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Influence of Environmental Temperature on the Corrosion Resistance of Various Aluminum Alloys: an Experimental Study

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The authors declare that there is no conflict of interest.

Abstract. One of the biggest challenges that engineers encounter in a variety of industry sectors is corrosion. The current research focuses on the corrosion behavior of various types of aluminum alloys widely used in the industry. In this regard, aluminum alloys Al2024, Al6061, and Al7075 were tested. Also, the effect of environmental temperature on the corrosion rate of each group of materials was investigated. Three statistical parameters, including total corroded area, corrosion rate (total corroded area to total sample area), and the maximum size of corroded point, were measured as corrosion indicators in the samples. In addition, the surface hardness of the samples was measured and presented by the Brinell method. Finally, the weakest aluminum alloy against corrosion under different temperature conditions was introduced. The corrosion test conducted in the presence of cold air produced the maximum hardness in any of the aluminum alloys (2024, 6061, and 7075) that were examined. Aluminum 7075 has the lowest corrosion resistance, while aluminum 6061 has the strongest corrosion resistance when various testing conditions are taken into account.

Keywords: aluminum alloys, corrosion rate, Optical Microscope (OM), observations, surface hardness

Authors' contribution:

Reza Kashyzadeh K. — conceptualization, methodology, software, writing; *Ghorbani S.* — writing, original draft preparation; *Averyanov A.S.* — writing, original draft preparation.

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Влияние температуры окружающей среды на коррозионную стойкость различных алюминиевых сплавов: экспериментальное исследование

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Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Одной из самых серьезных проблем, с которой сталкиваются инженеры в различных отраслях промышленности, является коррозия. В настоящее время основное внимание уделяется коррозионным свойствам различных типов алюминиевых сплавов, широко используемых в промышленности. В связи с этим были протестированы алюминиевые сплавы Al 2024, Al 6061 и Al 7075. Кроме того, было исследовано влияние температуры окружающей среды на скорость коррозии каждой группы материалов. В качестве индикаторов коррозии образцов были измерены три статистических параметра, включая общую площадь коррозии, скорость коррозии (отношение общей площади коррозии к общей площади образца) и максимальный размер точки коррозии. Кроме того, с помощью метода Бринелля была измерена и представлена поверхностная твердость образцов. Наконец, был представлен алюминиевый сплав, наиболее устойчивый к коррозии при различных температурных режимах. Испытание на коррозию, проведенное в присутствии холодного воздуха, показало максимальную твердость среди всех исследованных алюминиевых сплавов (2024, 6061 и 7075). Алюминий 7075 имеет самую низкую коррозионную стойкость, тогда как алюминий 6061 имеет самую высокую коррозионную стойкость, если принять во внимание различные условия испытаний.

Ключевые слова: алюминиевые сплавы, скорость коррозии, оптический микроскоп (ОМ), наблюдения, твердость поверхности

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Introduction

Corrosion is one of the biggest challenges faced by engineers in various industries [1–3]. This destructive phenomenon is a physical and chemical interaction between a metal material and the environment, which leads to a change in the properties of the metal and can cause a significant disruption in the performance of the metal, the environment, or the technical system of which they are a part of [4; 5]. Owing to the presence of an oxide layer on its surface, aluminum alloys show good corrosion resistance in corrosive environments with pH values in the range of 3 to 9. However, in environments with pH values lower than 3 or higher than 9, the outer porous layer is dissolved, and the aluminum surface is severely corroded. In other words, aluminum products are quickly destroyed as a result of long-term exposure to aggressive environments, especially those containing chlorine [6; 7]. Therefore, it is very important to understand the corrosion properties of aluminum alloys in special environments and under harsh working conditions. Failures caused by corrosion in metals have caused irreparable economic losses in large industries such as petrochemical, automotive, and aerospace, etc. [8; 9].

National Association of Corrosion Engineers (NACE), as a world leader in corrosion control, has estimated the total costs associated with global corrosion losses at 2.5 trillion dollars per year, which is equivalent to 3.4% of the world's Gross Domestic Product (GDP) [10]. According to the NACE international report, corrosion losses in the world's largest economies include 5% of GDP for Arab countries, 4.2% for China and India, 4% for Russia, 3.8% for the European Union (Norway and Switzerland), 2.7% for the United States, and 1% in the case of Japan. These statistics emphasize the importance of understanding corrosion phenomenon, as well as the development of plans that prioritize the long-term stability of materials and the use of optimal corrosion protection methods. As mentioned previously, aluminum alloys have many uses in industry. Therefore, considerable research has been conducted to investigate the destructive phenomena on aluminum. As schematically illustrated in Figure 1, a wide variety of corrosion types exist [11].

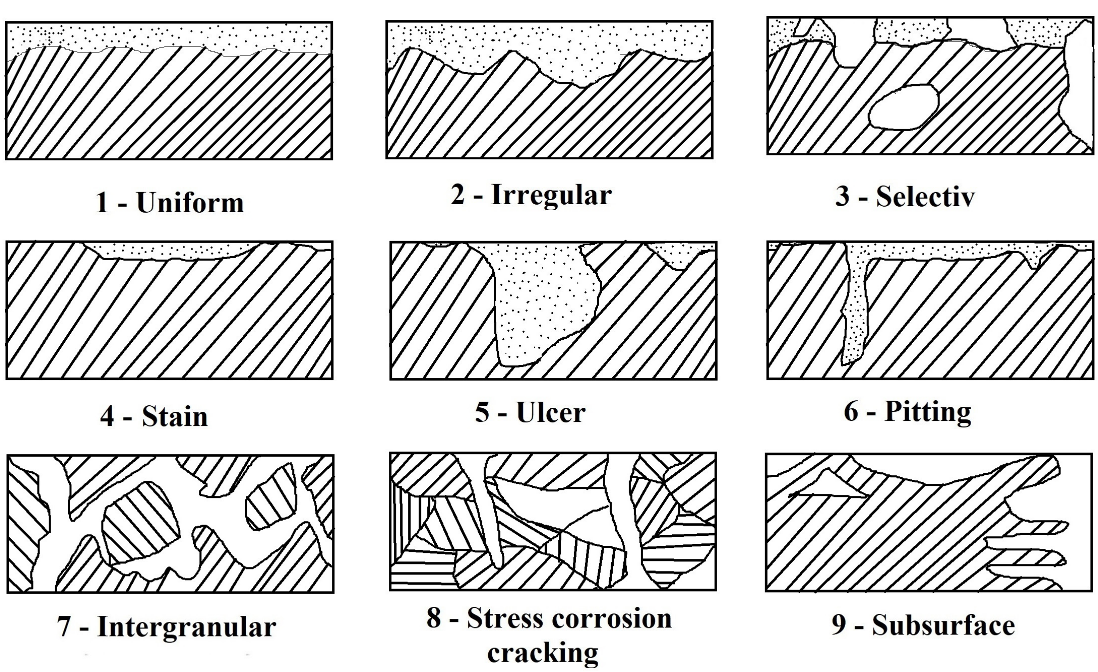


Figure 1. Schematics of different types of corrosion in aluminum alloys
S o u r c e: made by A.S. Averyanov, S. Ghorbani, K. Reza Kashyzadeh [11]

Among the corrosion mechanisms, pitting, intergranular, and exfoliation corrosion are the most prominent [12]. Moreover, exfoliation corrosion and stress corrosion are also the main types of corrosion in aircraft materials [13]. Paglia and Buchheit investigated the sensitivity of aluminum alloy friction stir welds to corrosion [14]. Because the microstructure of the material changes drastically in the Heat-Affected Zone (HAZ), intergranular corrosion occurs in this area. This corrosion becomes more severe as the grain boundary sediments become coarser. They reported that by using a short-term heat treatment after welding at a temperature similar to the welding temperature, the microstructure can be modified, and the corrosion rate can be reduced.

Xu X. et al. utilized an amorphous CrAlN coating to improve the corrosion resistance of aluminum alloy in a 3.5% NaCl solution [15]. They reported that material properties (i.e., microstructure and corrosion resistance) of the amorphous CrAlN coating depends on the nitrogen content of the coating. Sánchez-Amaya et al. studied the influence of heat treatment on the susceptibility of AA2024 and AA7075 alloys to intergranular corrosion [16]. They showed that slow quench step resulted in samples with high susceptibility to intergranular corrosion in both alloys.

Li X. et al. simulated a mechanical test in line with the corrosion behavior of 7005 aluminum alloys in atmospheric environments [17]. In other words, they believed that the stress concentration of the pits led to the destruction of the mechanical properties. Therefore, the effects of pit size and location parameters on stress concentration were analyzed using Finite Element (FE) method. Finally, they presented a Back Propagation Neural Network (BPNN) model to predict stress concentration.

As is clear from the above literature review, much research has been carried out in the field of aluminum corrosion and different methods to prevent or reduce the corrosion rate. Most research has been experimental. However, a limited number of simulation studies have been conducted. In addition, in recent years, machine-learning techniques have been used in this field. In simulation studies, laboratory data are required to validate the model. Furthermore, using machine learning techniques, experimental data is collected, and the machine is trained. Therefore, it can be concluded that laboratory data and tests are required in any case. In addition to the above-mentioned issues, not all the details of the corrosion phenomenon can be simulated in the software, and the main reason is the simplification of the software to solve various problems. Therefore, to achieve a system response with a higher accuracy, it is necessary to perform a series of tests. Therefore, this study was performed in a laboratory. In this study, different groups of aluminum alloys were prepared and immersed in a corrosive solution with a pH of approximately 12. Finally, the solution containing the sample was placed in three different environments at different temperatures. After a specified period of time, the samples were removed from the solution and the corrosion parameters were investigated. The subsequent parts of the article are organized in such a way that the second section is dedicated to materials and methods. The third section describes the experiment, and the obtained results are discussed in the fourth section. Finally, the achievements of the current study are presented in the last section.

1. Materials and methods

1.1. Materials

The studied materials are widely used aluminum alloys in industry, including 2000, 6000, and 7000 series sheets with a thickness of 4 mm. These sheets were prepared using a casting process. Then, using a wire cutter, they were cut into pieces with a square cross-section and side size of 10 mm. Quantometric test was performed to extract the percentage of the constituent elements in the raw materials. Table 1 illustrates the chemical composition of Al 2024, Al 6061, and Al 7075. Moreover, for each group, a specific heat treatment was defined according to what is most commonly used in the industry. For example, to perform T6 heat treatment, Al 7075 samples were fully tempered by heating at 480 °C for 5 h and then quenched in water below 120°C (slow cooling of approximately 28 °C per hour). Finally, they were kept at this temperature for 24 h [18].

Moreover, to determine the effect of heat treatment on the mechanical properties of each group of aluminum alloys, nine laboratory samples were prepared according to the ASTM E8/E8M standard. Tensile tests were performed at room temperature under controlled environmental conditions according to ISO 17025. The obtained results, including the key parameters, are listed in Table 2.

Table 1

Chemical composition of different aluminum alloys used in the current research, wt%

Material	Al	Si	Fe	Cu	Mn	Mg	Ni	Ti	Cr
Al 7075	96.68	1.15	0.32	0.01	0.73	0.99	0.01	0.01	0.10
Al 6061	97.72	0.58	0.36	0.21	0.03	0.93	0.00	0.01	0.16
Al 2024	97.57	0.64	0.14	0.27	0.12	1.00	0.01	0.03	0.22

Source: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

Table 2

The results obtained from tensile tests

Material	Yield strength	Ultimate tensile strength
Al 2024	98 MPa	186 MPa
Al 7075-T6	483 MPa	560 MPa

Source: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

1.2. Methods

This section describes the general idea behind conducting this research. The working algorithm is illustrated step by step in Figure 2.

This research includes two preparation steps, that is, aluminum samples and a corrosive solution with a minimum pH of 12. The tests were divided into three groups: primary, main, and secondary.

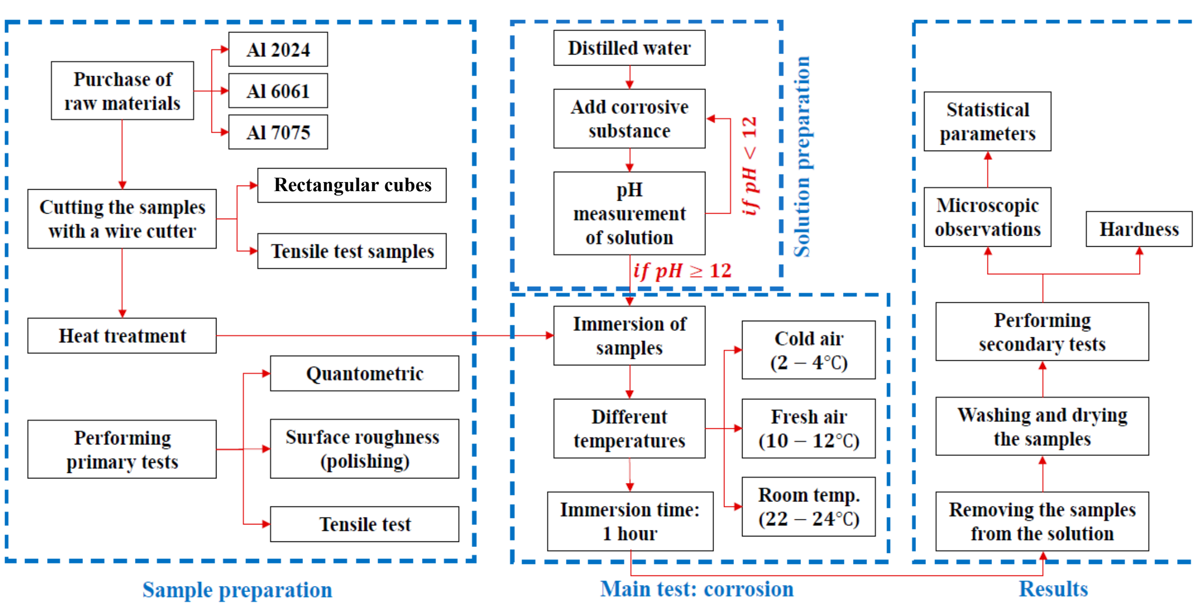


Figure 2. The working algorithm used in the current research
Source: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

In fact, primary tests are related to the tests performed before the main test, that is, corrosion, and the goal is to better understand the properties of the material. Subsequently, the main test is corrosion, which is done by immersing the samples in the corrosive solution for a certain period of time. Finally, there is a secondary test that is performed on the corroded samples to determine their corrosion rate through microscopic observations and measurement of statistical parameters. Furthermore, to determine the effect of corrosion on the properties of the raw material, hardness measurement is also done.

2. Experiments

Before performing the main test, the surfaces of the samples were polished with P800 grit sandpaper so that they had the same surface roughness. To create a corrosive solution, 20 g calcium hydroxide was added to 250 ml of distilled water (pH~6.5). In this time, the pH of the solution was measured and showed a value of 10.2. Subsequently, 20 g of sodium hydroxide was added; as a result, the pH value reached approximately 12.12. The solutions were poured into nine glass containers at the same height level and each sample was immersed in a solution container. The glass containers were placed in three different environments in terms of temperature, including 2–4 degrees called cold air, 10–12 degrees called fresh air, and 22–24 degrees called room temperature. The immersion time for all samples was considered one hour. Subsequently, the samples were removed from the solution, washed with distilled water, and their surface was dried with a heater, and finally they were not exposed to air.

The corrosion process in aluminum is based on the following reaction equations:

$$2Al+3Ca\left(OH\right)_2 \rightarrow 3Ca+2Al\left(OH\right)_3; \qquad (1)$$

$$Al\left(OH\right)_3 + NaOH \rightarrow Na\left[Al\left(OH\right)_4\right]. \qquad (2)$$

The surface analysis of the samples was performed using an Olympus GX53 optical microscope and the Olympus Stream program. In fact, Optical Microscope (OM) observations were conducted to monitor surface damage characteristics such as the maximum, minimum, and average diameters of pits, pit shapes, and corrosion rate. Thus, the area of the visible sample in the observation range of the microscope was measured in square micrometers S_t. Moreover, the area of each corrosion damage was measured and dis played as S_i,where i represents the number of damages caused on the surface of the sample owing to the corrosion. Eventually, the corrosion rate was obtained as the ratio of the total area of corrosion damage on the surface to the total area $R = \sum S_i / S_t$. In addition, the largest corrosion damage was identified on the surface, and assuming the shape of the damage to be circular or several circles connected together, the largest diameter of the damage was measured as D_{max}.

Finally, the hardness values of the samples were measured. For this purpose, a universal hardness tester METOLAB 703 was used with the ability to measure hardness based on Brinell, Rockwell, and Vickers methods. Three points were measured for each sample to verify the reproducibility of the results. The hardness test was performed based on the Brinell method with a ball (diameter of 10 mm), applying a load of 187.5 kg and a settling time of 30 s.

3. Results and Discussion

For ease of understanding, each sample was assigned a unique numeric and letter code that indicated the raw material and corrosion conditions. The four-digit number indicates the series of aluminum alloys, and the letter indicates the test conditions. In this regard, *X*, *K*, and *Y* represent cold air, room temperature, and fresh air, respectively. The samples after the corrosion test along with their identification codes are shown in Figure 3. It is clear that the images of the samples exposed to fresh air have a darker surface than the other samples. On the other hand, the images related to samples that are in the vicinity of cold air have a brighter surface, such as snow salt.

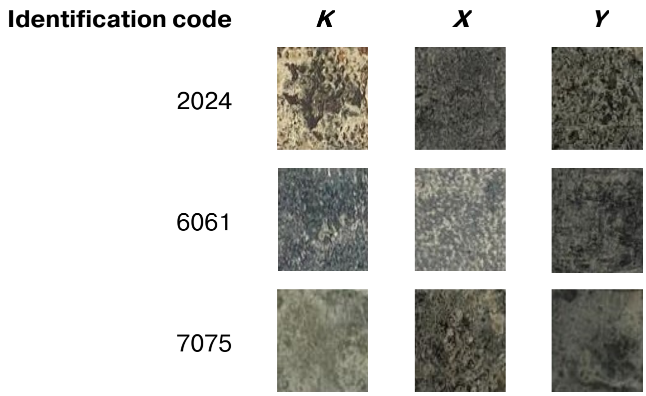


Figure 3. Samples after performing corrosion tests under different conditions
S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

In addition, Figure 4 illustrates the corroded surfaces of different samples under an optical microscope at 10 × magnification. These images were obtained after cleaning (washing with distilled water, drying with a heater, and not being in close proximity to air). Therefore, the corroded parts can be recognized as dark holes with prominent depths [19].

OM observations showed that aluminum 7075 suffered more corrosion damage under all temperature conditions than the other two aluminum series (6xxx and 2xxx) did. Moreover, among all the samples, the sample made of the 6061 alloy showed the least corrosion effects at room temperature, which is consistent with the results presented in the laboratory study of Kharitonov et al. [20] on the corrosion observations of the sixth series aluminum alloy.

Next, to measure the statistical parameters and compare the samples from the viewpoint of corrosion resistance, microscopic observations were performed at 100 × magnification. These images (Figures 5–7) are shown in detail, including the corroded areas with red lines and the largest corrosion damage in yellow. Also, the blue number indicates the largest size corresponding to the largest corrosion damage, which was extracted in micrometers using the software. In addition, the area of the corroded zones was extracted using the software and is reported in Tables 3–5. All corroded zones are indicated by numbers. Moreover, the zero number represents the total area of the examined surface.

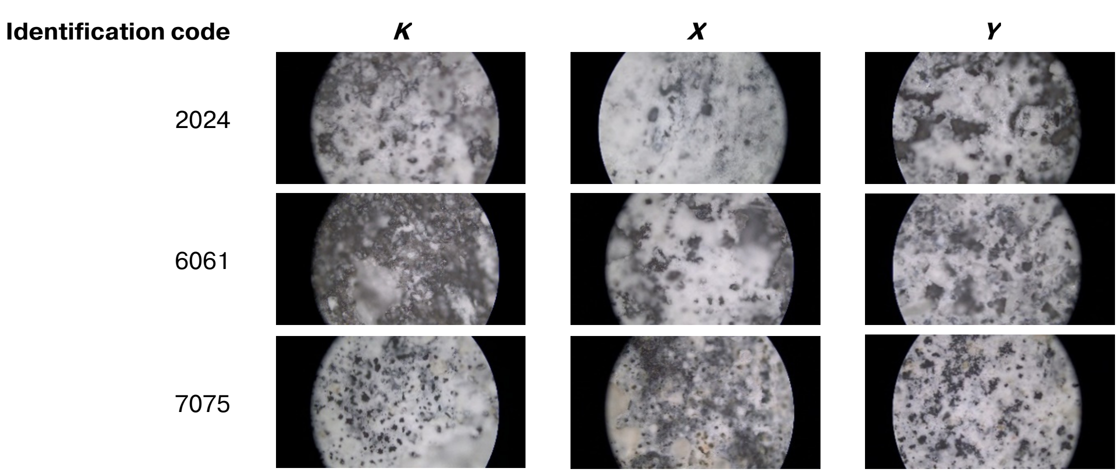
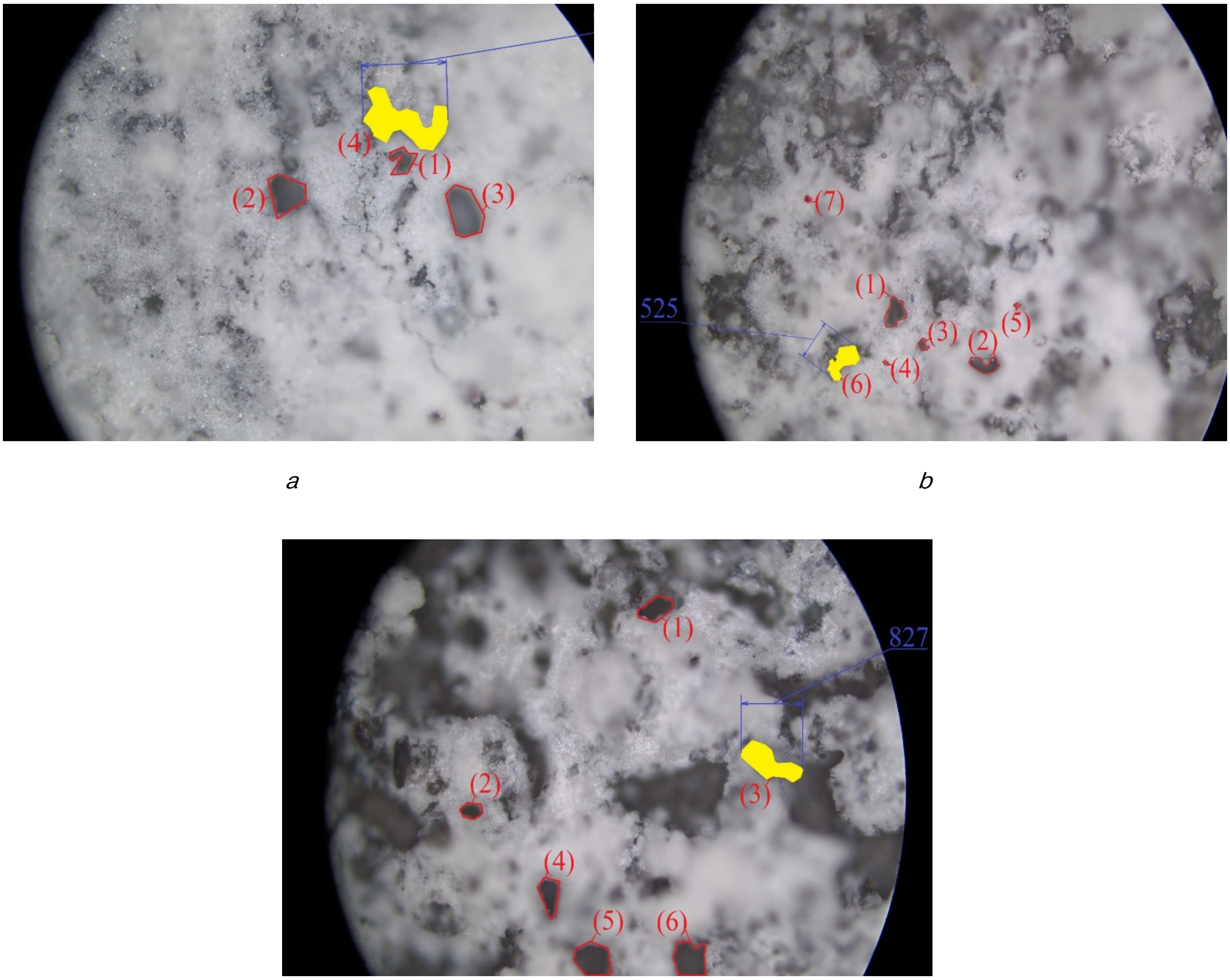


Figure 4. OM observations at 10 × magnification
S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov



a *b*

c

Figure 5. OM observations with 100 times magnification
for Al 2024 samples at different temperature conditions including:
a — in the vicinity of cold air; *b* — at room temperature; *c* — in the vicinity of fresh air
S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

Table 3

Statistical characteristics (area in $\times 10^3 \mu m^2$) corresponding to Figure 5

Zone No.	0	1	2	3	4	5	6	7
Part (a)	73913	81.4	180.5	190.8	386	–	–	–
Part (b)	74404	54	32	11	5	6	104	7
Part (c)	74695	108	47	333	113	248	265	–

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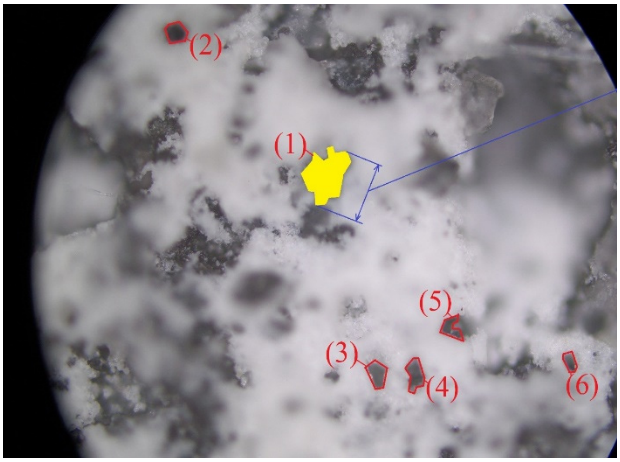

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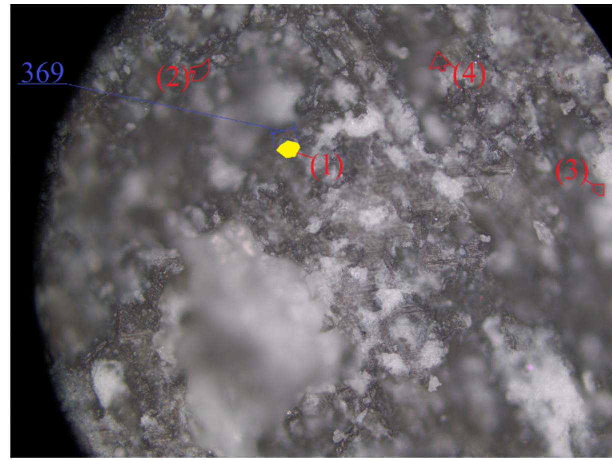

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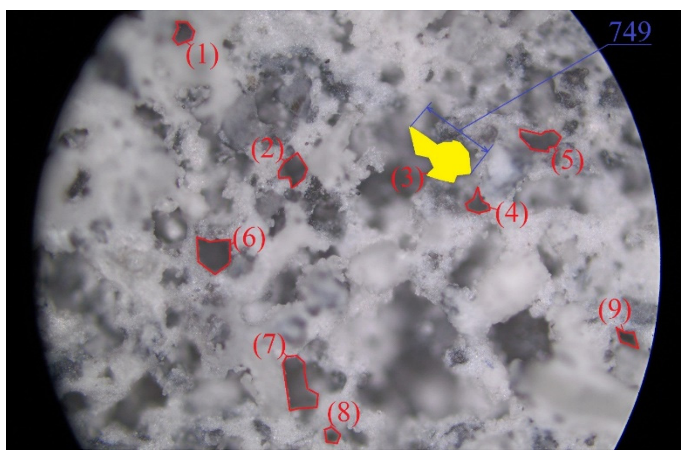


c

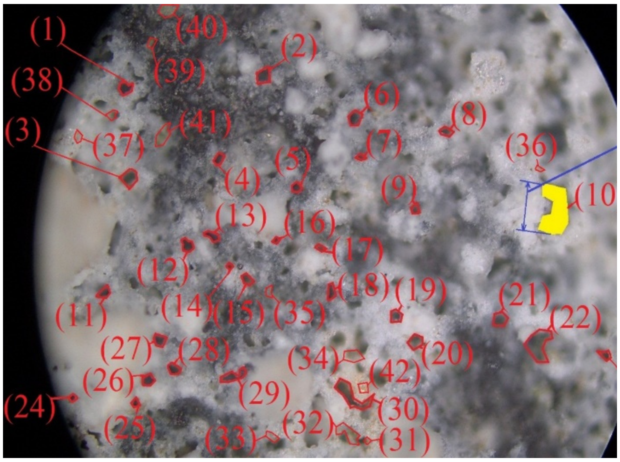
Figure 6. OM observations with 100 times magnification
for Al 6061 samples at different temperature conditions including:
a — in the vicinity of cold air; *b* — at room temperature; *c* — in the vicinity of fresh air
S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

Table 4

Statistical characteristics (area in $\times 10^3 \mu m^2$) corresponding to Figure 6

Zone No.	0	1	2	3	4	5	6	7	8	9
Part (a)	72766	234	106	121	119	114	102	–	–	–
Part (b)	74131	67	63	50	43	–	–	–	–	–
Part (c)	74237	86	104	306	71	106	145	232	52	54

S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov



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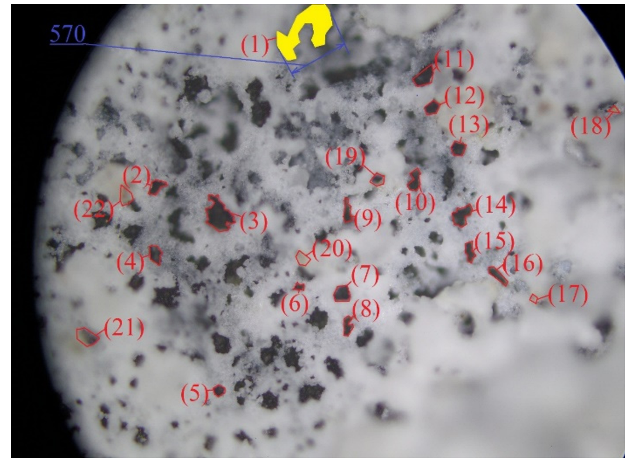

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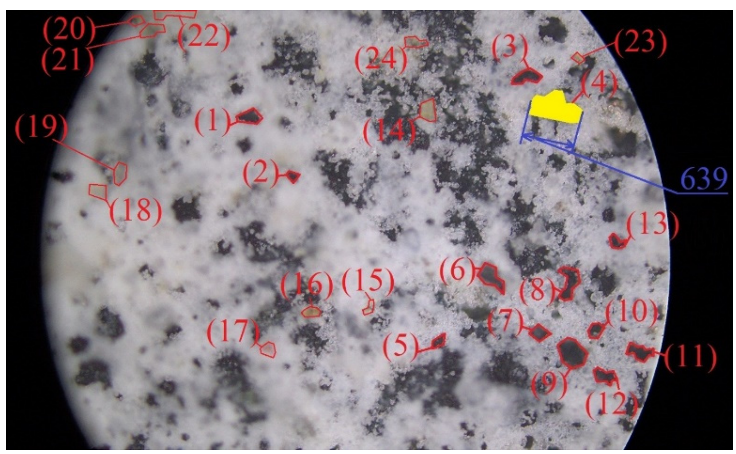

c

Figure 7. OM observations with 100 times magnification
for Al 7075 samples at different temperature conditions including:
a — in the vicinity of cold air; *b* — at room temperature; *c* — in the vicinity of fresh air
S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

Table 5

Statistical characteristics(area in $\times 10^3\,\mu m^2$) corresponding to Figure 7

Part (a)	**Zone No.**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Area	74208	20	24	33	17	15	27	10	17
	Zone No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
	Area	14	191	21	20	20	8	19	10	10
	Zone No.	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	Area	17	20	25	26	166	17	8	9	23
	Zone No.	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
	Area	23	23	54	151	10	116	36	91	20
	Zone No.	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**
	Area	16	22	24	22	90	103	18	–	–

Ending of the Table 5

	Zone No.	0	1	2	3	4	5	6	7	8
Part (b)	Area	74419	232	41	157	42	32	28	55	30
	Zone No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
	Area	34	45	54	41	43	51	34	47	25
	Zone No.	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	Area	24	43	47	51	44	–	–	–	–
Part (c)	**Zone No.**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Area	74028	42	15	49	112	19	63	40	58
	Zone No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
	Area	77	26	52	33	27	45	29	39	47
	Zone No.	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	Area	48	48	24	46	70	20	30	–	–

S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

Table 6

Corrosion rate and hardness in different aluminum alloys corroded under different environmental temperatures

Identification code	D_{max} $[\mu m]$	R	HB_1	HB_2	HB_3	HB_{ave}
2024 X	907.5	0.011307	13.2	12.1	12.8	12.7
2024 K	525.0	0.002953	11.3	10.6	10.3	10.7
2024 Y	827.0	0.015224	11.7	13.0	12.2	12.3
6061 X	644.5	0.009767	16.2	15.6	14.6	15.5
6061 K	369.3	0.003008	13.3	13.2	13.1	13.2
6061 Y	749.0	0.015612	12.5	11.0	11.8	11.7
7075 X	513.5	0.021644	21.7	23.5	20.3	21.8
7075 K	570.0	0.016127	19.2	18.2	20.2	19.1
7075 Y	639.3	0.014305	21.2	21.5	21.8	21.5

S o u r c e: made by K. Reza Kashyzadeh, S. Ghorbani, A.S. Averyanov

As is clear from the microscopic images, the number of corrosion damages on the surface of 7075 aluminum samples is much higher than the others, with the difference that the size of the pits is smaller. The corrosion rate in each of the samples, along with the hardness measurements including three different points and their average, are given in Table 6. In this table, D_{max} and R represent the maximum size of the maximum corrosion damage on the surface and corrosion ratio, respectively. Also, HB_i is the Brinell hardness at ith measurement, and the average value is indicated by HB_{ave}.

Conclusion

In this study, the authors investigated the corrosion rates of various series of aluminum alloys in the vicinity of a corrosive solution with a pH of 12 and different environmental temperatures in the laboratory. The most important achievements of this study are as follows:

– The largest corrosion damage occurred in aluminum alloy 2024 and in the vicinity of cold air.

– The highest corrosion rate was observed for aluminum alloy 7075 in the vicinity of cold air.

– Among all the studied aluminum alloys (2024, 6061, and 7075), the highest hardness was observed when the corrosion test was performed in the vicinity of cold air.

– The lowest corrosion rate was observed for aluminum samples 2024 and 6061 when the corrosive solution was at room temperature.

– Considering the different experimental conditions, it can be concluded that aluminum 6061 has the highest corrosion resistance, and aluminum 7075 has the lowest corrosion resistance.

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