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**EXPERIMENTS ON THE CORROSION
OF LIGHT METALS BY CORROSIVE WATERS**

By
Werner Mialki
Karl Popper

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Laboratory of the Eschebach Corporation
Radeberg, Saxony



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EXPERIMENTS ON THE CORROSION OF LIGHT METALS BY CORROSIVE WATERS

By Werner Mialki, and Karl Popper
Members of V.D.I. (German Engineers' Society)

Contribution from the Laboratory of the Eschebach Corporation,
Radeberg, Saxony

from Aluminium 23, 538-90 (1941)

In a previous publication¹ a few preliminary experimental results were given on the behavior of aluminum and aluminum alloys DIN 1712 and DIN 1713. The main purpose of this work was to find testing procedures which would enable one to judge the behavior of aluminum and its alloys towards tap-water by means of laboratory experiments. It was already evident that the salt procedure was not suitable for testing the corrosion behavior of light metals toward tap-water. It was also established that aluminum parts treated by the eloxal procedure showed promise of having a satisfactory resistance toward corrosive waters.

The economic importance of aluminum and its alloys will undoubtedly increase considerably after the war.² It is certain that the plumbing industry and its branches will have to give serious attention to the possibility of using aluminum and its alloys, as it is equally certain that copper will be made available only for uses in which it is essential, such as electronics and the building of chemical apparatus.

It should be mentioned here that zinc is also becoming of increasing importance in the plumbing field. It still remains to be seen which metal will be favored. It is probable that neither metal will take over the entire field; both metals will probably be used side by side. Much work is being done on the utilization of zinc alloys for plumbing purposes, and the results in many cases are quite favorable. Our tests have shown that aluminum bolts and valve stems whose surfaces have been eloxalated or treated in some special manner behave much better than similar articles made of zinc, especially in warm waters. This is true even when the surfaces have been treated by one of the well known phosphate or chromate procedures in order to improve their ability to take up greases. Practical tests which we have been carrying on continuously for four to five years shows that aluminum fittings will be able to live up to all claims.

It therefore seemed important to pay even greater attention to the question of using aluminum and its alloys for plumbing fixtures and hot water systems, and to continue and intensify the investigations which had already been begun. This requires the acquisition of detailed information

on the influence of the individual factors taking part in corrosion, - the form of the corrosion, the most suitable protective measures, and the most suitable testing method. Although the present paper represents a further step in this direction, it makes no claim to a final clarification to the question.

Such an investigation seems particularly important because modern technology does not yet offer any method of overcoming the corrosion of pure aluminum and thus making it possible to make use of its advantages in plumbing industry. Recent successes in this field were attained with sheets, tubes and similar parts which do not have to undergo any machining. The plating of pure aluminum on fittings, especially on holes and other inaccessible surfaces, is not yet a practical possibility. Thus if one wants to use aluminum and its alloys for the manufacture of fittings, - and the above considerations appear to prove this conclusively - , some other protective procedure must be considered. The eloxal procedure, followed by the deposition of other protective coatings, is particularly interesting in this connection.

The present paper is therefore an investigation of technical aluminum and a few alloys under the conditions which occur in tap-water.

Experimental Set-up

The experiment was carried out with 1 mm thick sheets of the three following metals:

Group 1: Al 99, DIN 1712

Condition: Soft

Total impurities 0.88%

Si 0.13, Fe 0.67, Zn 0.04, Mg 0.03, Ti 0.01;

Group 2: Al-Mg-Si DIN 1713

(Aludur 533M)

Condition: Soft

Composition in %:

Mg 1.05, Si 0.96, Mn 0.69; remainder pure aluminum (Fe 0.50, Zn 0.02, Cu 0.01, Ti 0.01)

Group 3: Al-Mg-Si DIN 1713

(Aludur 533 VA),

Condition: Hardened

Composition in %:

Mg 0.86, Si 0.81, Mn 0.74; remainder pure aluminum (Fe 0.40, Zn 0.-, Cu 0.01, Ti 0.01)

Most of the examples were prepared from a sheet measuring 1 x 1000 x 2000 mm. When one sheet was not sufficient, those samples taken from a second sheet were specially marked. The samples measured 1 x 21 x 210 mm, but were 15 mm wide in the center section. One portion of each of the untreated strips was polished, the greater part of the surface remaining unchanged; the rolling layer thus remained, as did the oxide layer resulting from the treatment of group 3.

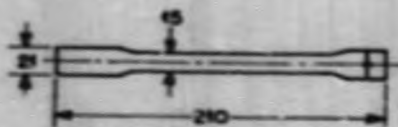


Figure 1.

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In order to hang the test strips in the test baths, a hole was bored below the middle of the upper edge. The samples were labeled by means of numbers stamped on the upper part of the strip; number 1 represented Al 99, number 2 represented soft Al-Mg-Si, and number 3 represented hard Al-Mg-Si. In addition to this, each strip had a number between 1 and 400 which identified the sample according to its origin and pretreatment. A note was made of the numbers of especially good test strips, particularly those whose edges were not affected.

The strips were tested with and without surface coatings. The following surface coatings were chosen:

1. Lacquers, - particularly karbol for maldehyde lacquers from whose resin the lighter fractions had been extracted by a special procedure. They are marked A below. The coating was applied in accordance with the directions supplied by the manufacturer. The baking temperature was 180°C. Part of the samples were treated with special lacquer B. This is an optical lacquer with a synthetic base (phthalate resin) and was baked at 130°C.

2. Eloxal layer with subsequent treatment.³ Great care was exercised in preparing the eloxal layer. It should be noted here that the simple form of the test strips greatly favored the preparation of a perfect eloxal layer. The quality of the eloxal layer on many of the samples was tested with indicator solutions² by means of Duffek's⁴ procedure. This test almost always indicated perfect layers.

3. Eloxalation and lacquering. The strips were first eloxalated and then coated with one of the lacquers mentioned in paragraph 1.

The investigations were concerned principally with determining the corrosion behavior toward tap-water in 8 different baths, in each of which one of the corrosion factors was particularly emphasized, as is shown in table 1.

Table I

<u>Vat</u>	<u>Corrosive Medium</u>	<u>Condition</u>	<u>Average temperature</u>
1	Distilled water	Still	18° C
2	3.5% NaCl solution in tap-water	Still	18° C
3	Tap-water	Flowing @ 3 l/min*	11° C
4	Tap-water	Flowing @ 4 l/min*	52° C
5	Tap-water enriched with oxygen (~17mg/l)	Flowing @ 3 l/min*	11° C
6	Tap-water enriched with oxygen (~17mg/l)	Flowing @ 4 l/min*	52° C
7	Tap-water enriched with heavy metals	Flowing @ 1 l/min*	48° C
8	Tap-water enriched with CO ₂ (~320 mg/l)	Flowing @ 4 l/min*	52° C

*Average values. The flow rate could not be kept even in all baths.

The following details should be mentioned: The warm water was obtained from the usual type of gas water heater. The enrichment of the tap water with carbon dioxide or oxygen took place in a pressure chamber

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which was directly above the bath. The enrichment of the water with heavy metals was accomplished by first collecting the water in a container above vat 7, and allowing it to come into intimate contact with small pieces of iron, copper and lead. The average heavy metal content was iron: 3.8 mg/l, copper 1.5 mg/l, lead 2.0 mg/l.

The following are the principal characteristics of the original tap water:

Total hardness: 4.4° dH. (average value).
 Carbonate hardness 3.5 dH. (average value).
 Free carbon dioxide 33 mg/l
 Oxygen: 7 mg/l
 Bound chlorine 20 mg/l
 Iron 0.17 mg/l
 Residue on evaporation 190 mg/l

The conditions mentioned for vats 3-8 refer only to the period of operation. In the intervening periods, the water was still, and had an average temperature of 18° C in all vats. The ratio of operating time to rest time was 1:3. The steady state described in table I lasted for eight hours each day. It was attained in a few minutes once operation had begun.

The vats in which the experiments were carried out were enameled; the mixing vessels and their leads were galvanized and lacquered. The room in which the experiments were carried out had an average temperature of 20°C; the humidity was relatively high. The experimental arrangement is shown in figure 2.



Figure 2.

The test strips were made in the shape of tensile strength specimens (figure 1) since tensile strength tests were to be made upon them. It was possible that corrosion might occur at the cut edges as well as on the surface. As a matter of fact, there were differences between the corrosion of surfaces which were covered with a rolling layer and the cut edges, which had suffered a change in potential.

Before the experiments were begun, the strips were degreased, and then suspended in the vat in such a manner that the largest part of the strip was under water, and the influence of the border zone between water and air could make itself felt. About 30 specimens were suspended in each vat. Some of these were unprotected, some eloxalated, some lacquered, and the rest eloxalated and lacquered. In a few cases, the eloxal layers were purposely damaged beforehand.

The experiment covered a period of 13 months. The samples covered with lacquer D, however, were an exception; the experiments in this case

covered only a half a year. The condition of each strip was tested monthly, and in some cases the strips were photographed. Note was made of the occurrence, appearance and number of new spots. Weight determinations were made in the case of some samples. At the conclusion of the experiments, the tensile strength and the elongation of the specimens were determined. For comparison purposes, the same values were determined for non-corroded test strips from the same heat, which had been kept in a dry room during the experimental period.

Experimental Results

The measurements of the change of mechanical properties give a good idea of the corrosion behavior. Unfortunately, it was impossible to investigate changes in texture (intercrystalline corrosion).

1. Tensile strength and elongation.

These values are given in table 2. The values at the top are referred to the test strip in their original condition. All data are average values.

Table 2

Material No.	Tensile Strength in kg/mm ²		Elongation %		
	Average	Extremes values	Average	Extreme values	
Unprotected	1	8.16	(7.7 -- 8.4)	39.5	(34.0 -- 43.8)
	2	13.33	(13.1 -- 14.0)	23.0	(18.5 -- 28.8)
	3	30.40	(28.0 -- 32.4)	16.7	(8.8 -- 21.3)
eloxalated	1	7.87	(7.60 -- 8.05)	37.5	(35 -- 40)
	2	13.3	(13.1 -- 13.4)	19.7	(18.5 -- 20.7)
	3	30.8	(29.7 -- 32.3)	9.1	(8.8 -- 10.0)

Vat	Material No.	Unprotected		Eloxalated		Elox. & Lacq.		Lacquered	
		T.S.	Elong.	T.S.	Elong.	T.S.	Elong.	T.S.	Elong.
1	1	8.3	19.7	8.3	29.4	8.7	35.0	8.8	26.3
	2	12.8	7.5	13.9	13.5	13.8	18.8	13.5	16.6
	3	28.0	7.9	30.3	19.0	30.2	7.5	32.1	14.9
2	1	--	--	7.4	10.0	7.7	17.5	8.6	30.5
	2	--	--	12.4	7.8	13.5	14.3	13.1	11.3
	3	10.8	2.1	27.9	5.0	31.3	6.3	29.8	7.8
3	1	4.7	7.9	8.5	26.3	8.0	16.2	8.4	25.0
	2	6.6	5.1	13.0	10.0	13.7	13.7	13.4	10.7
	3	16.8	2.8	30.0	6.9	32.0	12.5	28.6	4.7
4	1	4.4	7.8	7.9	20.0	8.4	30.0	8.5	24.4
	2	5.0	4.3	9.5	5.8	13.6	7.5	13.8	12.5
	3	13.9	2.8	27.9	16.9	32.1	6.9	30.4	3.2
5	1	4.6	8.0	7.9	14.4	7.8	12.5	8.3	19.1
	2	6.2	7.7	12.9	7.2	13.5	13.8	13.3	10.3
	3	15.5	2.8	27.6	21.3	32.2	7.5	28.1	4.1

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(Table 2 continued.)

Vat	Material No.	Unprotected		Eloxalated		Elox. & Lacq.		Lacquered	
		T.S.	Elong.	T.S.	Elong.	T.S.	Elong.	T.S.	Elong.
6	1	4.2	6.9	6.7	10.7	8.34	18.8	7.9	19.7
	2	3.0	5.1	13.3	20.0	13.7	13.0	13.4	18.5
	3	11.2	2.7	30.6	25.7	33.7	7.5	29.2	7.5
7	1	3.6	7.4	7.3	13.5	8.3	30.0	8.3	19.7
	2	4.8	7.1	14.0	12.8	13.8	15.0	12.9	12.2
	3	15.8	2.8	30.3	12.5	32.4	8.0	28.3	5.1
8	1	4.1	8.6	7.8	13.8	7.9	13.0	8.0	17.7
	2	5.4	8.5	13.3	19.4	13.9	17.5	13.0	11.4
	3	16.4	2.5	29.3	12.9	32.9	8.8	27.1	3.8

Since the tensile strength fluctuated, a decrease was assumed to have occurred only when the average value was below the lower limiting value for the comparison strips. In connection with these data, it should be noted that the corroded region of the air-water boundary lay within the region tested. (See also below).

In distilled water (vat 1) both unprotected strips of Al-Mg-Si seem to have undergone a slight decrease in average tensile strength, whereas no change could be observed in the case of pure aluminum.

In the NaCl solution, vat 2, the unprotected Al and Al-Mg-Si specimens became soft at the boundary between air and water, and broke off before the end of the experimental period. The tensile strength of the Al-Mg-Si was reduced to about one-third of its initial value; this alloy would also have been eaten through if the experimental period had been longer. The eloxalated strips had apparently undergone a small decrease in tensile strength, but the lacquered strips showed no change.

The unprotected test strips which were immersed in flowing waters, vats 3 to 8, showed a definite decrease in tensile strength. The corrosion in these cases was principally in the form of spots; in many cases holes had been eaten completely through the strips, so that the cross-sections no longer had their original values. Since their decrease in cross-section could not be measured exactly, the tensile strength values were always referred to the original cross-section. In these cases, therefore, the changes in tensile strength cannot be used to draw conclusions concerning changes in texture.

On the average, the tensile strength decreased by about 50% in a year. Considerable variations occurred, however. The greatest decrease in tensile strength occurred in the case of the soft Al-Mg-Si; the figure in this case was always over 50%. It was greatest in vat 6 (warm water with oxygen), where it reached 77%. The decrease was smallest in vats 3 and 5, which contained cold water. In the case of hardened Al-Mg-Si, the greatest decrease in tensile strength was also clearly in vat six. For pure aluminum, however, the greatest decrease occurred in vat 7 (warm water, treated with heavy metals), whereas the smallest decrease in tensile strength also occurred in the cold baths in this case.

Corrosion in oxygenated water was always heavier than that in water containing CO₂, although the difference was not very great in the case of

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pure aluminum. Surprisingly enough, the decrease in tensile strength of the Al alloys in warm water containing CO_2 was smaller than that which occurred in ordinary warm water. In this case, pure aluminum was the only substance which behaved in the expected manner. Otherwise, our results agreed with the observation of Mengerlinghausen⁶ that the acceleration of corrosion by increase in temperature is greater in the case of aluminum alloys than in the case of pure aluminum. One should note particularly, however, that the hardened Al-Mg-Si alloy, despite its relatively heavy corrosion in warm water, was still considerably superior to pure aluminum in tensile strength, as is shown in table 2.

In general, there was no decrease in tensile strength in the eloxalated and lacquered strips. In individual cases, - especially in the warm corrosion bath, a decrease in tensile strength of at most 10% was noted. There was no justification, however, for preferring any one of the materials in either sense.

An interesting and surprising fact should be pointed out: table 2 shows that the test strips which were lacquered without any preliminary treatments showed little or no decrease in tensile strength, despite the fact that in many cases the lacquer had peeled off before the end of the experimental period. This will be discussed further below. In general, it can be said that the pure aluminum seems to have lost some tensile strength because of eloxalation alone, whereas the Aludur did not.

The results of the elongation measurements were not quite so clear-cut as those of the tensile strength measurements. The average scattering of the values was quite large. Eloxalation alone seemed to cause a definite decrease in the elongation of the aluminum alloys.

All three materials, when unprotected, showed a strong decrease in elongation in distilled water; the greatest effect was noted in the case of the soft Al-Mg-Si. For this material, the elongation decreased even in the case of the eloxalated and lacquered test strips.

In the NaCl solution, the elongation of the hardened Al-Mg-Si alloy decreased by about 86%. The elongation also decreased for eloxalated specimens and for the lacquered alloy specimens. Whereas the eloxalated strips showed little change in the appearance and tensile strength, the decrease in elongation was quite definite. Even considering that the eloxalation itself causes a decrease in elongation, regardless of whether they were pure aluminum or aluminum alloys. This is probably due to the fact that experience has shown that alloys which can be hardened will permit temperatures of only 130° when the lacquer is baked, whereas lacquer A was baked at 180° .

The unprotected strips showed a decrease in elongation in all baths in which the liquid was flowing. This decrease averaged 80%. The best behavior was shown by soft Aludur. In the latter material, there was also a difference in the decrease in elongation between the cold and warm baths, whereas the decrease was the same in all baths for the other two materials.

The eloxalated strips of aluminum and Al-Mg-Si always gave elongations which differed from the non-corroded but eloxalated strips, whereas the hardened Al-Mg-Si alloy usually showed no change. The lacquered strips gave large fluctuations, which makes it inadvisable to mention specific individual results.

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2. Changes in size and weight.

No general statement can be made concerning the changes in external measurements of the test strips, since the corrosion occurred mainly in the form of pitting and cut-edge corrosion rather than as a uniform destruction of the surface.

In the case of the unprotected strips, however, there was almost always a clearly evident decrease in weight, the measurements being taken after the removal of the corrosion products. Without removal, there was usually an increase in weight.

In the case of some of the test strips, the decrease in weight was determined several times during the experimental period. It was shown that this decrease was greatest at the beginning. This is probably connected with the fact that the course of the corrosion was affected by the removal of the corrosion products, as will be described later.

No decrease in weight could be detected in distilled water. The decrease was also not very important in NaCl solution, probably because the corrosion occurred almost entirely at the air-water boundary.

In the bath in which the water was flowing, however, there was always a decrease in weight. Unfortunately, the values obtained show no general trend. This is probably due to the fact that the loss in weight is due to pitting, and not to a uniform attack of the surface. In the following table the decrease in weight is given in percent (data given as mg/mm^2 would have no meaning here).

Table 3

Vat	Al 99		Soft Al-Mg-Si		Hardened Al-Mg-Si	
	Weight Decrease %	No. of Corrosion Points	Weight Decrease %	No. of Corrosion Points	Weight Decrease %	No. of Corrosion Points
3. Cold	3.8	40	3.7	32	3.7	30
4. Warm	3.0	125	4.3	52	3.9	80
5. O ₂ Cold	5.8	65	5.4	44	5.2	39
6. O ₂ Warm	6.5	107	4.5	71	5.0	87
7. Heavy Metal	5.0	101	4.6	42	5.2	61
8. CO ₂ Warm	6.3	83	8.1	51	5.6	58

It should be noted that the CO₂ bath behaved the worst in this regard, in contrast to its behavior with regard to tensile strength measurement. This is especially true in the case of the alloy. No loss in weight could be detected in the case of the eloxalated test strips.

3. Surface changes.

The corrosion was observed from the beginning of the experimental program on, - at close intervals at the beginning, and then at least monthly thereafter. A few results of subjective observations will now be given.

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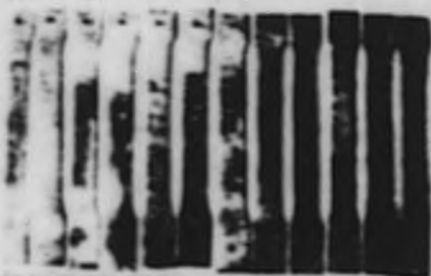


Fig. 3—Test strips from vat 1
(distilled water).



Fig. 7—Test strips from vat 5
(tap-water, warm, enriched with O_2).



Fig. 4—Test strips from vat 2
(3.5% Na-Cl solutions).



Fig. 8—Test strips from vat 6
(tap-water, cold, enriched with O_2).



Fig. 5—Test strips from vat 3
(tap-water, cold).



Fig. 9—Test strips from vat 7
(tap-water, warm, enriched with
heavy metals).

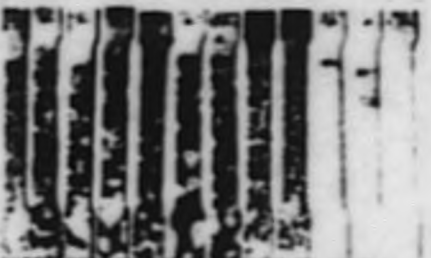


Fig. 6—Test strips from vat 4
(tap-water, warm).



Fig. 10—Test strips from vat 8
(tap-water, warm, enriched with O_2).

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We will again begin with the results obtained in the two vats in which the water was at rest. In the distilled water vat, some of the unprotected strips showed gray spots, in the middle of which there was a corrosion point consisting of a depression about the size of a pin head. The spots appeared in the first month. Their number did not increase very much during the rest of the experimental period. On the average, there were 5-10 corrosion points whose area was at most 1 mm^2 and whose depth was 0.2 mm. The corrosion spots seem to congregate to some extent about the air-water boundary. The soft Al-Mg-Si did not behave quite as well as the other two materials. A whitish gray coating appeared on all the strips. This must have had some protective effect. Summarizing, one might say that the corrosion in distilled water was very small over the entire experimental period. The eloxalated strips showed no corroded areas. To some extent, the strips which had only been lacquered showed more spots than the unprotected strips. The corrosion, however, was of a different sort. It was similar to that suffered by lacquered strips in baths with flowing water (see below).

The corrosion caused by the NaCl solution was in a class by itself. After only a few days, whitish gelatinous blooms appeared at the air-water boundary of the unprotected strips. The metal beneath was heavily corroded, although the other sections of the strip had not yet showed any change. The worst behavior was shown by the polished pure aluminum strips. The tensile strength had also decreased considerably at these places, so that the pure aluminum strips could easily be broken after 1 to 2 months.

After 5 months, most of the unprotected pure aluminum strips were completely eaten through at the air-water boundary, and the strips broke of their own accord. The soft Al-Mg-Si alloy did not behave much better.

(Figure 3-10: tested after an experimental period of 13 months. From left to right:)

- 3 test strips of unprotected Al-99
- 3 test strips of unprotected Al-Mg-Si
- 3 test strips of unprotected Al-Mg-Si, hardened
- 1 test strip of eloxalated Al-99
- 1 test strip of eloxalated Al-Mg-Si, soft
- 1 test strip of eloxalated Al-Mg-Si, hardened

In this case, most of the test strips had broken off after six months. The best behavior was obtained from the hardened aluminum alloy, but even in this case there was heavy corrosion at the border area. The fact that the corrosion was so much heavier at the water surface than it was over the rest of the metal must be attributed to the combined effect of the NaCl in the tap-water and the oxygen of the air. For comparison, we might point out that the corrosion of aluminum by NaCl in aqueous solutions is greatly intensified by the presence of H_2O_2 .⁷ The corrosion of the test strip within the NaCl solution was not very intense at any time during the test period. In summary, one might say that 1 year's experiments do not permit one to draw any unequivocal conclusions regarding the general corrosion in the water itself.

The eloxalated test strip showed a few corrosion points, in contrast to the case of distilled water. Pitting thus occurred very easily where

there were flaws in the aloxal coat. There was a particularly large number of corrosion points at the edges and at the air-water boundary.

The lacquer held up rather poorly on those test strips which were lacquered only. It softened, and came off at several places. The surface



Figure 11.

beneath was corroded. The air-water boundary was also the worst in this case. As was the case with the unprotected strips, however, there was never any serious damage to the material at the air-water interface.

In the baths with flowing water, however, the unprotected test strips showed very serious pitting. There was also a great deal of corrosion at the cut edges; the corrosion was so heavy in some cases that punctures occurred. Corroded areas which started at some of the edges reached almost to the middle of the strip. Some test strips, especially in the warm baths, showed blistering. This partial undermining of the surface was probably a particular kind of pitting.

In order to correlate these results with the changes in tensile strength, one must know not only the number of corrosion spots, but their size and depth as well. Table 3 gives a general idea of the number of corrosion points.

The greatest amount of corrosion probably occurred in the soft Al-Mg-Si alloy, - not according to the number of spots, but according to their size and depth. This agrees on the data on the decrease in tensile strength. The largest number of corrosion spots occurred in vat 6, whereas

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the carbon dioxide and heavy metal salts baths were the worst as far as the size and depth of the corrosion spots were concerned. The edge corrosion was also worst in the CO_2 -enriched water.

The hardened Al-Mg-Si alloy showed the largest number of corrosion points in the oxygen-enriched water. This alloy showed an extremely small number of corrosion spots at the center of the strip in cold baths, the corrosion was stronger at the edges. The latter type of corrosion was particularly bad in oxygenated cold water. This is the reason why the tensile strength showed a relatively strong decrease in this bath. Summing up the behavior of this alloy, one may say that it is the best of the three materials, especially with regard to the size and number of the surface corrosion points. In many of the baths, however, this alloy showed worse corrosion at the edges than the others.

No difference could be detected in the action of the various warm baths on pure aluminum. Edge corrosion was not more noticeable than general surface corrosion. With regard to the number of corrosion spots, however, pure aluminum showed the greatest number, in all the warm as well as the cold baths. The polished strips of the three materials differed little in



Fig. 12--Test strips of Al-Mg-Si, (hardened) from vat 8 (CO_2).

their surface corrosion from the unpolished strips. The number of corrosion points was usually smaller, but the individual spots were in some cases larger and deeper. A clear picture was given only by the changes in mechanical properties. While the polished strips of the aluminum alloys differed very little from the unpolished strips, the polished of pure aluminum showed a much greater decrease in tensile strength and elongation.

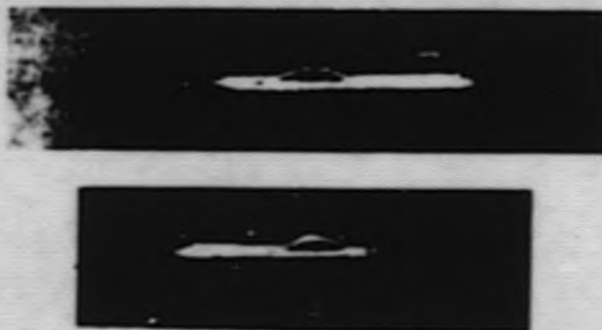


Fig. 13--Section along A-B, from Figure 12.

Those test strips which had been prepared with particular care and whose edges even showed no damage did not differ from the others in their corrosion behavior.

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As far as the individual baths are concerned, there was a considerable difference between the effects of cold and warm water. The corrosion points were always more numerous in the warm baths. The spots were also larger and deeper in the case of aluminum alloys, but no great difference could be detected in the case of pure aluminum.

In all vats in which water was flowing, the bottom of the vat was covered with a brown deposit which was rich in iron; this deposit had formed from the corrosion products in the water, which contained iron. This iron-rich water is naturally of decisive importance in determining the course of the corrosion. The heavy metal content is principally responsible for the corrosive effect of the water with regard to the light metal. The fact that the corrosion in vat 7 was not a great deal heavier than that in the other baths is probably due to the following considerations: the average temperature was somewhat lower and the flow-rate considerably lower than that in the other vats.⁸ Both of these factors tend to improve the corrosion behavior. As has been said before, however, the water itself was very rich in iron, both in this bath and the others. Later, however, the difference between this bath and the other warm baths disappeared as far as the number of corrosion points on the test strips was concerned.

On the whole, the corrosion did not appear to be any heavier at the air-water boundary, although there was some tendency for the first corrosion points to be formed there. There was no change in corrosion behavior with depth of immersion. The side facing the current showed a few more points, but the points on the opposite side were somewhat larger. It should be mentioned here that observations were also made on the influence of gas bubbles on the surface of the strip. Gas bubbles appeared on the surface of the strip at the beginning of the experiment; however, no unequivocal connection could be found between the gas bubbles and the corrosion of the strip. When the alternating periods of rest and flow were begun, however, experimental conditions were arranged in such a way that no gas bubbles could remain on the surface of the strips.

The following facts were noted in connection with the formation of corrosion points: most of the points appeared within the first 14 days. This was especially true of the warm baths. In the cold baths, spots continued to form for about one month longer. The spot formation was slowest in the case of the soft Al-Mg-Si alloy. In this case, the number of points often eventually tended to decrease because of the merging of several small spots.

Interesting information on the formation of corrosion spots was obtained from the strips whose corrosion products were removed for weighing. These strips always developed through the corrosion spots, so that after the one year experimental period, these strips had developed five to ten times as many spots as the others. This, of course, occurred only in the warm baths. The increase in the depth and size of the corrosion spots, however, was much smaller. It therefore appears that if corrosion had already occurred at a certain place but the corrosion points had been removed, further corrosion occurred only very slowly, but new corrosion spots formed all the more easily. This was particularly noticeable in the cases of pure aluminum hardened Al-Mg-Si, but the behavior of soft

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Al-Mg-Si was somewhat different. Although the latter alloy tended to give a larger number of points even when the corrosion products were removed, the increase amounted only to 10-20%. In this connection, it should also be recalled that the spots were slowest to appear on the soft Al-Mg-Si alloy. Since the phenomenon described occurred only in the warm baths, and since the corrosion points tended to appear first at the air-water interface, and since this led to a larger number of corrosion spots only in the case of the warm baths, we may conclude that the initiation of corrosion spots is favored considerably in warm waters. For the sake of completeness, however, it should be mentioned that an exception occurred in the case of warm water containing CO_2 . Whereas pure aluminum showed this effect in this bath as in all other warm baths, the other two aluminum alloys did not. In water which was rich in CO_2 , the appearance of corrosion spots on the aluminum alloys was hindered rather than favored. (decreased in tensile strength).



Fig. 14--Pure Aluminum Strips from vat 4 (warm water)
This test strip on the left was kept free of corrosion products.

A discoloration of the surface was observed in the case of most of the test strips. This discoloration is certainly connected with the formation of a protective layer. No discoloration of the surface occurred underneath the places where corrosion products were deposited; at these places, no protective layer existed, and the metal was open to attack. If the corrosion products were removed, the corrosion slowed up at these points, since a protective coating could be formed at these locations as well. The removal of the corrosion product probably also led to damaging of the surface, which disrupted the protective layer and thus gave rise to the formation of many new corrosion spots. In general, the eloxalated strips behaved well in all the baths. However, one to two corrosion spots occurred in the middle of almost all of the test strips. These usually

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appeared after two or three months. The spots appeared earliest and in the greatest number in the case of pure aluminum. The spots were found almost exclusively at the edges and corners. The corrosion, of course, was not nearly as serious as in the case of the unprotected strips.

The difference between the cold and warm baths was especially evident in the case of both Al-Mg-Si alloys, whereas pure aluminum showed almost the same number of spots in the cold baths as in the warm baths. This again confirmed Mengerlinghausen's observation that aluminum alloy test strips, even when eloxalated, have a greater tendency toward corrosion in warm water than does pure aluminum. Although the eloxalated strips were strongly attacked in vats 6 and 8, the greatest effect was shown in vat 7. The corrosion points appeared soonest there and all strips were attacked. A good eloxalation is therefore particularly important for waters which contains heavy metal salts. In vat 7, the portions where the eloxal layer was purposely scratched were heavily corroded. This was not the case in the other baths, so that one may say that places where the eloxal layer was later purposely damaged did not, on the whole, behave as badly as places where defects in the eloxal layer had been present from the beginning. There were even a few corrosion points on the strips which had been lacquered after eloxalation. Although a coat of lacquer adheres well to an eloxal layer, and eloxalation is thus a good way to prepare the surface for lacquering, the lacquering of the eloxalated strips did not cause any noticeable increase in their corrosion resistance.



Fig. 15--Test strip of hard Al-Mg-Si, eloxalated, from vat 7 (heavy metals).

The first appearance of corrosion spots occurred later on the lacquered strips than on the unprotected strips. At the end of the experimental period, however, there was usually a large number of corrosion spots present; in some cases, there were even more than on the unprotected strips. The following observations were made concerning the corrosion itself: the corroded spots were usually at the edge, and the corrosion

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products were found over a crack in the lacquer. The lacquer had bulged up for a considerable distance around these spots. It could easily be removed, the metal below had been etched quite uniformly. There was thus no pitting in this case. The corrosion tended more to take the form of an even attack. As a result of this difference in the type of corrosion, there was usually little change in the tensile strength. In connection with the various baths and materials, it might be said that the lacquer adhered best to the hardened Al-Mg-Si; it held better in the cold waters than in the warm waters, so that here again, the warm baths showed the worst corrosion properties. At several places, the lacquer merely pulled away from the surface, and the metal below was not attacked. This also occurred in the case of the strips coated with lacquer B, in which case the lacquer showed only a few blisters, no damage to the metal below being visible.



Fig. 16--Pure Aluminum Test Strip from vat 6 (O₂)

Left: Unprotected,
Right: Lacquer strip after
removal of the (partly
destroyed) lacquer coat.

Summary

Continuing previous work by one of the authors, further investigations were carried out on the behavior of aluminum and aluminum alloys with and without surface protection in various corrosion baths in order to throw further light on their behavior under the conditions existing in tap-water. It was confirmed that pitting is quite serious in the CO₂ bath, but the number of corrosion spots and the decrease in tensile strength is lower in this case than in the oxygen bath.

The corrosion behavior of aluminum alloys in the carbonic acid baths does not give any unequivocal picture of its behavior toward tap-water.

2. The experiments have shown that hardened Al-Mg-Si alloy has the greatest tensile strength and also has the best corrosion behavior toward flowing waters under adverse conditions.

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3. Etching considerably increases corrosion resistance toward "aggressive" waters. If the conditions of the etch procedure are observed during manufacture, Al-Mg-Si alloy can then be regarded as a usable material for plumbing fittings which will be stable toward tap-water.

4. In all cases where etching is impossible, proper lacquering can also be regarded as a protective measure. Even if the lacquer coat is eventually damaged at certain spots, our experiments have shown that the corrosion which occurs is not the dangerous fitting type, but surface etching, which is a good deal less harmful.

5. The quantitative difference in corrosion behavior between warm and cold waters was confirmed. It was also proven that the initial formation of corrosion spots and thus the progress of the corrosion itself, is favored in warm water.

6. An oxide film is formed on all aluminum alloys. These may behave in various ways electrochemically. This is due to the fact that edge corrosion sometimes exceeds surface corrosion, and sometimes does not. Hardened Al-Mg-Si alloy clearly showed more edge corrosion than surface corrosion.

7. Enrichment of the corroding waters in heavy metal salts is of decisive importance. Iron salts were seen to favor corrosion quite strongly. This is important when one considers that unprotected iron pipe is often used in water supply installations, even with waters which do not form a protective calcareous layer.

8. The particularly strong corrosion which occurred at the air-water boundary is of secondary importance in the construction of plumbing fittings.

9. It has not yet proven possible to give a quick testing procedure which will give unequivocal results.

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