristics and low cost, while iron-based alloys have good machinability /20, 21/.

Also, experimental research in real environmental conditions /22, 23/ or in the laboratory /24/ provided answers to numerous questions related to changes in chemical composition of alloys, the appearance of different physical forms of corrosion, or the development of corrosion over time in SMA alloys.

From all the above, it becomes clear that the benefits of researching corrosion processes are immeasurable. However, researchers very often face the problem of lacking sufficient empirical data. Measurements of corrosive damage on metal samples are very expensive and most researchers face the problem of an insufficient number of records in empirical databases. Therefore, it is necessary to upgrade empirical databases with artificially generated records to achieve sufficiently large database dimensions, which would allow reliable research, especially in cases where more demanding and sophisticated research techniques are applied, such as neural networks, machine learning, techniques of artificial intelligence, regression, etc.

The idea in this paper is based on analysis of a technique of expanding the empirical database with artificially generated records, to achieve a greater number of adequate data, over which techniques could be applied that require more data than currently available.

The paper is divided into sections as follows. The second section is devoted to the description of how the empirical database is formed. In addition, this chapter outlines the technique of adding new synthetic data to an existing empirical database, thus forming an expanded database. The third section describes the probabilistic methodology used for analysis of empirical and extended databases. A comparative presentation of results obtained with empirical databases and the same techniques applied to extended synthetically generated databases, provide insight into the effects produced by embedded artificially generated data. The fourth section gives conclusions based on conducted research.

EMPIRICAL AND EXTENDED CORROSION DEPTH DATABASES

The paper uses empirical databases formed based on corrosion damage measurements on samples of two forms of nitinol alloys produced by two different processes and one CuAlNi alloy. Pure metals are used to produce NiTi alloys: Ni (99.99 wt.%) and Ti (99.99 wt.%) supplied by Zlatarna Celje d.o.o. Slovenia. The NiTi as a cast alloy is produced by classic casting and rolling in the form of a disc with a diameter of 42.3 mm and thickness of 3.4 mm. The NiTi CC alloy is produced by a combination of vacuum melting and continuous casting methods. Its shape is a rod of diameter 11.9 mm and length 50 mm. A total of 18 NiTi alloy samples (9 NiTi as cast samples and 9 NiTi CC samples) are used in the experiment. CuAlNi SMA rods (9 samples) are produced by continuous casting using a laboratory device for vertical continuous casting, Technica Guss, connected to a medium frequency furnace (4 kHz) with a vacuum melting induction (VIM) of 60 kW, Leybold Hereaus. The traction parameters are programmable, so an almost arbitrary time velocity curve can be achieved (limits are set by engine performance and inertia of moving parts). The formed empirical databases are previously used in the works of the authors /23, 25/.

All three alloys are observed under the influence of three marine environments, where the first is constant influence of the atmosphere; the second is constant influence of the sea; while the third influence represents changing influences of the sea and atmosphere. All samples are placed at clearly defined locations in the boundary zone of the sea and atmosphere. Samples exposed to the atmosphere are placed near the sea, three meters above sea level, samples exposed to the sea are immersed in the sea near the shore at a depth of three meters, while samples exposed to changing tides are located on the sea surface. Due to corrosive processes caused by marine environment, the damage is created on samples, the depth of which is measured by a focused ion beam (FIB) on a scanning electron microscope. After 12 and 18 months of exposure, the corrosion depth expressed in nm is detected on the surface of the samples by FIB method, thus completing the process of forming empirical databases. Upon measuring depth of corrosion, no additional factors influencing corrosion processes (temperature, pressure, salinity, particle flow, conductivity, etc.) are considered.

Figure 1a shows the FIB measurement position on the CuAlNi sample surface exposed to the seawater influence over 12 months, while Fig. 1b shows a sample surface under 6000-fold magnification. Images of sample surface under magnification of 20 000, 30 000, 60 000, and 100 000 times (depending on sample and location) are produced, and measurements are performed as shown in Fig. 2a. A total of 4 recordings per sample are considered, for each location and time intervals of 6, 12, and 18 months of environmental exposure. As can be seen from the figure, measurements on the sample are performed at 6 positions. On all other samples, between 5 and 7 measurement data are collected.

(a)
(b)

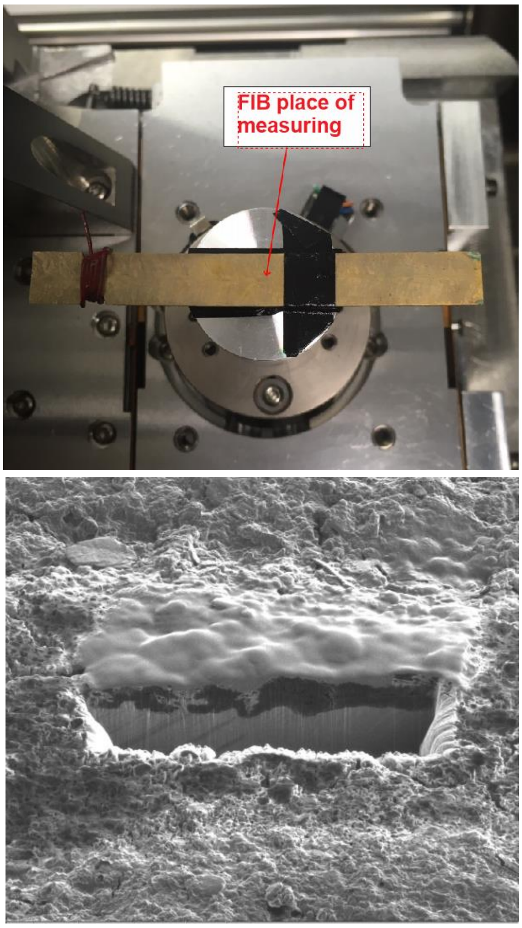


Figure 1. FIB measurements: a) location of FIB measurements on CuAlNi sample on sea surface after 12 months exposure, b) magnification of 6000.

The formed empirical databases serve as a basis for the creation of artificially generated extended databases. Namely, we have systematically supplemented empirical databases with additional data in the following way. To create a larger database, the empirical data are interpolated in such a way that each image is interpolated with 25 additional measured locations. The original (basic) data are an integral part of the interpolated data (Fig. 2b).

(a)
(b)

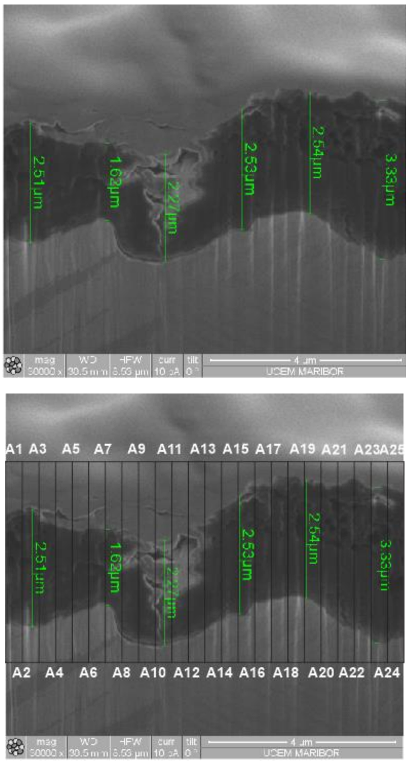


Figure 2. Example of empirical and extended database values: a) display of empirical measurements of CuAlNi sample at sea surface after 12 months of exposure; b) display of interpolated data for CuAlNi sample at sea surface after 12 months of exposure.

In this way, the empirical (input) database is increased to 25 measuring points per image. Values of interpolated data, corresponding to Fig. 2b are given in Table 1. In this table, the empirical values obtained by FIB measurement are indicated with the green background of the cell.

Table 1. Empirical and synthetically inserted values of corrosion depth for one observed sample.

A1	A2	A3	A4	A5
2468	2510	2210	1980	1620
A6	A7	A8	A9	A10
2252	2142	2270	2170	2269
A11	A12	A13	A14	A15
2420	2530	2510	2575	2540
A16	A17	A18	A19	A20
2540	2975	3100	3330	3100
A21	A22	A23	A24	A25
2850	2620	2510	3000	2856

Based on photometric representations and FIB measurements, we are able to detect areas on samples where corrosion processes occur, but which are not considered in the FIB analysis. By comparing the measured values of corrosion depth for points for which we knew values expressed in nm, we were able to read the adequate values of corrosion depth on sample areas that are not part of the empirical database. For precision, we used image analysis software tools in the process. In this way, approximate but realistic values of corrosion depth are obtained for each of the three considered alloys, in all three marine environments, and extended databases with a fixed, predefined number of records are formed. In the continuation of the research, both types of 18 databases are comparatively analysed: empirical and artificially generated databases:

- 3 empirical databases for the influence of air on corrosion depth of CuAlNi, NiTi as cast, and NiTi CC alloys;
- 3 empirical databases for tide influence on corrosion depth of CuAlNi, NiTi as cast, and NiTi CC alloys;
- 3 empirical databases for seawater influence on corrosion depth of CuAlNi, NiTi as cast, and NiTi CC alloys;
- 3 artificially generated (extended empirical) databases for the influence of air on the depth of corrosion of CuAlNi, NiTi as cast, and NiTi CC alloys;
- 3 artificially generated (extended empirical) databases for the effect of tide on corrosion depth of CuAlNi, NiTi as cast, and NiTi CC alloys;
- 3 artificially generated (extended empirical) databases for the influence of seawater on corrosion depth of CuAlNi, NiTi as cast, and NiTi CC alloys.

Basic descriptive characteristics of all listed databases from the point of view of the depth of formed corrosion on samples of CuAlNi, NiTi as cast, and NiTi CC alloys measured after 12 and 18 months of exposure to the marine environment are shown in Tables 2-4.

As can be seen from Tables 2-4, for all three considered alloys, extended databases are formed so that they have a constant number of data, regardless of the number of corresponding empirical data. For extended databases related to corrosion depth detected after 12 months of exposure to the environment, the number of records is 200, while extended databases related to corrosion depth values after 18 months of exposure to air, tide, and sea have 300 data each. Extended databases also contain original, empirical data, in addition to the inserted adequate realistic values of corrosion depth

Table 2. Descriptive statistics of empirical and extended databases related to the three different alloys and their corrosion.

AIR	CuAlNi				NiTi as cast				NiTi CC			
DB type	Original		Extended		Original		Extended		Original		Extended	
Stat./months	12	18	12	18	12	18	12	18	12	18	12	18
Sample size	47	68	200	300	25	55	200	300	82	82	200	300
Range	90.28	90.3	109.9	109.9	5.6	5.6	5.6	5.6	5.4	5.3	5.3	5.3
Mean	38.8	39.8	39.3	40.4	5.0	3.8	4.6	4.0	3.9	3.9	4.6	4.1
Std. Dev.	22.4	19.2	21.4	18.3	2.0	1.7	2.0	1.8	1.4	1.4	1.5	1.4
Min	9.7	9.7	8.8	8.8	2.1	2.1	2.1	2.1	2.3	2.3	2.3	2.3
Q1	16.0	27.9	18.2	29.2	2.7	2.6	2.7	2.7	2.9	2.9	3.1	3.1
Median	37.5	41.4	38.5	41.6	5.8	3.0	4.4	3.2	3.2	3.2	4.2	3.5
Q3	51.4	49.8	51.7	50.4	6.5	5.6	6.3	5.8	5.2	5.2	5.8	5.6
Max	100.0	100.0	118.6	118.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6

Table 3. Descriptive statistics of empirical and extended databases related to three different alloys and their corrosion depth formed under the influence of tide.

TIDE	CuAlNi				NiTi as cast				NiTi CC			
DB type	Original		Extended		Original		Extended		Original		Extended	
Stat./months	12	18	12	18	12	18	12	18	12	18	12	18
Sample size	41	62	200	300	40	66	200	300	47	79	200	300
Range	262.4	316.3	340.8	340.8	10.8	10.8	10.8	10.8	45.3	47.4	68.9	70.8
Mean	185.0	140.3	186.5	141.0	4.5	3.9	4.6	4.1	11.2	13.1	11.8	13.4
Std. Dev.	64.3	82.0	60.4	81.3	2.5	2.1	2.5	2.2	9.0	9.9	10.8	10.7
Min	91.0	37.0	12.5	12.5	1.7	1.7	1.7	1.7	4.4	2.2	4.4	2.4
Q1	138.2	58.5	145.0	54.2	2.5	2.6	2.5	2.7	6.9	6.9	6.3	6.9
Median	180.8	138.2	184.2	145.6	4.0	3.1	4.0	3.1	7.9	8.8	8.1	8.8
Q3	211.3	200.2	220.0	197.8	6.3	4.9	6.3	5.0	9.6	17.7	9.7	17.2
Max	353.3	353.3	353.3	353.3	12.5	12.5	12.5	12.5	49.7	49.7	73.2	73.2

Table 4. Descriptive statistics of empirical and extended databases related to three different alloys and their corrosion depth formed under the influence of seawater.

SEA	CuAlNi				NiTi as cast				NiTi CC			
DB type	Original		Extended		Original		Extended		Original		Extended	
Stat./months	12	18	12	18	12	18	12	18	12	18	12	18
Sample size	40	61	200	300	52	77	200	300	46	75	200	300
Range	106.3	117.2	140.0	151.4	74.7	74.7	74.7	74.7	50.0	57.5	61.0	61.0
Mean	148.9	136.9	150.5	139.2	26.3	26.2	24.7	25.7	22.1	25.3	23.5	27.4
Std. Dev.	25.5	31.3	27.5	32.2	19.4	16.6	22.4	19.2	10.6	12.1	10.6	13.0
Min	80.4	69.4	75.0	63.6	6.6	6.6	6.6	6.6	7.5	7.5	7.5	7.5
Q1	132.3	110.2	135.0	114.4	8.4	14.5	7.4	8.3	14.7	15.3	15.1	16.2
Median	151.7	142.8	152.5	142.6	21.2	23.8	9.7	21.9	18.0	22.2	20.0	24.3
Q3	167.5	163.3	170.0	165.7	36.5	31.3	41.7	38.0	28.1	32.9	28.2	35.6
Max	186.7	186.7	215.0	215.0	81.3	81.3	81.3	81.3	57.5	65.0	68.5	68.5

from the same samples on which original empirical measurements are performed. The values of all descriptive statistics related to extended databases are the same or very close to values of descriptive statistics of corresponding empirical databases. This fact indicates the systematic insertion of artificial data into empirical databases. In this way, basic statistical characteristics of empirical databases are preserved and the requirement that the inserted artificial data simulate real empirical data is met.

PROBABILISTIC CORROSION DEPTH MODELLING

In many articles dealing with the study of corrosion processes /6, 7, 23, 25-27/, it has been proved that the wear of the plate thickness, $d(t)$, can be successfully modelled as a function of time in the following way

$$d(t)=c_1(t-T_{cl})^{c_2} . \tag{1}$$

Time (t) is usually expressed in months or years and corrosion depth $d(t)$ in mm or nm. In Eq.(1) T_{cl} is service life of the coating, while c_1 and c_2 are positive real coefficients. Parameter c_1 can be considered as corrosion rate expressed in mm/year or nm/month, while coefficient c_2 is usually taken to be 1 or 1/3, /27/. In our previous works that analyse corrosive behaviour of SMA, we start from the basic assumption that T_{cl} = 0 months, i.e. samples are not treated with anticorrosion coatings. In addition, in all our previous studies of the linear corrosion model /6, 7, 23, 25/ the coefficient c_1 is not considered linear, but we observe corrosion processes as stochastic quantities influenced by many different factors. More precisely, the coefficient c_1 is considered as a continuous random variable.

Based on formed empirical and extended databases, and applying model Eq.(1), our research in this paper is focused on modelling the corrosion depth in all three observed alloys in three different marine environments. The probabilistic approach to modelling the c_1 coefficient is based on fitting Cumulative Distribution Functions (CDF) of known continuous distributions into data describing the corrosion depth of each alloy in each considered seawater environment /23, 25/. In this procedure, a total of 65 multiparameter (MP) distributions are considered (number of parameters vary between 1 and 6), of which 27 are three-parameter (3P) and 27 are two-parameter (2P). We use well-known continuous distributions, such as Log-Logistic (Log-Log), Generalized Extreme Value (GEV), Phased Bi-Weibull (PBW), Generalized Pareto (GenPareto), Inverse Gaussian (InvGaussian), etc.

From each set of continuous distributions, based on the value of the Kolmogorov-Smirnov test, all distributions are ranked according to quality of fitting and thus the three best distributions are determined that can adequately describe the corrosion depth behaviour under the influence of marine environment. Standard Anderson-Darling (AD) and Chi-Squared (χ^2) tests are used as additional tests to determine the goodness of fit. Based on these three tests, the null hypothesis is tested, that claims the data follow the chosen theoretical distribution, where values of 0.2, 0.1, 0.05, 0.02, and 0.01 for significance level are considered. The hypothesis regarding the distribution form is rejected for the selected significance level if the test statistically exceeds a predefined critical value. The p-value is calculated based on test statistics and marks the significance level threshold. The null hypothesis is rejected if the p-value is lower than the selected critical value, i.e. it could be concluded that the theoretical distribution does not describe the observed data for the selected level of significance. The results of the described procedure of fitting continuous distributions into data distributed in 18 different databases are shown in Tables 5-10. In these tables, cells are colour-coded as follows:

- the green colour indicates that the presented theoretical distribution has passed all statistical tests for all the stated significance levels, that is, the null hypothesis is not rejected in any of the cases;
- the yellow colour of the cell indicates that certain problems occur that can be overcome either by changing the statistical test or by reducing the levels for significance;
- the red colour of the cell indicates that the null hypothesis is rejected for each of the proposed statistical tests and each proposed significance level.

Table 5 shows the three best-fitted multiparameter, two-parameter, and three-parameter distributions, for all three considered seawater environments (air, tide, and sea) for the empirical depth of corrosion caused by CuAlNi alloy, after 12 and 18 months of exposure to the environment. The ranking of the three best distributions is defined by the values of KS test statistics. The goodness of fit was additionally tested with AD and χ^2 tests, for all the stated significance levels. The green colour in all cells of the table indicates that all tests for all considered significance levels showed that the null hypothesis cannot be rejected, that is, that the stated theoretical distributions describe well the empirical data of the corrosion depth of CuAlNi alloy.

NiTi alloys show significantly more complex corrosive behaviour in all marine environments, compared to CuAlNi alloy. These differences are especially notable if the air and tide environments are observed /25/ because NiTi alloys show similar corrosive behaviour in these two environments. Tables 6 and 7 show the goodness of fit results for the empirical databases of the two NiTi alloys. The green marked cells indicate that there are no restrictions for any of the considered statistical tests or for any of the selected significance levels, that is, that the presented theoretical distributions adequately follow empirical data. The yellow background of the cell indicates that individual constraints must be considered to accept the null hypothesis. It is evident that more than two parameters are needed to adequately describe the complex corrosion processes in these alloys, that is, two-parameter distributions are not an adequate choice for NiTi alloys (two red cells appear, indicating that all statistical tests reject the null hypothesis). In addition, as exposure time to the environment increases, the corrosive behaviour of these alloys changes and becomes more complex, thus after 18 months of exposure to the environment, some deviations may appear in the data, which may affect the quality of distribution fitting. Therefore, outlier removal techniques should be additionally introduced into the analyses /25/, which is especially indicated by a large number of yellow cells in Tables 6 and 7.

Table 5. Three best fitted multi-, 2-, and 3-parameter distributions related to CuAlNi alloy corrosion depth empirical database.

CuAlNi		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	GenPareto	GenLogistic	JohnsonSB	Wakeby	Wakeby	Wakeby
	2	Weibull	Burr	Dagum	Normal	GenPareto	JohnsonSB
	3	Normal	Wakeby	Wakeby	Chi-Squared	JohnsonSB	GenGamma
2P	1	Weibull	FatiqueLife	GumbelMin	Normal	Weibull	Uniform
	2	Normal	Lognormal	Weibull	Chi-Squared	Reciprocal	GumbelMin
	3	Nakagami	Log-Log	InvGaussian	Logistic	Normal	Weibull
3P	1	GenPareto	GenLogistic	Dagum	Error	GenPareto	GEV
	2	Error	Burr	GEV	GEV	Error	PowerFun
	3	GEV	Log-Pearson3	Log-Pearson3	Dagum	PowerFun	GenPareto

Table 6. Three best fitted multi-, 2- and 3-parameter distributions related to NiTi as cast alloy corrosion depth empirical database.

NiTi as cast		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	Beta	GenPareto	Wakeby	Pearson5	Burr	Wakeby
	2	GenPareto	Wakeby	JohnsonSB	Pearson6	GenPareto	Gamma
	3	Wakeby	Pert	GenPareto	Frechet	Wakeby	Weibull
2P	1	Uniform	Gamma	Weibull	Frechet2P	Frechet	Gamma
	2	Normal	FatiqueLife	Gamma	Exponential	Log-Gamma	Weibull
	3	Weibull	InvGaussian	Log-Log	Pareto	InvGaussian	GumbelMax
3P	1	GenPareto	GenPareto	GenPareto	Pearson5	Burr	GenGamma
	2	Error	Pert	Gamma3P	Frechet	GenPareto	GenLogistic
	3	GEV	Log-Pearson3	GEV	Log-Log	Log-Log	GEV

Table 7. Three best fitted multi-, 2- and 3-parameter distributions related to the NiTi CC alloy corrosion depth empirical database.

NiTi CC		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	Burr	Burr	Burr	Burr	Log-Log 3P	JohnsonSB
	2	JohnsonSB	GenPareto	GEV	JohnsonSB	Log-Log	GenPareto
	3	Dagum	Wakeby	Log-Log	Dagum4P	Log-Gamma	Burr4P
2P	1	Frechet	Chi-Squared	Pearson5	Frechet2P	Log-Log	Pearson5
	2	Exponential	Cauchy	Log-Gamma	Exponential	Log-Gamma	Log-Gamma
	3	Erlang	Frechet	Log-Log	Erlang	FatiqueLife	Frechet
3P	1	Burr	GenPareto	Burr	Burr	Log-Log3P	GenPareto
	2	Log-Log	GEV	GEV	Log-Log	Dagum	Dagum
	3	Frechet3P	GenLogistic	Log-Log	Frechet	Frechet3P	InvGaussian

Tables 8-10 show the results of fitting the best continuous distributions into an artificially formed extended database. In the process of testing the null hypothesis, the same technique is applied as for testing empirical databases, with the same statistical tests, ranking, and significance level values.

Even though the expanded databases are obtained by inserting records in empirical databases in a systematic way, and not by random, completely artificially generated values, as can be seen in Tables 8-10, significant problems arise in selecting adequate theoretical distributions. The number of yellow cells has increased significantly, but a more worrying fact is the drastic increase in the number of red cells.

Yellow cells indicate problems with the application of statistical tests, what can be easily overcome by changing statistical test, or by lowering significance level. Depending on the type of research being conducted, it is possible, e.g. to choose AD test as the leading test, instead of KS test. Decreasing the significance level allows the null hypothesis to be rejected. However, lowering the significance level reduces the probability of the occurrence of a Type I Error, i.e. it is more difficult to reject the null hypothesis in case it is not true.

The empirical database related to CuAlNi alloy and its corrosive behaviour in all three marine environments shows the most stable behaviour when all three considered alloys are compared, and thus, inserting artificially generated data into the existing empirical database for CuAlNi alloy does not produce significant problems concerning the process of fitting theoretical distributions into the resulting extended databases. With small interventions over the formed extended databases, very reliable results of fitting continuous distributions can be obtained. A characteristic result is obtained for 18 months of exposure to the tide, where all statistical tests indicate that the null hypothesis should be rejected. The influence of changing sea level with the additional influence of air proves to be the most dominant factor in the occurrence of corrosion processes. This is the characteristic behaviour in the case of CuAlNi alloy as well, which results in a complex data structure of the formed extended database. Even small interventions on such measurements significantly change the image of corresponding histograms of frequencies of corrosion depth values. In particular, in CuAlNi alloys, several peaks appear in histograms due to redundant values of corrosion depth. By simply deleting these multiple values, the problem of fitting theoretical distributions is eliminated, and statistical tests show that the selected best distributions fit well into the observed values of corrosion depth.

A large number of red fields occur primarily in extended databases related to NiTi alloys. As is already mentioned, the reason for this is the very complex corrosive behaviour of these alloys. The increase in the number of considered data further complicates analysis of the formed extended databases. In the case of NiTi alloys, the proposed statistical tests can hardly be applied in all cases. The reason for this is the large number of outliers detected in the empirical data. The insertion of new data further increases the frequency of these non-standard corrosion depth values, resulting in the problematic fitting of theoretical distributions into extended databases. In addition, many redundant data are detected, which significantly increases the frequencies of individual corrosion depth values. This increase in frequencies affects the structure of the histogram that describes the observed data. The associated histograms show a tendency of very high bars for individual values of corrosion depth, which makes it almost impossible to fit standard shapes of theoretical distributions into the formed histograms. To overcome this problem, it is necessary to implement redundant data reduction techniques and eliminate outliers before inserting synthetic data into empirical databases. Also, for alloys that show complicated corrosion properties as NiTi alloys, it is necessary to conduct specific research based on extreme value theory methodologies.

Table 8. Three best fitted multi-, 2- and 3-parameter distributions for CuAlNi alloy corrosion depth extended database.

CuAlNi		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	GenPareto	Log-Log	Dagum	Wakeby	Beta	Wakeby
	2	Nakagami	Burr	GEV	Normal	Ph. Bi-Weibull	GEV
	3	Weibull	Dagum	LogPearson3	Dagum	Wakeby	JohnsonSB
2P	1	Nakagami	Nakagami	Weibull	Normal	Uniform	Weibull
	2	Weibull	Logistic	InvGaussian	Logistic	Weibull	Uniform
	3	Chi-Squared	Chi-Squared	GumbelMin	Hypersecant	Lognormal	Normal
3P	1	GenPareto	Log-Log	GEV	Dagum	GenPareto	GEV
	2	Dagum	Dagum	LogPearson3	GEV	Error	Burr
	3	Burr	GenLogistic	Burr	Error	Gamma	Weibull3P

Table 9. Three best fitted multi-, 2- and 3-parameter distributions for NiTi as cast alloy corrosion depth extended database.

NiTi as cast		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	Beta	GenPareto	FatiqueLife	GenGamma	Burr	Kumaraswamy
	2	PBW	Wakeby	GenGamma	FatiqueLife	JohnsonSB	Beta
	3	Rayleigh	JohnsonSB	Log-Log	Log-Log	Dagum	JohnsonSB
2P	1	Uniform	Exponential	Levy	Frechet	Frechet	Nakagami
	2	Weibull	Pearson5	Frechet	Exponential	Log-Gamma	GumbelMax
	3	Rice	Lognormal	Pareto	Pareto	Exponential	Gamma
3P	1	Error	GenPareto	FatiqueLife	FatiqueLife	Burr	GenPareto
	2	GenPareto	Pert	Log-Log	Log-Log	Frechet3P	PowerFunction
	3	Pearson6	Weibull	Lognormal	Lognormal	Log-Log3P	Gamma3P

Table 10. Three best fitted multi-, 2- and 3-parameter distributions for NiTi CC alloy corrosion depth extended database.

NiTi CC		12			18		
		Air	Tide	Sea	Air	Tide	Sea
MP	1	JohnsonSB	Burr	Burr	JohnsonSB	Frechet	JohnsonSB
	2	PowerFun	Log-Log	JohnsonSB	Burr	Burr	Wakeby
	3	Reciprocal	Dagum	GenPareto	Chi-Squared2P	JohnsonSB	GenPareto
2P	1	Reciprocal	Cauchy	Frechet	Chi-Squared2P	Frechet	Gamma
	2	Uniform	Frechet	Log-Gamma	Exponential	Pearson5	Log-Gamma
	3	Exponential2P	Pearson5	InvGaussian	Frechet2P	Log-Gamma	InvGaussian
3P	1	PowerFun	Log-Log	Burr	Burr	Burr	GenPareto
	2	GenPareto	GenPareto	GenPareto	Frechet3P	GenPareto	FatiqueLife
	3	Error	Burr	Log-Log	Pearson5	Dagum	Weibull3P

Reliability analysis based on selected extended databases

After the elimination of redundant data and extreme outliers, the expanded databases are left with only consistent values that allow further analysis from the standpoint of reliability of the observed samples of CuAlNi and Nitinol alloys. Thus, empirical and reduced extended databases relating to each alloy and measurements made after 12 and 18 months of exposure to air, tide, and sea, are subjected to a re-fitting process of multiparameter distributions. The best values of all parameters that characterize the observed continuous distributions are determined by maximum likelihood estimation method. As multi-parameter distributions are analysed, it is necessary to determine values for the scale, location, and shape parameters. Scales and location parameters are standard parameters of each distribution, while other parameters that do not belong to scale and location, belong to the group of shape parameters. The location parameter translates the distribution graph along the *x*-axis, while the scale parameter affects the stretch out of the graph. As the name suggests, shape parameters affect the shape of a graphic and not its position. Values of the best-fitted continuous distributions, together with the set of the most suitable parameter values, are shown in Table 11.

Table 11. Three best fitted multiparameter distributions and their parameter specifications.

CuAlNi	Empirical database-12 months	Extended database-12 months	Empirical database-18 months	Extended database-18 months
Air	GenPareto (-0.53938, 49.387, 6.7163)	GenPareto (-0.66385, 52.939, 7.4368)	Wakeby (97.049, 2.3047, 2.7605, 0.50936, 4.8038)	Wakeby (117.68, 3.3477, 6.8306, 0.22498, 4.5524)
Tide	GenLogistic (0.13486, 35.101, 177.06)	LogLog (14.716, 504.52, -321.5)	Wakeby (176.09, 0.51073, 0, 0, 23.735)	Beta (1.1788, 1.9907, 11.25, 353.33)
Sea	JohnsonSB (-1.5142, 1.205, 178.53, 14.858)	Dagum (0.17946, 14.44, 117.08, 63.7)	Wakeby (183.05, 2.4407, 19.427, -0.36606, 69.458)	Wakeby (194.33, 3.5512, 36.215, -0.40481, 70.689)
NiTi as cast	Empirical database-12 months	Extended database-12 months	Empirical database-18 months	Extended database-18 months
Air	Beta (0.50687, 0.46129, 2.0833, 7.6384)	Beta (0.4375, 0.51884, 2.08, 7.64)	Pearson5 (2.1352, 2.5917, 1.722)	GenGamma (0.94515, 0.91815, 2.0188, 2.0833)
Tide	GenPareto (-0.24115, 3.708, 1.5472)	GenPareto (-0.22546, 3.7749, 1.5561)	Burr (0.22341, 10.354, 2.3794)	Burr (0.22017, 9.7252, 2.3707)
Sea	Wakeby (-35.223, 38.884, -0.35191, 6.1091)	FatiqueLife (2.4854, 4.3434, 6.482)	Wakeby (29.432, 3.6788, 16.054, -0.01691, 4.0931)	Kumaraswamy (0.50967, 1.5787, 6.5967, 89.032)
NiTi CC	Empirical database-12 months	Extended database-12 months	Empirical database-18 months	Extended database-18 months
Air	Burr (0.13932, 21.768, 2.7051)	JohnsonSB (0.23172, 0.45807, 4.8081, 2.5342)	Burr (0.13815, 21.901, 2.702)	JohnsonSB (0.62632, 0.41403, 4.6877, 2.716)
Tide	Burr (0.23915, 6.8103, 3.6211, 2.6246)	Burr (0.21363, 6.7779, 3.2692, 2.8149)	LogLog (2.1192, 8.9052, 1.0816)	Frechet (1.9355, 7.8809)
Sea	Burr (0.28178, 8.7615, 14.05)	Burr (0.16685, 13.451, 14.075)	JohnsonSB (1.3935, 0.99166, 74.341, 7.7465)	JohnsonSB (1.0052, 0.76881, 62.197, 10.617)

In this section, the focus is only on extended databases related to the impact of all three observed alloys in the three seawater environments, after 18 months of exposure. This database is selected as relevant because of its dimension, i.e. because of the largest number of corrosion wear values of samples that can be adequately analysed.

Each continuous distribution can be described with the corresponding Probability Density Function (PDF), representing the probability that a random variable will take a specified value. The following applies to PDFs (denoted as $f(x)$) for continuous random variable X:

$$f(x) \geq 0 \quad \text{for all} \quad x \in \mathbb{R}\,, \tag{2}$$

$$\int_{-\infty}^{\infty} f(x)dx = 1\,, \tag{3}$$

$$P(a \leq x \leq b) = \int_a^b f(x)dx\,. \tag{4}$$

The cumulative density function (CDF), denoted by $F(x)$, represents the probability that a random variable X takes a value less than or equal to the observed value x, i.e.

$$F(x) = P(X \leq x)\,. \tag{5}$$

For continuous distributions CDF is related to PDF as:

$$F(x) = P(X \leq x) = \int_{-\infty}^{x} f(t)dt \quad \text{for} \quad x \in \mathbb{R}\,. \tag{6}$$

The reader can find details of probability theory in /28/.

In the process of fitting multiparameter continuous distributions into data from extended databases for all three seawater environments and all three considered SMA alloys, after 18 months of exposure to the marine environment on corrosion processes, Beta, Burr, Frechet, Generalized Gamma, Johnson SB, Kumaraswamy, and Wakeby distribution are detected as the most adequate. As all these functions are well known in probability theory, their PDF and CDF functions can be easily given in analytical form, based on determined values of their parameters (see Table 11).

Analyses of system failures and the reliability of the use of their structural elements are best analysed if the PDF and CDF characteristics of random variables that characterize the observed process are known. As the best multiparameter distributions have been detected in this paper so far, which can adequately describe the corrosive behaviour of CuAlNi and Nitinol alloys in three seawater environments, using well-known expressions from the theory of reliability, it is possible to easily determine the corresponding survival and hazard functions.

Reliability is defined as the probability that an element will remain functional, i.e. that the observed system will not collapse in a given time interval. System failure occurs due to a large number of stochastic parameters, and thus, it is usually considered as a random variable. The previously defined CDF Eq.(6) can be viewed as a function of failure distribution. It is clear that reliability is essentially the probability of failure-free operation, so the reliability (or survival) function $R(x)$ is defined as

$$R(x) = 1 - P(X \leq x) = P(X > x)\,. \tag{7}$$

Then the failure density function $f(x)$ can be obtained as

$$f(x) = \frac{dF(x)}{x}\,. \tag{8}$$

The hazard function $h(x)$ or instantaneous rate of occurrence of the event is defined as

$$h(x) = \lim_{dx \to 0} \frac{P(x \leq X \leq x + dx \mid X \geq x)}{dx} \quad \text{or} \tag{9}$$

$$h(x) = \frac{f(x)}{R(x)} = \frac{f(x)}{1 - F(x)}\,. \tag{10}$$

A good overview of these terms and more details on the theoretical foundations of reliability can be found in /29-31/.

Below are listed analytical forms for survival and hazard functions of all three observed alloys in all three observed environments. In all the expressions that follow, the previously defined standard notations and formulas for $R(x)$ and $h(x)$ are used (see Eqs.(7) and (10)), with index containing the ordinal number of the observed alloy, while the superscript gives the abbreviation for the observed environment. The CuAlNi, NiTi as cast, and NiTi CC alloy, are numbered as 1, 2, and 3, respectively. To obtain explicit analytical forms for survival and hazard functions, the parameter values for the observed distributions listed in Table 11 are used. More precisely, only databases whose characteristics reflect distributions presented in the last column of Table 11 are observed, i.e. measurements related to 18 months of exposure to the marine environment.

Reliability functions for corrosion processes caused by marine environment influence for the three observed alloys have the following analytical forms, taking into account parameter values from Table 11:

– Air influence

Wakeby distribution for CuAlNi alloy is defined by its quantile function $W_1^a(x)$, as follows:

$$W_1^a(x) = 4.5524 - 30.361\left(1 - \frac{1}{(1-x)^{0.22498}}\right) + 35.152\left(1-(1-x)^{3.3477}\right), \tag{11}$$

where: $0 \le x \le 1$.

Wakeby's CDF can be obtained by numerically inverting the quantile function Eq.(11). By inserting the calculated expression for CDF into Eq.(7), the corresponding formula for $R_1^a(x)$ can be obtained.

$$R_2^a(x) = \begin{cases} 1 & x \le 2.0833 \\ 0.948\mathrm{Gamma}[0.91815,\ 0.515(-2.0833+x)^{0.94515}] & \text{otherwise} \end{cases} \tag{12}$$

where: $\mathrm{Gamma}[a,z] = \int_z^\infty t^{a-1}e^{-t}dt$, and represents the incomplete Gamma function.

$$R_3^a(x) = \begin{cases} \frac{1}{2}\mathrm{Erfc}\left[0.443 + 0.293\mathrm{Ln}\left[\frac{2.716-1.x}{-7.4037+x}\right]\right] & 2.716 < x < 5.05985 \\ \frac{1}{2}\left(1 - \mathrm{Erf}\left[0.443 + 0.293\mathrm{Ln}\left[\frac{2.716-1.x}{-7.4037+x}\right]\right]\right) & 5.05985 \le x < 7.4037 \\ 0 & x \ge 7.4037 \\ 1 & \text{otherwise} \end{cases} \tag{13}$$

where: $\mathrm{Erf}[z] = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$ is the Error function, i.e. the integral of Gaussian distribution; while Erfc[z] is the complementary error function that can be calculated as Erfc[z] = 1 – Erf[z].

– Tide influence

$$R_1^t(x) = \begin{cases} 1 & x \le 11.25 \\ 1 - 2.555\mathrm{Beta}[-0.033 + 0.003x,\ 1.1788,\ 1.9907] & 11.25 < x \le 353.33 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

where: $\mathrm{Beta}[z,a,b] = \int_0^z t^{a-1}(1-t)^{b-1}dt$ represents the incomplete Beta function.

$$R_2^t(x) = \begin{cases} \frac{1}{\left(1+36.151x^{2.3707}\right)^{9.7252}} & x > 0 \\ 1 & \text{otherwise} \end{cases} \tag{15}$$

$$R_3^t(x) = \begin{cases} 1 - e^{-\frac{54.365}{x^{1.9355}}} & x > 0 \\ 1 & \text{otherwise} \end{cases} \tag{16}$$

– Sea influence

Analogously as in the case of determining $R_1^a(x)$, the reliability function $R_1^s(x)$ is obtained based on the defined quartile function $W_1^s(x)$ which has the formula

$$W_1^s(x) = 0.689 + 89.462\left(1-(1-x)^{0.40481}\right) + 54.722\left(1-(1-x)^{3.5512}\right), \quad \text{where} \quad 0 \le x \le 1. \tag{17}$$

$$R_2^s(x) = \begin{cases} \left(1 - 0.106(-6.5967+x)^{0.50967}\right)^{1.5787} & 0 < 0.012(-6.5967+x) < 1 \\ 1 & 0.012(-6.5967+x) \le 0 \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

$$R_3^s(x)=\begin{cases}\frac{1}{2}\text{Erfc}\left[0.711+0.544\,\text{Ln}\left[\frac{10.617-1.x}{-72.814+x}\right]\right] & 10.617<x<41.7155\\ \frac{1}{2}\left(1-\text{Erf}\left[0.711+0.544\,\text{Ln}\left[\frac{10.617-1.x}{-72.814+x}\right]\right]\right) & 41.7155\le x<72.814\\ 0 & x\ge 72.814\\ 1 & \text{otherwise}\end{cases} \tag{19}$$

Based on the previously calculated analytical forms of reliability functions and CDF functions with inserted values of parameters from Table 11, by simply applying Eq.(10), the corresponding formulas for the hazard function are obtained as follows:

– Air influence

The Wakeby distribution is defined by a quartile function. Thus, it is necessary to first compute the CDF function by numerical methods. As suggested in /32/, PDF for Wakeby distribution is calculated based on its CDF as

$$f(x)=\frac{\left(1-F(x)\right)^{1.22498}}{117.68\left(1-F(x)\right)^{3.57268}+6.8306}\,. \tag{20}$$

By applying previously calculated expression $R_1^a(x)$ and Eq.(10), the hazard function $h_1^a(x)$ for CuAlNi alloy can be obtained.

$$h_2^a(x)=\begin{cases}\dfrac{0.514e^{-0.515(-2.0833+x)^{0.94515}}}{(-2.0833+x)^{0.132}\,\text{Gamma}\left[0.91815,\ 0.515(\text{-}2.0833\text{+x})^{0.94515}\right]} & x>2.0833\\ 0 & \text{otherwise}\end{cases} \tag{21}$$

$$h_3^a(x)=\begin{cases}\dfrac{1.549e^{-0.086\left(1.513+1.\text{Log}\left[\frac{-2.716+x}{7.4037-x}\right]\right)^2}}{(-7.4037+x)(-2.716+x)\left(-1.+\text{Erf}\left[0.443+0.293\,\text{Log}\left[\frac{2.716-x}{-7.4037+x}\right]\right]\right)} & x>2.0833\\ -\dfrac{1.549e^{-0.086\left(1.513+1.\text{Log}\left[\frac{-2.716+x}{7.4037-x}\right]\right)^2}}{(-7.4037+x)(-2.716+x)\,\text{Erfc}\left[0.443+0.293\,\text{Log}\left[\frac{2.716-x}{-7.4037+x}\right]\right]} & 2.716<x<5.05985\\ 0 & \text{otherwise}\end{cases} \tag{22}$$

– Tide influence

$$h_1^t(x)=\begin{cases}\dfrac{0.000003(353.33-x)^{0.991}(-11.25+x)^{0.179}}{-0.391+\text{Beta}[-0.033+0.003x,\ 1.1788,\ 1.9907]} & 11.25\le x\le 353.33\\ 0 & \text{otherwise}\end{cases} \tag{23}$$

$$h_2^t(x)=\begin{cases}\dfrac{833.486x^{1.371}}{1+36.151x^{2.3707}} & x>0\\ 0 & \text{otherwise}\end{cases} \tag{24}$$

$$h_3^t(x)=\begin{cases}\dfrac{105.224}{\left(-1+e^{\frac{54.365}{x^{1.9355}}}\right)x^{2.9355}} & x>0\\ 0 & \text{otherwise}\end{cases} \tag{25}$$

– Sea influence

Hazard function $h_1^s(x)$ is calculated based on previously determined CDF and $R_1^s(x)$ determined on the basis of Eq. (17). After this pre-processing step, by applying Eq.(10) with inserted expression for PDF

$$f(x)=\frac{(1-F(x))^{0.59519}}{194.33(1-F(x))^{3.14639}+36.215}\,, \tag{26}$$

the final expression for $h_1^s(x)$ can be calculated.

$$h_2^s(x)=\begin{cases}0 & x\ge 89.032\ \text{ or }\ x\le 6.5967\\ \dfrac{0.805}{(9.475-(-6.5967+x)^{0.50967})(-6.5967+x)^{0.49}} & \text{otherwise}\end{cases} \tag{27}$$

$$h_3^s(x)=\begin{cases}\dfrac{38.153e^{-0.296\left(1.307+1.\mathrm{Log}\left[\frac{-10.617+x}{72.814-x}\right]\right)^2}}{(-72.814+x)(-10.617+x)\left(-1.+\mathrm{Erf}\left[0.711+0.544\,\mathrm{Log}\left[\dfrac{10.617-1.x}{-72.814+x}\right]\right]\right)} & 41.7155\le x<72.814\\ 1 & 10.617<x<41.7155\\ 0 & \text{otherwise}\end{cases} \quad (28)$$

For the case of CuAlNi alloy and its extended databases containing measurements related to the corrosive behaviour of this alloy under the influence of air, tide, and sea after 18 months of exposure to the environment, we also give a graphical representation of analytically determined reliability functions whose expressions are represented by Eqs.(11), (14), and (17) as well as hazard functions represented by Eqs. (20), (23), and (26). Figure 4 shows the graphs of survival functions (left column) and hazard functions (right column) for NiTi as cast alloy and its corrosive behaviour under the influence of air, tide, and sea, after 18 months of exposure to the observed environment. The reliability graphs $R_2^a(x)$, $R_2^t(x)$, and $R_2^s(x)$ are formed based on analytical forms of functions presented in Eqs.(12), (15), and (18), while the hazard function graphs $h_2^a(x)$, $h_2^t(x)$, and $h_2^s(x)$ are obtained based on Eqs.(21), (24), and (27).

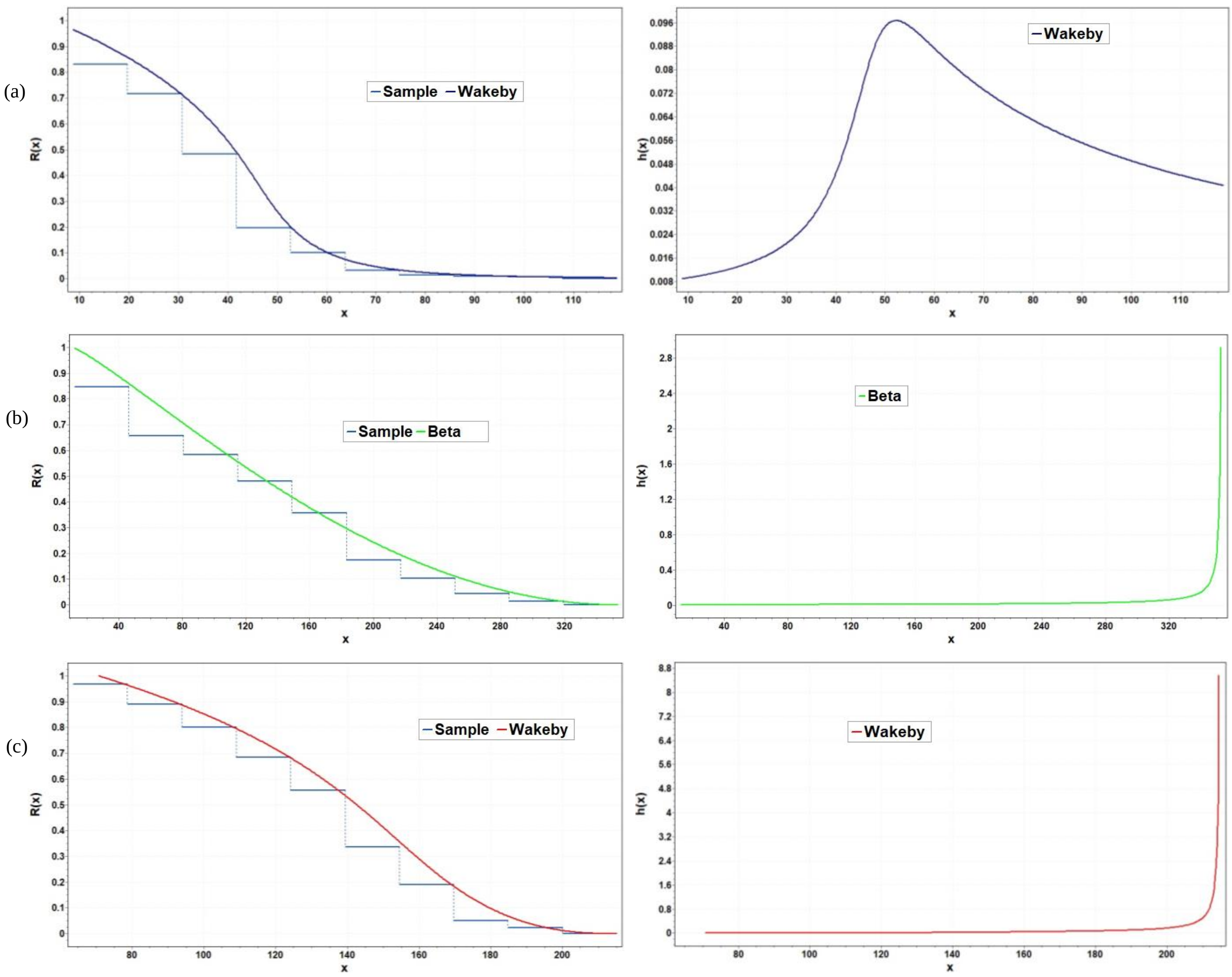


Figure 3. Graphical representation of survival and hazard functions for CuAlNi extended database and alloy behaviour after 18 months of exposure to: a) air; b) tide; and c) sea.

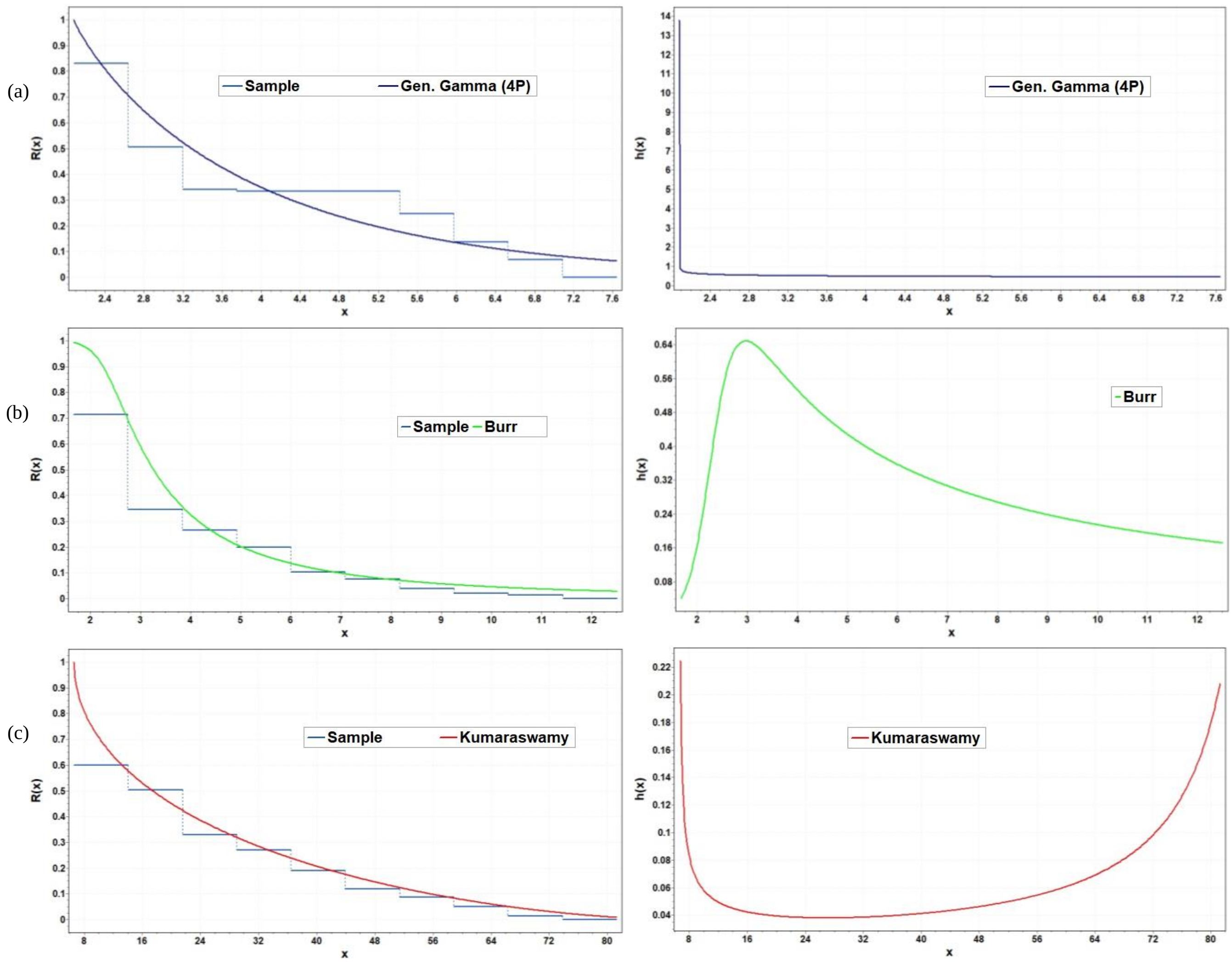
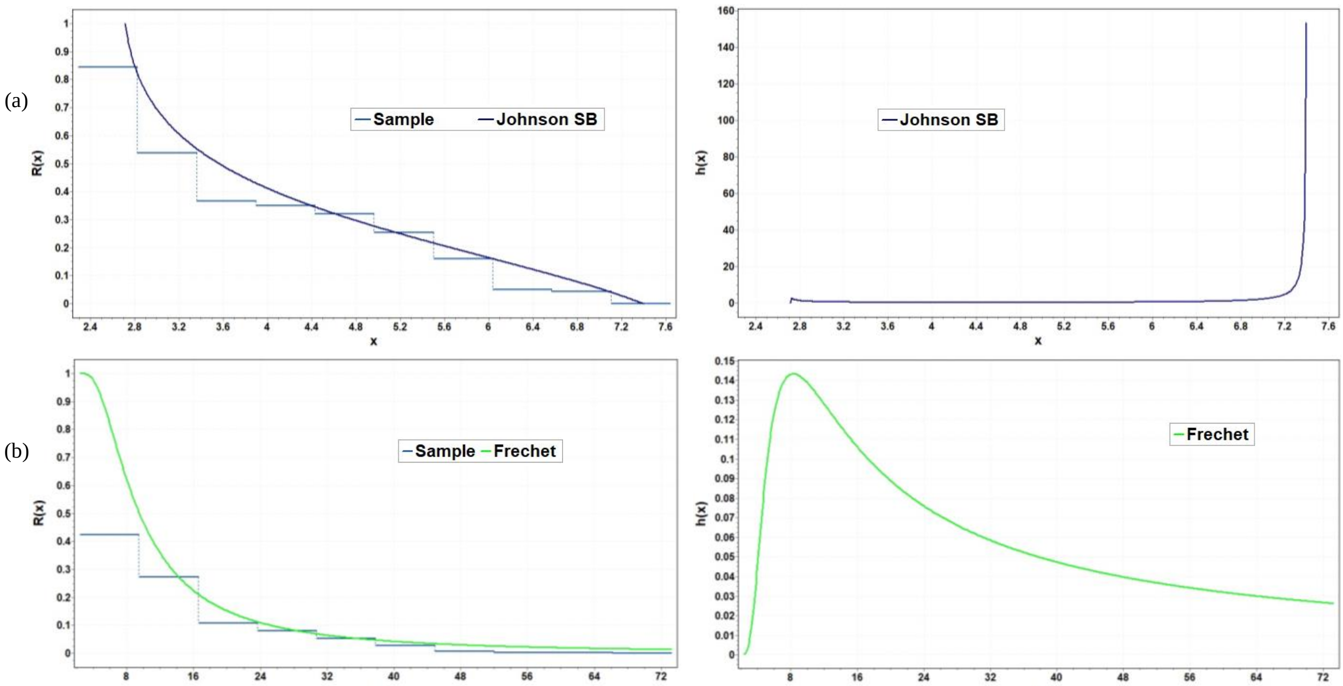


Figure 4. Graphical representation of survival and hazard functions for NiTi as cast extended database and alloy behaviour after 18 months of exposure to: a) air: b) tide: and c) sea.



(c)

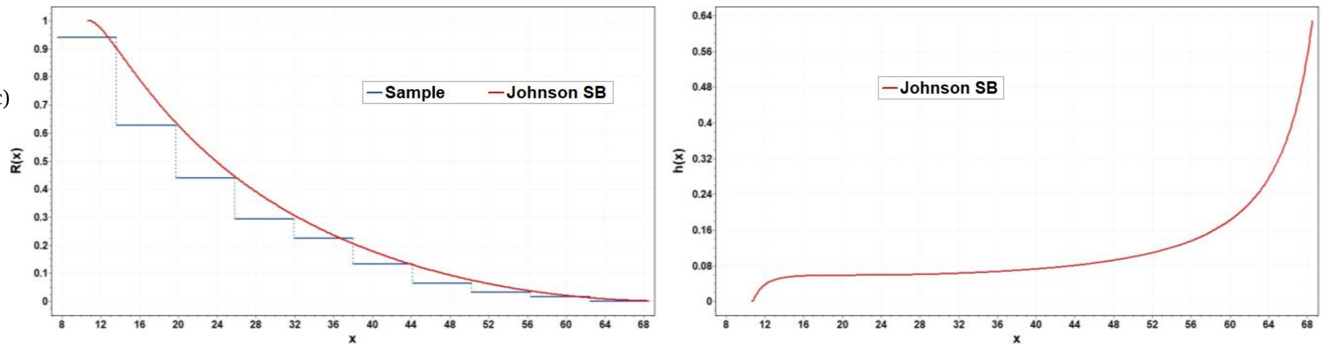


Figure 5. Graphical representation of survival and hazard functions for NiTi CC extended database and alloy behaviour after 18 months of exposure to: a) air; b) tide; and c) sea.

The first column in Fig. 3 shows survival functions for CuAlNi alloy, for measuring the depth of corrosion caused by air, tides, and sea, respectively, while the second column in Fig. 3 graphically shows the hazard functions.

The corrosive behaviour of NiTi CC alloy from the standpoint of its reliability and hazard functions is given in Fig. 5. Adequate representations of analytically calculated reliability functions for NiTi CC alloy behaviour under the influence of air, tide, and sea after 18 months of environmental exposure are given in the left column of Fig. 5. The right column in Fig. 5 shows associated hazard functions for NiTi CC alloy and its corrosive behaviour after 18 months.

In Figs. 3-5, the step functions represent empirical survival functions obtained based on corresponding extended databases for the observed alloy in the marine environment. Based on detected best fitted three-parameter continuous distributions, but also by looking at Figs. 3-5, it becomes clear that all three observed alloys show significantly different corrosive behaviour in different marine environments. In addition, if two alloys are compared two by two, mutual significant differences in their corrosion characteristics can be also observed.

Under tide influence, CuAlNi alloy shows accelerated corrosion rate, due to the more heterogenic chemical content of the environment. CuAlNi alloy develops considerably slower corrosion under air influence. In addition, prolonged exposure to air does not significantly accelerate resulting corrosion processes. The tide causes the greatest corrosion processes on the surface of CuAlNi samples, followed by the influence of the sea, while air has the least influence on the development of corrosion on the surface of this alloy. Survival functions that describe the behaviour of the alloy under the influence of air and sea have a similar shape, but corrosion processes are significantly greater if samples are exposed to the sea. The likelihood of failure rate is almost constant and then grows rapidly in the influence of tide and sea. In contrast, under the influence of air, the failure rate increases and then shows a declining trend.

In the air and sea environment in the case of NiTi as cast alloys, with increasing corrosion depth values the probabilities decrease evenly, while this is not the case with tidal influences. Namely, under the influence of tide, a significant amount of data is concentrated in the interval of small corrosion depths, i.e. small values of corrosion depth appear with very high probabilities. This alloy shows most pronounced corrosion processes under the influence of the sea. Large values of corrosion depth occur much more frequently and with a higher probability than is the case if the alloy samples are exposed to the influence of air and tide.

The NiTi CC alloy shows the most significant corrosion processes under the influence of tide, which is not surprising, bearing in mind that this environment is very aggressive due to constant changes in the dry-wet state. The Frechet distribution, that proved to be the most adequate to describe the data in the extended database, shows a tendency of a very long and thin tail, with significant right-skewed characteristics.

Thus, it can be said that under the influence of tide, NiTi CC alloys with a high probability develop small values of corrosion depth, while large values are very rare. Under the influence of air, this alloy develops small values of corrosion depth with high probability, but unlike the influence of tide, the distribution of higher values is much more uniform, and higher values of corrosion depth occur with statistically significant probabilities. Under the influence of the sea, the probabilities of occurrence of higher values of corrosion depth decrease much more slowly concerning the shape of the curve formed under the influence of tide. This means that the core processes of NiTi CC alloy are significantly pronounced if the samples are exposed to the sea.

Nitinol alloys exhibit similar behaviour from a hazard rate standpoint in a tide environment, whereas this is not the case for air and sea. The NiTi CC alloy shows an almost constant hazard rate trend in air and sea environment, which then rises sharply. In the case of NiTi as cast alloy, there is an opposite behaviour expressed by a sharp drop in the hazard rate which then stabilizes to an almost constant value. NiTi as cast alloys under the influence of tide develop most complex corrosion processes. The hazard rate decreases sharply then equalizes to an almost linear form, and finally, the value of the hazard rate shows a sharp upward trend.

CONCLUSIONS

In most cases, the problem with artificially generated databases related to corrosion depth arises due to data redundancy or due to the insertion of a large number of extreme values that affect shape, location, and skewness of formed histograms. These problems can be overcome by removing outliers as well as eliminating data that is frequently repeated, whereby corresponding data histograms can be adjusted to follow the structure of empirical histograms. Also, if researchers have sufficient knowledge of mathematical statistics, it is possible to obtain relevant conclusions by changing the statistical tests, or possibly by reducing the significance level. In the case of very complicated corrosion behaviour of alloys, it is possible that the solution to the problem of fitting continuous distributions lies exclusively in changing the research methodology, and it is logical to explore other directions, such as extreme value theory.

Applying the method of reliability based on the detected best fitted three-parameter continuous distributions on alloys with memory shape, from the obtained results it is clearly concluded that they show significantly different corrosive behaviour in different marine environments. The reliability of alloys decreases with the time of exposure to environmental influences, with different intensities and depending on environmental conditions in which they are placed. In all three alloys, the influence of the sea predominantly affects the degree of reliability, where the reliability of CuAlNi and NiTi CC is the lowest in changing conditions on the sea surface, which corresponds to alloys produced by continuous casting methods, while alloy NiTi as cast characterizes the lowest reliability when it is immersed in the sea.

In general, it can be concluded that it is very important that researchers pay attention to techniques for inserting artificially generated data into empirical databases that tend to depict complex corrosive behaviour of alloys. In addition to the systematic way of inserting synthetic data into empirical databases, it is possible to consider other known techniques for artificial data generation, such as probability sampling (Samples from Probability Distributions, Simple Random Sampling, Cluster Sampling, Multi-stage Sampling, etc.) and non-probability sampling (Quota Sampling, Convenience Sampling, Purposive Sampling, etc.).

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