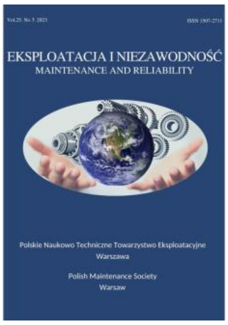

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Mathematical Calculation of Material Reliability Using Surface Roughness Feature Based on Plasma Material Interaction Experiment Results

Indexed by: Web of Science Group

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Highlights

- Aluminum bulk materials as electrodes in dc glow discharge helium plasma is studied in experimental work.
- Surface Roughness (Root Mean Square and Surface Mean) parameters of the aluminum electrodes are measured under Atomic Force Microscope.
- Weibull reliability is calculated for the aluminum electrodes' based on their surface roughness features and provided its material lifecycle predictions.

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Abstract

The choice of reactor structural material design must take into account the TOKAMAK fusion reactors' structural reliability. Due to their high levels of heat and energy, fusion reactions have significant deformation effects, which reduce the efficiency of energy production in reactors. Material selection, erosion and damage, heat and stress management, reliability analysis, maintenance, and inspection are crucial elements in determining how reliable fusion reactors are. The focus of this work is on material selection and reliability analysis based on these parameters. The most common wall materials used in fusion reactors are tungsten, beryllium, steel, or graphite. It is advised to utilize aluminum because harmful Beryllium dust limits the study of this element. For this purpose, a target of aluminum samples is established with a plasma of He ions created by glow discharge. The dependability of the samples is determined by calculating the Weibull Distribution and measuring the roughness of the sample surfaces following exposure.

Keywords

tokamak, material reliability, Weibull, Divertor, PMI (Plasma Material Interaction)

1. Introduction

One of the most challenging problems in this century is the energy demand due to the population growth with better living standards. Unfortunately, the primary energy sources are fossil fuels, which will soon run out. However, in order to have sustainable energy, other sources of energy such as renewable and nuclear energy is needed [34, 43]

Nuclear energy is produced at the final stage of the exothermic nuclear reactions. Two major nuclear reactions are known as fission and fusion. Nuclear fission is a process where a heavy unstable nucleus is split into two or more smaller nuclei and a huge amount of energy is released. Today, almost all of the nuclear power stations are based on nuclear fission.

The second type of nuclear energy is the nuclear fusion in which two or more nuclei are come together to form different atomic nuclei and other subatomic particles. In this process, an energy is generated due to the different masses of the reactants and products. However, in order for a fusion reaction to take place, about 100 million degrees of temperature is needed. Nuclear fusion is a unique solution which has unlimited fuel resources that can be found everywhere in the globe.

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Furthermore fusion reactor will uniquely produce short-lived radioactive waste and inherently safe [19-35]. The most widely known fusion reaction is the reaction between two hydrogen (H) isotopes, deuterium (D), and tritium (T). In this reaction, a neutron (n) with an energy of 14.1 Me V is generated and then this hot neutron is used in heating a coolant fluid (e.g. water) for producing steam to make the turbine work. However, a helium nucleus (He) with energy of 3.5 Me V is also produced [7,14,17,20,31]. Because the helium nuclei have charge, they will stay inside the reactor and give their energy to the plasma, to preserve its heat [8,9,11,23,28,32]. In a typical thermonuclear fusion reactor, the plasma is held in a magnetic field, thus forcing the fusion reagents with the adequate density to fuse. Confining plasma in magnetic field ensures plasma be separated from the first wall of the reactor. Particles that have high energy, leaves the confined plasma and collide to the surrounding walls. The highest erosion occurs in the divertor region, where lower energy plasma is deliberately guided by magnetic field lines to the divertor wall.

Fusion research focuses on wall materials and plasma-first-wall interactions. The generated Helium (fusion ash) must be removed from the plasma. This removal process causes the contact of the He with divertor walls [14,15,18,24,33,37,38,39,42].

This process causes the divertor and the reactor walls to deteriorate over time shorten their lifetime and release neutrals into the environment. Graphite, beryllium, molybdenum, steel and tungsten are the resistant materials against the reactor wall erosion in a Tokamak. Tungsten is the most resistant material against plasma with high atomic number and melting point [10,22,26,30,36].

In literature of reliability only specific study that most concentrated structural reliability investigation is performed is the nuclear fission reactors. Lifetime, reliability and risk analysis methods and application for structural systems and components of nuclear fission reactors are reviewed in [22]. In this source structural mechanics, fracture mechanics, probability mathematics, material science and fluid mechanics are used. In perspective of nuclear fusion reactors, since the reliability is concentrated on the fusion reactions in most case, structural reliability is minority in study literature. Recent studies are given in [3] states a review in structural and thermo-mechanical analyses standpoint. Methods of breeding blankets, magnets and diagnostics are collected in the review work. Another issue in reliability for fusion devices are concentrated on reliability and safety analysis of a fusion device [3]. It explains the reliability, availability, maintainability and inspectability analysis is performed in ITER, DEMO and Wendelstein 7-X fusion devices (international fusion devices for researchers) to complete their reliable and efficient operation for experiments or for energy production purposes [2]. This work only concentrate on the general components of the fusion devices. Most compatible study for reliability estimation of the Tokamak fusion reactor structural reliability is the application of of surface coating in commercial applications of the plasma. Study of the commercial application reliability [5] used a Burr III distribution, the IA PrgCS-II method is applied as a novel censoring mechanism and afterwards SSRe model parameter is attained for frequentist and Bayesian aspects are presented. As these reliability studies evaluated no useful method complement the prediction of the Tokamak fusion reactor structures. This study brings a new perspective in selection of material and reliability analysis with the industrial structural prediction method of Weibull prediction to determine the structural reliability of the reactor walls. In order to implement a statistical method in Tokamak fusion reactors, operational process conditions should be known and stability of the process need to be waited for calculations. Results of the real experimental data is used in calculations which also underlines the results presented in the study resembles the template of the Weibull prediction theorem graphs. There are many issues related to He plasma Tokamak reactor structural material interactions. In divertor regions He ash accumulation measurements in ITER or DEMO type reactors are shown in recent studies. Studies showed that the effects of alpha particle concentration on plasma operation is explored and the calculations are performed as in zero dimensional power and particle balance equations so that the He fusion reactions and optimum conditions are trying to explore. The studies showed that Helium as the ash of deuterium-tritium reaction cannot be avoided. Especially in ITER and DEMO class reactors, experimental studies aim to investigate low-activation materials usch as steels SiC ceramic composites and vanadium alloys. With the help of investigations new type of diagnostic tools and measurement techniques are researched. In EUROfusion project WP PFC (workpackage-package) on plasma facing components, He plasma loads, including the influence of plasma impurities is explored. He as a plasma impurity is of great interest when investigation of plasma wall relations because it will exist in a fusion plasma as an intrinsic impurity. He also has an impact on the surface morphology during plasma exposure, He created fuzz growth on the surfaces. That is more frequent in the divertor region wall material surfaces [4,29,37,40].

Above phenomena brings a question how does the structural reliability of Tokamak fusion reactors is assessed and criteria for designing a reactor wall how does the life time cycle will be determined according to the selected material.

The structural reliability of Tokamak fusion reactors refers to the assessment and prediction of reliability and safety of reactors building material. It includes assessment of the structural integrity, durability, performance of materials and components under the extreme parameters of occur in the fusion reactor. Key factors in evaluating the structural reliability of the Tokamak fusion reactors include material selection, erosion and damage, heat and stress management, reliability analysis, maintenance and inspection factors. In material selection perspective choosing the right material which can resist to the tough operating conditions that includes high temperatures, intense radiation, and particle bombardment.

Cheap and wide used materials need to be used in the structures of the Tokamak fusion reactors are also a design criteria. Aluminium for instance is not used as wall material in a fusion reactor because of its low melting temperature. It is used as an insulator material, without contact to the plasma. However, Aluminium may be used as “substitute” for beryllium. This is sometimes done since the toxic Beryllium dust prevents studies of Beryllium. Therefore, Aluminium is investigated as a test material in this study.

Reliability analysis criteria is important in determination of reactor structures for their resilience and low maintenance operations. Reliability methods use probabilistic risk assessment and Random distribution methods such as Weibull distribution, to quantify in assessing the likelihood of failure and predict the lifetime of reactor components. In this study He plasma-Al surface interaction was investigated from the perspective of Surface Roughness property to calculate the Weibull prediction to analyse the life time structural material.

2. METHOD

The experimental setup shown in Figure 1 was designed to perform the plasma-wall interaction.

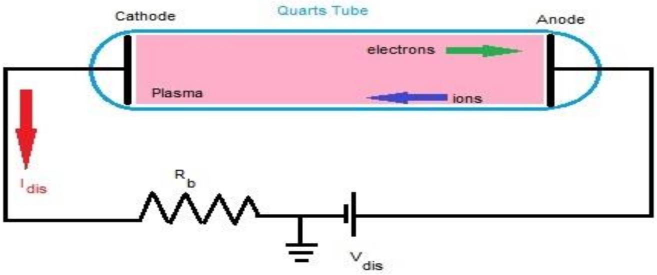


Figure 1. Experimental Setup Schema.

Before exposure to the plasma the surfaces of sample Aluminum pellets were polished and cleaned and Atomic Force Microscope (AFM) images of them were taken. In the experimental setup, He gas is fed into the boiler after vacuum is provided. A high DC voltage is then applied such that He plasma is generated. Since the Al pellets were placed on cathode and anode sides of the boiler, He ions hit the cathode while electrons hit the anode.

A vacuum was created up to 10-3 Torr pressure in the glass tube and He is fed into the tube. A 10 kV DC voltage source was applied between cathode and anode so that He plasma is created. In order get best glow as seen in Figure 2, the distance between the anode and cathode plates was set as 5 cm. The used He gas was 99.999% pure and the total gas flow rate was 100 ml/min.

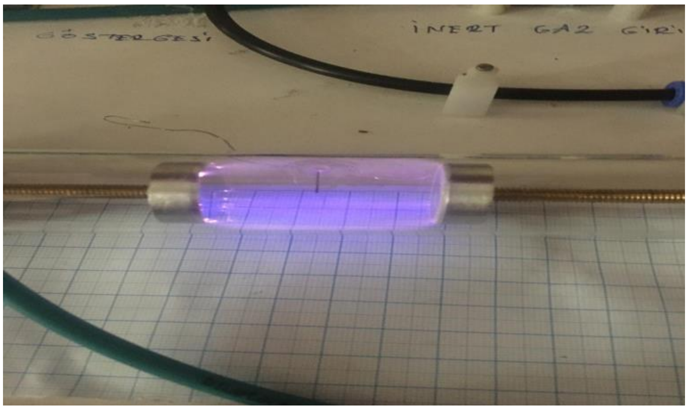


Figure 2. Generated He Plasma.

Each time two plates were placed at cathode and anode respectively and subjected to the radiation for a time value. Then, pellets are removed and replaced to observe interaction at another time value. Thus, different pellets were irradiated at time values of 60, 120, 180, 240, 300 and 360 minutes.

The irradiated pellets were then analyzed by Metal Microscope (Nikon LV100ND) and Atomic Force Microscope (Ambios Q-Scope 250). The Metal Microscope can magnify the sample 50x, 100x, 200x and 500x percentages. Mid-surface sections on the sample were taken for analysis before and after the experiment.

AFM measurements were carried out at room temperature and ambient conditions with NCS-16 cantilever was used. The scan rate in all the image acquisitions was 1 Hz. Non-contact mode was used to take topographic images. The surface roughness of each irradiated pellet at different exposure time is observed by AFM. The metal microscope and AFM digital images taken from analyzed areas for each exposure time are given in figure 3. AFM calculates the Surface Roughness (RMS) and average peak of surfaces based on ASME B46.1 standard [6,12,16,46,47]. As described in ASME B46.1 standard, Sa (Mean surface roughness) is the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. In other words, Sa is the average of a set of individual measurements of a surface peaks and valleys. Surface roughness is the root mean square average of the profile height deviations from the mean line, recorded within the evaluation length. It is also defined in ASME B46.1 standard. Sa and RMS both represent surface roughness, but each is calculated differently. Sa is calculated as the Roughness Average of a surfaces measured microscopic peaks and valleys. RMS is calculated as the Root Mean Square of a surface measured microscopic peaks and valleys. Aluminum pellet surface deteriorations' by the He plasma are quantified by surface roughness and mean surface roughness values under AFM. So that these measured parameters can be used in reliability calculations as input parameters.

Surface roughness (RMS) and surface mean roughness (Sa) values are used to calculate to predict reliability of the aluminum plate. Table-1 shows the Aluminum anode and cathode samples that are irradiated with He plasma with different time processes, AFM surface RMS and Sa values. RMS and Sa values obtained from AMF images are given in Table 1. These values are used in three-parameter Weibull formula in order to calculate the reliability of the Aluminum under He plasma.

Table 1. He Plasma Al plate Roughness Failure Data Set.

Sample Label	Process Time (min)	RMS (μm)	Sa (μm)
60 min,5μm,Cathode	60	92.1	77.5
120 min, 5μm,Cathode	120	79.0	61.8
180 min,5μm,Cathode	180	16.2	12.9
240 min,5μm,Cathode	240	28.2	22.0
300 min,5μm,Cathode	300	27.1	21.8
360 min,5μm,Cathode	360	7.2	5.3
60 min,5μm,Anode	60	130.9	103.4
120 min,5μm,Anode	120	271.3	223.3
180 min,5μm,Anode	180	85.6	58.6
240 min,5μm,Anode	240	39.4	30.9
300 min,5μm,Anode	300	158.1	132.0
360 min,5μm,Anode	360	504.1	419.8

Three-parameter Weibull Distribution equation is given as follows [27]:

$$R(t) = e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \quad (1)$$

Where t is the irradiation time ($t \geq \gamma$), β is the shape parameter (slope)(β>0), α is the scale parameter (characteristic life) (α>0) and γ is the location parameter. In calculations γ is generally taken as γ=0 because it is the displacement of the reliability distribution graph origin. The probability of failure function is defined as

$$F(t) = 1 - R(t) \quad (2)$$

$$1 - F(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (3)$$

where γ=0 and with 0<F(t)<1. The equation may be rearranged as

$$\ln\left(\ln\frac{1}{1-F(t)}\right) = \beta lnt - \beta ln\alpha \quad (4)$$

In order get an equation in the form of y=mx+n, let

$$y(t) = \ln\left(\ln\frac{1}{1-F(t)}\right), \text{m=β and n=}-\beta ln\alpha \quad (5)$$

Bernard Approximation for Median Ranks can be used to obtain an estimate of the unreliability for each failure [1]. Bernard Approximation of Median Rank is given as follows:

$$F(t) = MedianRank = \frac{Rank-0.3}{N+0.4} \quad (6)$$

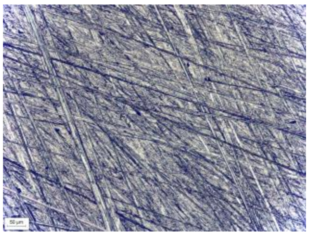
where rank is the order number in data set table and N is the maximum number of orders in the table set. Table-1 RMS and Sa values are used in (5) and (6) to calculate the Table-2 and Table-3 values. By calculating the F(t) and y(t) in Table-2 and Table-3, equation (4) is used to calculate (3) and (2) to find the characteristic equation of the Aluminum samples given in equation (1).

3. RESULTS & CONCLUSION

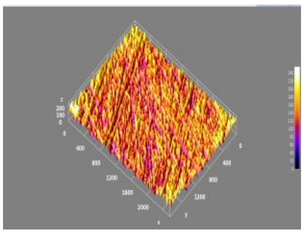
In figure 3 shows physical changes on the surface of Al samples at anode and cathode at 60, 240, 300 and 360 minutes under He plasma interaction respectively. In these sample areas grains, black points, semi gray spots were observed. Also the area and face-to-face measurements were performed for black points or gray points. Metal microscope showed hills (high areas) and holes (low areas) on the aluminum plates surfaces.

Selected Area on Al Pellet

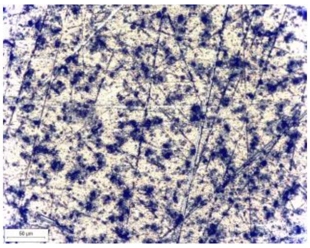
3D Surface Plot



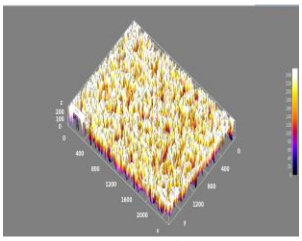
60 min cathode image He plasma processed 100x magnification under light



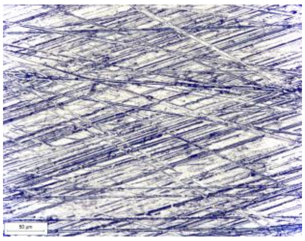
60 min cathode 3D surface plot He plasma processed 100x magnification under light



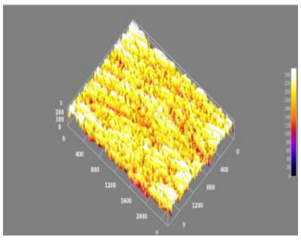
240 min anode image He plasma processed 200x magnification under light



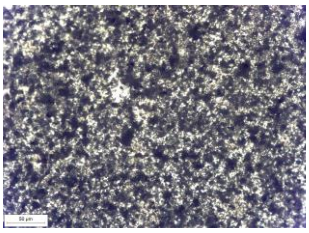
240 min anode 3D surface plot He plasma processed 200x magnification under light



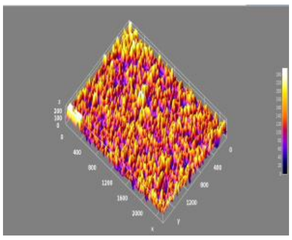
300 min cathode image He plasma processed 200x magnification under light



300 min cathode 3D surface plot He plasma processed 200x magnification under light



360 min anode image He plasma processed 200x magnification under light



360 min anode 3D surface plot He plasma processed 200x magnification under light

Figure 3. Al surface observation images and their 3D plot graph of anode and cathode with different process time of He plasma on Metal Microscope.

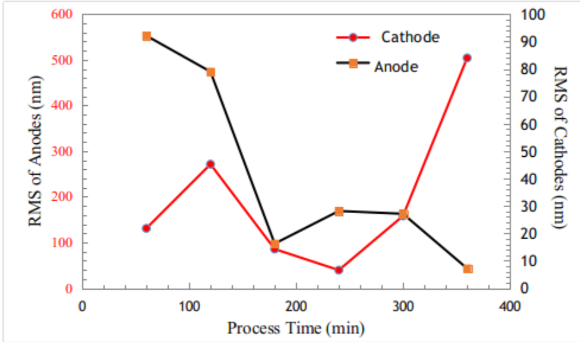
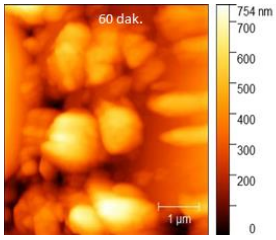
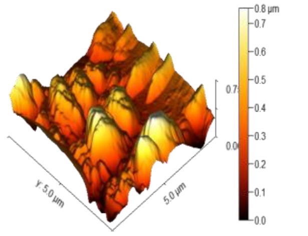


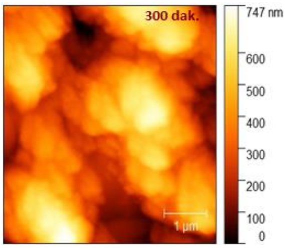
Figure 4. RMS values of anode and cathode plates.



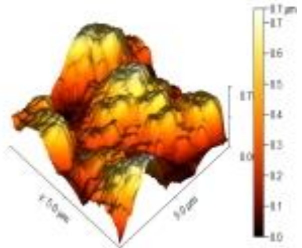
AFM image of Al plate with 60 min process time



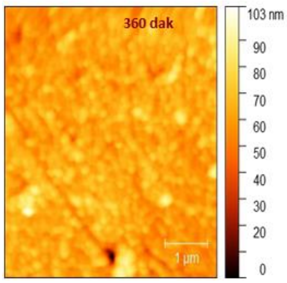
3D plot AFM image of Al plate with 60 min process time



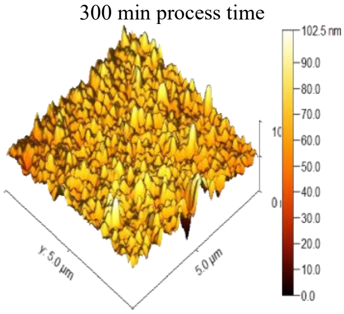
AFM image of Al plate with 300 min process time



3D plot AFM image of Al plate with 300 min process time



AFM image of Al plate with 360 min process time



AFM image of Al plate with 360 min process time

Figure 5. AFM images and 2D and 3D profiles of Al plates under 0, 300 and 360 min process time.

Figure 4 shows the AFM surface roughness of Al plates under He plasma at anode and cathode. AFM measurements were defined as surface roughness data. Surface roughness will represent the physical change of the target material surface that possessed with the He plasma. Target material aluminum plates are observed and inspected under AFM. The Aluminum material was inspected with a cross section of 5µm radius is selected from the center section on the plates. Figure 5 shows two- and three-dimensional AFM profile graphs with 60, 300 and 360 minutes of process time pseudo colored images.

The calculated F(t) and y(t) values are given in Tables-2 and 3 for anode and cathode Al plates, respectively.

Tables 2 and 3 demonstrate anode and cathode surface roughness-dependent outcomes. The plasma sheath at cathodes and anodes is thought to affect cathode and spot structure, electrode erosion, thermionic emission, plasma heat flux to the wall, and other electrode processes. Plasma glow discharge regime altered anode-cathode plasma interactions, according to experiments. Electrons gathered on the anode and influenced by high-kinetic energy thermionic emission are thought to have damaged it more than the cathode.

Table 2. F(t) and y(t) values calculated by equations 5 and 6 for Al plate at anode.

Process time (min)	Sa (m)	RMS (μm)	F(t)	ln(RMS)	ln (Sa)	y(t)
60	103,4	130,9	0,1093	4,8744	4,6386	-2,1556
120	223,3	271,3	0,2656	5,6032	5,4085	-1,1752
180	58,6	85,6	0,4218	4,4496	4,0707	-0,6015
240	30,9	39,4	0,5781	3,6737	3,4307	-0,1472
300	132	158,1	0,7343	5,0632	4,8828	0,2819
360	419,8	504,1	0,8906	6,2227	6,0397	0,7943

Table 3. F(t) and y values calculated by equations 5 and 6 for Al plate at cathode.

Process time (min)	Sa (m)	RMS (μm)	F(t)	ln(RMS)	ln (Sa)	y(t)
60	77,5	92,1	0,1093	4,5228	4,3502	-2,1556
120	61,8	79	0,2656	4,3694	4,1239	-1,1752
180	12,9	16,2	0,4218	2,7850	2,5572	-0,6015
240	22	28,2	0,5781	3,3393	3,0910	-0,1472
300	21,8	27,1	0,7343	3,2995	3,0819	0,2819
360	5,3	7,2	0,8906	1,9740	1,6677	0,7943

Figure 6 and 7 show calculated y(t) values versus ln(t) based on surface roughness and mean surface roughness for Al plate placed at cathode while.

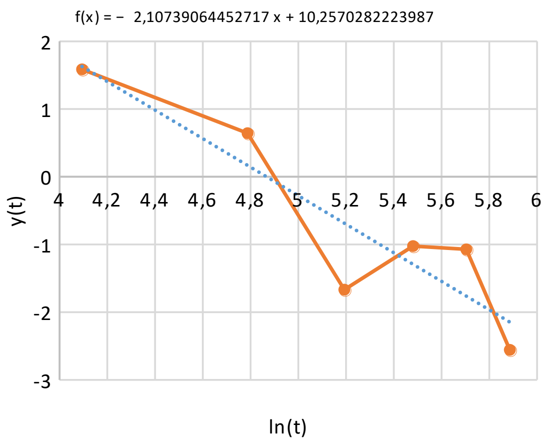


Figure 6. Calculated y(t) values as a function of ln(t) by using measured RMS values for cathode plate.

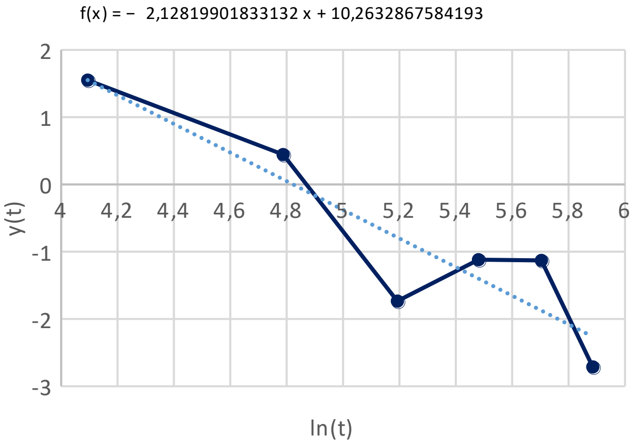


Figure 7. Calculated y(t) values as a function of ln(t) by using measured Sa values for cathode plate.

Figure 8 and 9 show calculated y(t) versus ln(t) based on roughness and mean surface roughness for Al plate placed at cathode.

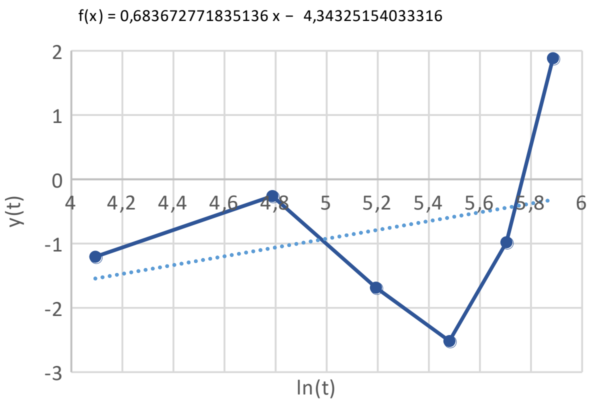


Figure 8. Calculated y(t) values as a function of ln(t) by using measured RMS values for anode plate.

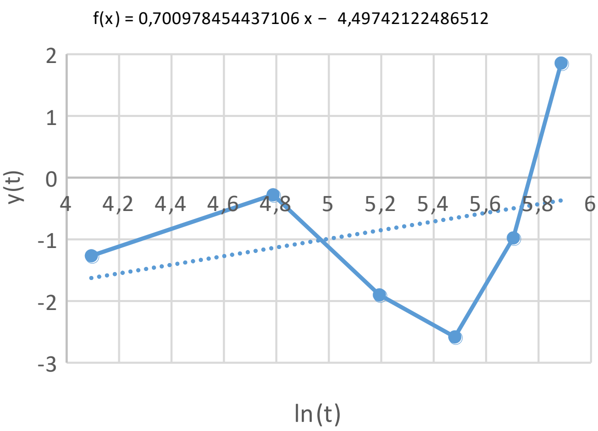


Figure 9. Calculated y(t) values as a function of ln(t) by using measured Sa values for anode plate.

Trend line function of graphs (Figures 6–9) determines β and α values in equations 4 and 5. Then, using α and β and assuming =0, eq.1's dependability is calculated. Figure 10 shows RMS and SA reliability values for Al surfaces at anodes as a function of process duration in minutes.Al surface at anode is extensively scratched by He plasma and dependability declines with time. Al surface reliability decreases over time, increasing anode failure rate. Increasing failure rate indicates ion radiation may induce material flaws or death over time.

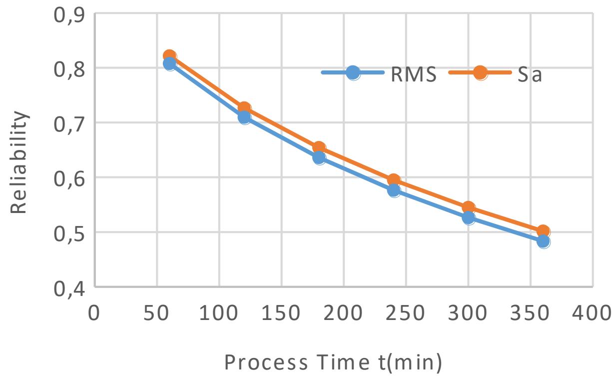


Figure 10. Calculated reliability roughness (RMS) and mean roughness (Sa) for Al surface placed at anode.

Figure 11 shows roughness (RMS) and mean roughness (Sa) reliability values for Al surface at cathode as a function of process duration in minutes. Al cathode surface roughness (Sa).

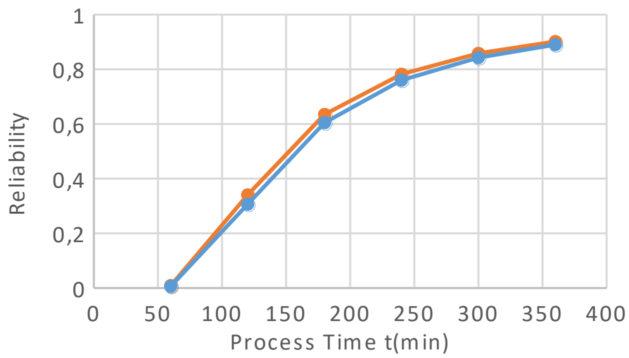


Figure 11. Calculated reliability roughness (RMS) and mean roughness (Sa) for Al surface placed at cathode.

Helium plasma etching of Al surface at cathode enhances roughness and mean roughness reliability.

Anode is more damaged than cathode. Ion particles gathered on the cathode aluminium sample, and the electron particle beam damaged the anode sample.

Al degrades as He accumulates on the anode surface. He can diffuse a lengthy channel and create vacancy defects by self-trapping at kinetic energies below metal displacement threshold due to his insolubility in metals, such as Al in our study. He vacancy complexes can trap He atoms until hill-type surfaces solidify. When these reactions occur near to the surface, metal atoms move, flake, and nanofibers are created. Backscattered He neutrals interact with the Al surface, causing the same effect as He ion implantation inside metals. Al depositing atoms improve surface mobility and kinetic energy. These coupled mechanisms yield porous microstructures [21][25]. Metal microscope and AFM reliability calculations reflect this.

Weibull distribution is a useful way for calculating plasma material contact event structural reliability, according to calculations. The nuclear fission industry predicts structural reliability in pipes and pumps using this technology. Future plasma parameter experiments can apply Weibull technique in plasma material interactions. Plasma collisionality and anode/cathode sputtering yields can be studied in the future. Tokamak fusion reactor structural reliability ensures safe, secure, and efficient operations. This comprises material selection, erosion and damage evaluation using surface roughness factor, effective plasma process time to manage heat and stress, reliability analysis using Weibull prediction, and proactive maintenance.

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