

Structural Features of Oxide Coatings on Aluminum¹

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ABSTRACT

The structural features of the porous type of anodic oxide coating applied to aluminum have been investigated with the electron microscope. These coatings consist of close-packed cells of oxide, predominately hexagonal in shape, each of which contains a single pore. Pore size is a function of the electrolyte used and is independent of forming voltage. Wall thickness and barrier thickness are primarily a function of forming voltage and are affected to a minor degree by the electrolyte type. Pertinent dimensions of anodic coatings formed in sulfuric acid, oxalic acid, chromic acid, and phosphoric acid electrolytes are presented, and formulas are given for calculating the cell size and pore volume of these coatings.

INTRODUCTION

Anodic oxide coatings can be formed in various electrolytes under a wide variety of forming conditions, and, as a result, exhibit characteristics and behavior which are many and varied. Earlier work (1, 2) indicated the porous, cellular nature of certain of these coatings and developed fairly clear concepts of their manner of formation. This paper describes new and unique methods by which the intimate structural details of anodic oxide coatings can be revealed and by which the actual dimensions of the pores and oxide cells comprising these coatings can be determined. It also demonstrates the changes in dimensions effected by changes in electrolyte and forming voltage, and relates these microdimensions to the characteristics and behavior of the oxide coating.

CLASSIFICATION OF OXIDE COATINGS

Anodic oxide coatings may be classified according to whether or not the electrolyte exerts appreciable solvent action on the oxide. In electrolytes that possess little or no ability to dissolve the oxide, the coatings are thin and nonporous, form rapidly, and have a thickness proportional only to the applied voltage. Coatings of this type, such as those formed in boric acid and borate electrolytes, possess unique electrical properties and have been used extensively in electrolytic capacitors and rectifiers.

With coatings formed in electrolytes that exert appreciable solvent action on the oxide, however, a relatively high, steady current flow and continued coating growth are observed. The amount of oxide formed is generally a function of current and time

according to Faraday's law, although the final thickness of oxide obtained is naturally reduced by the solvent action of the electrolyte which is most pronounced at and near the outer surface of the oxide layer. Coatings of this type, such as those formed in sulfuric and chromic acid electrolytes, have been widely used for decorative purposes and in applications requiring resistance to wear and corrosion.

A specialized case of anodic coating formation in electrolytes that attack the oxide occurs with electrobrightening treatments. Here, the oxide is dissolved about as fast as it forms with the result that, at the end of the brightening treatment, only a very thin oxide film remains. This simultaneous formation and rapid solution of oxide tends to smooth out surface irregularities and thus produces a bright highly reflective surface.

The mechanism of formation is relatively simple for the first type, the "barrier" or "blocking" type of oxide coating. Initially, high current flows and oxide is formed rapidly but, after a relatively short time, current flow has decreased to a relatively low steady value and the coating is completely formed. Thickness is a function of applied voltage at a rate of approximately 14 Å per volt and can be increased only by increasing the applied voltage (3). The low residual current represents, in part, "leakage" through constituent particles on which coating does not form and, as such, varies with the alloy and temper of the material under treatment.

In the second case, the process of coating formation is more complex. A barrier layer of oxide starts to form in the usual manner, but as soon as any oxide is formed, solvent action by the electrolyte also starts which tends to reduce the thickness of the barrier. From observation of the voltage and current excursions which occur at the start of

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coating formation, these processes appear to reach a balance within a relatively short time, after which coating formation proceeds at a uniform rate.

EVOLUTION OF OXIDE CELL STRUCTURE

Considering further the simultaneous solution and formation of oxide, it is possible to derive theoretically the basic structure of the porous type of oxide coating. This derivation is simplified by considering first the formation of a single cell of oxide by virtue of solvent action at a single point. When solvent action begins at this single point, the thickness of the oxide is reduced and current flows to repair the damage to the oxide layer. This raises the electrolyte temperature at this point and more rapid solution of oxide occurs. This mechanism would perpetuate a pore once it is formed, although other factors may halt the formation of some pores and start the formation of others.

As current continues to flow through the single pore under consideration and additional oxide forms, it is evident that an oxide cell must be created. Because the voltage and current fields about a point tend to be spherical, the advancing front of the oxide cell would be spherical if the pore was actually a point source. Since the pore is of finite size, however, the cell front will have the shape of a spherical section somewhat less than a hemisphere. The thickness of oxide between the metal and the pore base must be less than the value corresponding to 14 \AA per volt because appreciable current is flowing. Also, the cell wall cannot be thicker because such thicknesses cannot form. Thus, as oxide is formed, a cylindrical cell, having a roughly hemispherical end and a central cylindrical pore, will be formed.

In actual practice, however, a continuous compact oxide layer rather than isolated ideal cells is formed. Consequently, the changes in shape necessary to form a compact layer must be considered. At the start of coating formation, the ideal cells probably do start to form, but if only cylindrical cells formed, intervening pillars of metal would remain. These pillars would still be in the effective electrical circuit and, therefore, would be converted to oxide. If consideration is given to the behavior that would be encountered if the oxide layer was composed of close packed cylinders, the final shape of the oxide cell is realized.

In such a close-packed array of cylinders, each cylinder would have line contact with six surrounding cylinders, and between each group of three contacting cylinders there would be a triangular pillar of metal with concave surfaces. As these pillars are converted to oxide anodically, the metal will be consumed equally from each face under the

influence of the current from the pores of the three surrounding cells. When all the metal pillar is consumed in this fashion, the oxide layer will be continuous and the cells will have the form of hexagonal prisms rather than cylinders.

With this conversion of the ideal cylindrical cell to the actual close-packed array of hexagonal cells, changes in the shape of the pore also must occur. As the array changes from cylindrical to hexagonal shapes and the intervening metal is consumed, appreciable current will flow and localized heating and relatively rapid solvent action will result. Inasmuch as the metal to be consumed between

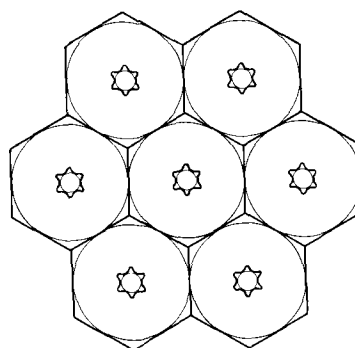


FIG. 1. Relation between ideal cylindrical oxide cells with cylindrical pores and close-packed hexagonal cells with star-shaped pores.

the cylindrical cells is not evenly distributed, current flow, heating, and solvent action will be localized, and the pore will be enlarged in proportion to the amount of metal consumed. Thus, the pore will no longer be cylindrical, but will have six projections, each directed toward a corner of the hexagon. The cross section of this shape should be roughly that of a six-pointed star, which will vary somewhat in shape according to the size of the pore. The relationship between the cylindrical structure and the hexagonal cell structure is shown in Fig. 1.

The change from isolated cylindrical cells to close-packed hexagonal cells also requires a change in the shape of the end of the oxide cell where it contacts the metal. Metal toward the junction of three adjoining cells will be under the influence of current from the pores in these cells and should be converted to oxide more rapidly by virtue of the higher current density resulting from the overlapping current fields. Consequently, the front of a single cell in a close-packed array will have a larger radius of curvature than that of a single isolated cell, and the cell front will have the shape of a spherical section somewhat less than a hemisphere.

On this basis, it can be predicted that an anodic oxide coating formed in an electrolyte that exhibits appreciable solvent action on the oxide is composed

of close-packed cells of oxide, each of which has the shape of a hexagonal prism. Each prism has a spherical shaped end and contains a centrally located pore, star-shaped in cross section. Through a combination of old and new methods of microscopic examination, it has now been proved that this is not merely the theoretical structure but is the actual structure of this type of anodic oxide coating.

METHODS OF EXAMINATION

In this investigation, the electron microscope was used almost exclusively because of the extreme fineness of the structures. In all, three different methods of approach were used. Cell base contours were determined through the use of polystyrene impressions and silica replicas (4) of cross sections of the oxide coatings. Considerable information regarding pore distribution and approximate pore size was gained by forming very thin anodic films and examining the oxide film itself by transmission in the electron microscope (2). When the oxide film is examined in this manner, the electron beam is blocked by the mass of the coating but passes through the pores and penetrates the thin oxide barrier at the pore bases. The pore structure is then seen on the viewing screen of the microscope as many fine, light dots, each of which corresponds to a pore in the coating.

The third method, and the one which was used most extensively, was extremely simple and is believed to be unique. This consisted of examining, through the use of aluminum oxide (5) and formvar replicas, the metal surface from which the oxide coating had been stripped. Inasmuch as the metal surface is in contact with the oxide coating at all times during coating formation, the cell base pattern in the metal reproduces in every detail the contour of the advancing oxide front. Thus, the dimensions of the metal surface are those of the oxide front.

In practice, the coating to be investigated was formed on a sample of high purity aluminum, the coating was stripped chemically, and either a plastic or aluminum oxide replica was made of the metal surface. The oxide was stripped by immersion in a hot (180°F) solution containing 35 cc of 85 per cent phosphoric acid and 20 grams of chromic acid per liter of solution. This dissolved the oxide coating but did not attack the metal. The aluminum oxide replicas were prepared by anodically coating the stripped aluminum sample at 17 volts in a 3 per cent tartaric acid solution adjusted to a pH of 5.5 with ammonium hydroxide. This produces a structureless replica about 240 Å thick, inasmuch as this tartrate solution is a "blocking" electrolyte.

Removal of the oxide replica from the metal is

accomplished by amalgamation. The surface of the specimen is scribed to cut the replica into squares of a convenient size for handling, and the entire specimen is then immersed in concentrated mercuric chloride solution. When amalgamation has started,

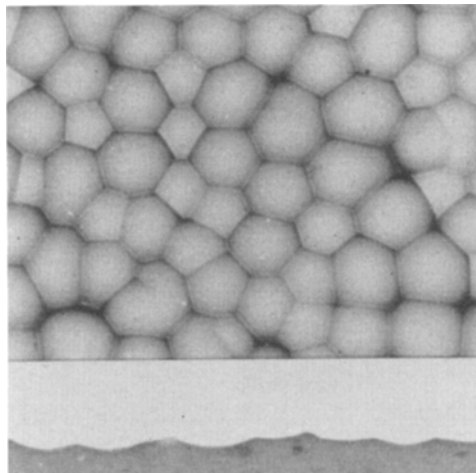


FIG. 2. Cell base pattern (top) of 120-volt phosphoric acid coating showing hexagonal cell structure and contour of cell base (bottom). Electron micrograph. Oxide film replica. 35,000 \times .

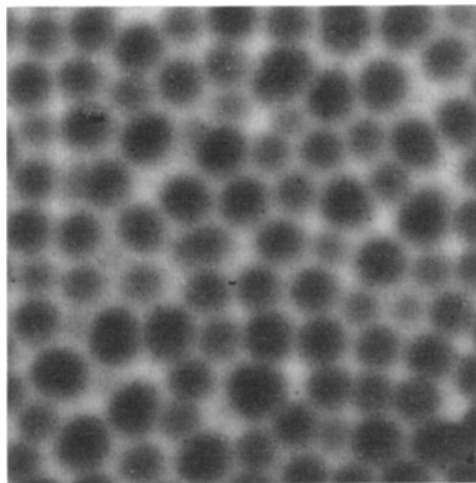


FIG. 3. Cell base pattern of 120-volt phosphoric acid coating showing hexagonal cells and peaks and ridges between cells. Electron micrograph. Formvar replica. 35,000 \times .

as indicated by deposition of mercury along the scribed lines, the specimen is transferred to distilled water and amalgamation is allowed to continue until the squares of oxide separate from the metal. These squares are transferred to a distilled water wash, then picked up on the electron microscope screens, and allowed to dry.

OXIDE STRUCTURES

Coatings formed in sulfuric acid, chromic acid, phosphoric acid, and oxalic acid electrolytes were

examined as described above. The basic structure of the coatings formed in all of these electrolytes was the same, and proved that the structure of the coatings derived theoretically is correct. Coatings formed in a 4 per cent phosphoric acid electrolyte are

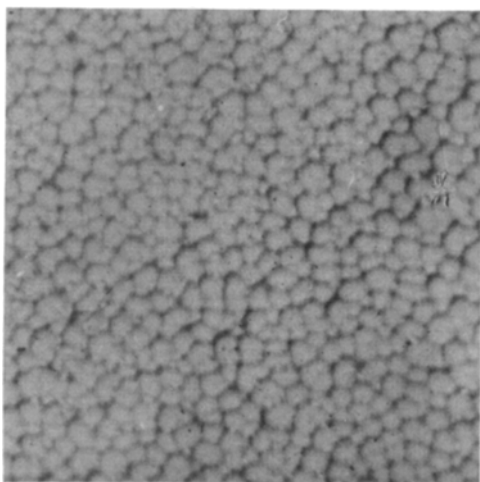


FIG. 4. Cell base structure of 30-volt phosphoric acid coating. Electron micrograph. Oxide film replica. 35,000 \times .

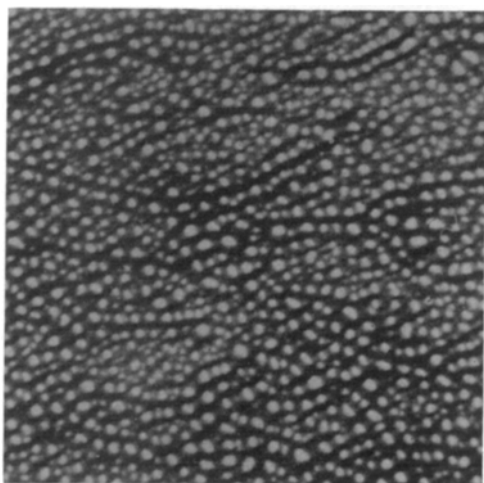


FIG. 5. Pore structure of 30-volt phosphoric acid coating as seen by electron transmission. Electron micrograph. Oxide film replica. 35,000 \times .

used to demonstrate the cell and pore structure and the manner in which the dimensions of the porous type of oxide coating can be determined.

The predominately hexagonal shape of the cells of oxide in this type of coating is shown very clearly by the cell base pattern of a coating formed at 120 volts in the 4 per cent phosphoric acid electrolyte (Fig. 2). In a formvar replica (6) of the same surface, the hexagonal cell shape is again visible and, in addition, the minute ridges and peaks between cells are apparent (Fig. 3). In this type of replica, depressions are filled by the formvar, whereas high points retain only a thin coating of plastic. Consequently,

the cups representing the ends of the cells appear dark and the peaks and ridges between cells appear lighter in shade. The contour of the end of the oxide cells is seen in a replica of a cross section of this same sample (Fig. 2). The scalloped appearance of this section shows clearly that the ends of the cells represent a spherical section less than a hemisphere. All the scallops are not of equal size because this particular section did not run directly across the centers of the cups.

Examinations of the pore structure by electron transmission could not be carried out with the

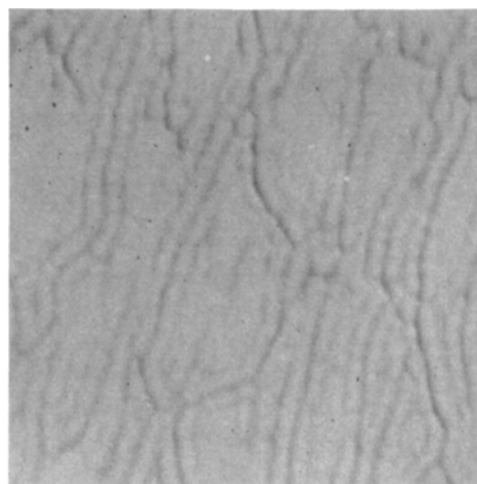


FIG. 6. Cell base pattern of 40-volt phosphoric acid coating at 1½ min showing start of cell formation along subgrain boundaries. Electron micrograph. Oxide film replica. 35,000 \times .

120-volt phosphoric acid coating, because the barrier at the pore bases was too thick to be penetrated by the electron beam. The relation between cell structure and pore structure is evident, however, by comparison of the cell base pattern (Fig. 4) and the pore pattern (Fig. 5) of a coating formed in the same phosphoric acid electrolyte at 30 volts. From these electron micrographs, it is apparent that there are as many pores as cells and that the cell size and pore spacing are the same.

It has not yet been possible to see the star-shaped contour of the pores, because the difference in size between the star and the ideal cylindrical pore would be only about 45 Å even with the largest pores examined.

Following this same line of approach, some interesting and unique facts are revealed regarding the method of formation, dimensions, and behavior of the porous type of anodic oxide coating. Of considerable interest is the manner in which this type of coating starts to form. Initially, single rows of cells form along either side of the subgrain boundaries of the aluminum as shown by Fig. 6. Forma-

tion starts in these regions because the natural oxide film at such boundaries is not as compact or continuous and offers less resistance to current flow. As the coating process continues, additional rows of cells are formed within the subgrains (Fig. 7) until, finally, a well developed cell pattern is apparent and the identity of the subgrain structure has been masked (Fig. 4). Once the cell pattern has been well established, further formation does not alter the pattern unless forming conditions are changed.

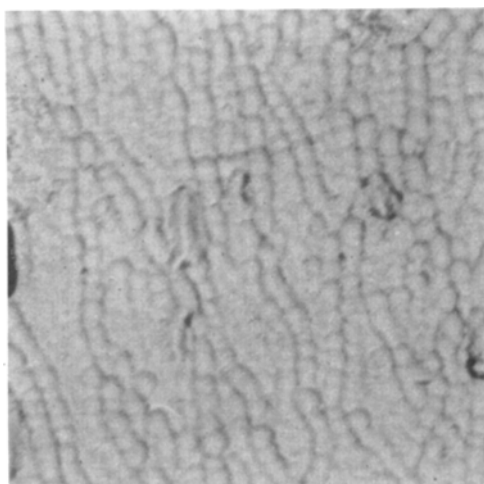


FIG. 7. Cell base pattern of 40-volt phosphoric acid coating after 2 min showing formation of additional cells within subgrains. Electron micrograph. Oxide film replica. 35,000 \times .

OXIDE CELL DIMENSIONS

Interesting information is gained by following the changes that occur in the cell base pattern with changes in formation voltage. As might be expected, the oxide cell size increases with voltage (Fig. 8) and, if cell size is plotted against forming voltage, it is apparent that this increase is linear (Fig. 9). Thus, cell size is a direct function of voltage as it is in the case of coatings formed in electrolytes that do not dissolve the oxide. In the present case, however, the straight-line plot does not go through the origin so that cell size must also be a function of some other factor.

The structure of the individual oxide cells reveals the variables that affect cell size, and permits actual determination of the cell dimensions. Basically, each cell is composed of a pore, an oxide wall, and a barrier oxide layer at its base. The over-all cell size can be measured directly from micrographs of the cell base pattern. This cell is not solid oxide, however, and has a diameter equal to twice the thickness of the oxide wall plus the diameter of the pore.

With this in mind, it is evident that the straight-line plot seen in Fig. 9 can be obtained in either of two ways. Such a plot would result if the oxide wall

did not increase linearly with voltage, and any departure from linearity was offset by an equal and opposite change in pore diameter. Such a balance

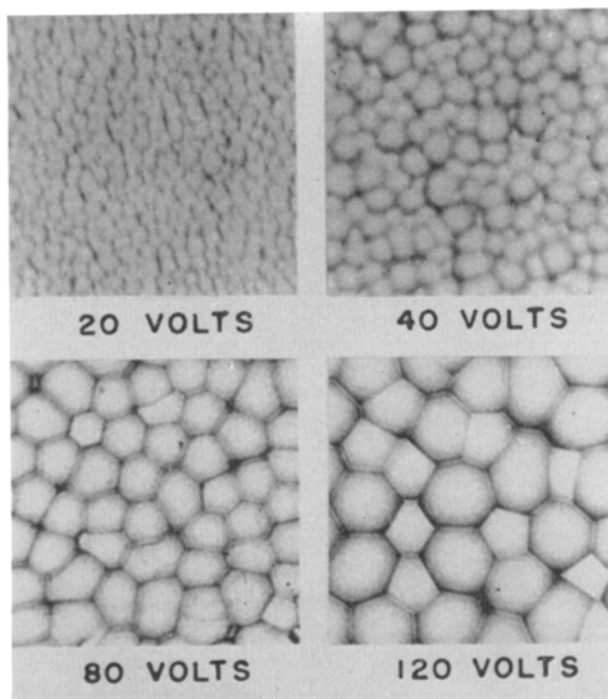


FIG. 8. Cell base patterns of coatings formed in 4% phosphoric acid electrolyte showing increase in oxide cell size with forming voltage. Electron micrograph. Oxide film replicas. 35,000 \times .

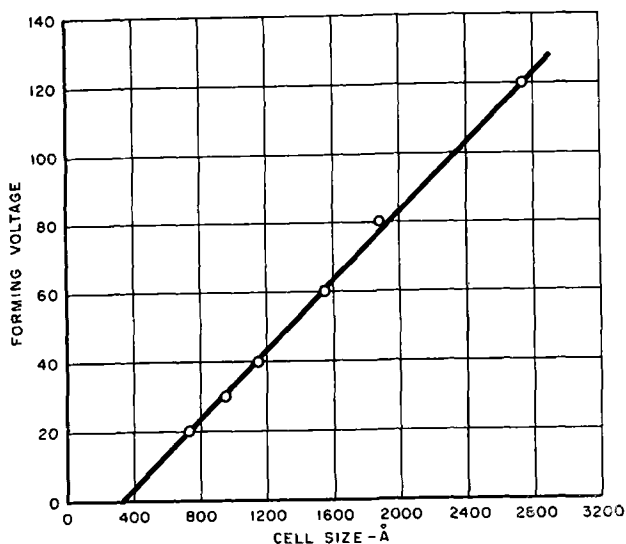


FIG. 9. Relation between cell size and forming voltage in 4% phosphoric acid electrolyte.

does not appear reasonable. The more likely reason for the straight-line plot is that the thickness of the oxide wall does increase linearly with voltage, and the pore diameter remains constant. On this basis, the difference between the cell size and the

thickness of oxide comprising the two sides of the cell wall should be a constant value, the pore diameter. This value is obviously the amount by which the plot of cell size against voltage is transposed from the origin. Accordingly, pore size is represented by the point at which the straight line intersects the size axis. Thus, in the case of the coating formed in the 4 per cent phosphoric acid electrolyte, the pore diameter is found to be about 330 Å.

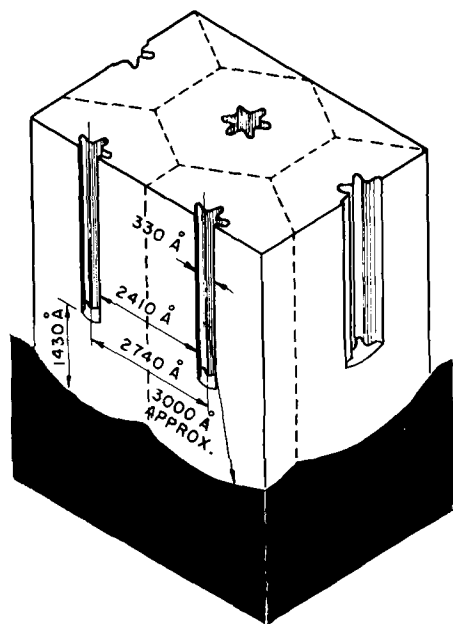


FIG. 10. Structure of 120-volt phosphoric acid coating constructed on cross section of cell base pattern. Dimensions of pore, cell, cell wall, barrier, and radius of curvature are shown. 65,000 \times .

Having established the pore diameter, it is now possible to determine other dimensions of the oxide cell. By subtracting the constant pore diameter from the cell sizes measured for various forming voltages, the total thickness of oxide wall per cell is found. Half this value is then the cell wall thickness. If wall thickness is divided by forming voltage, the thickness of oxide in the cell wall for each volt of applied potential is obtained. In the case of the 4 per cent phosphoric acid electrolyte, this value is 10.0 Å per volt. From this value, the cell size at any forming voltage may be calculated by multiplying the forming voltage by 10.0, doubling this value to take into account the oxide thickness at both sides of the cell, and adding the 330 Å pore diameter. From these relationships between cell size, forming voltage, and pore size, a scale model of the oxide cell array formed in this electrolyte may be constructed. Such a scale model of the 120-volt phosphoric acid coating is shown in Fig. 10 with the corresponding cross section of the cell base pattern.

Referring to the contour of the cell base pattern, which consists of spherical sections less than a hemisphere, it is possible to determine the radius of curvature and the location of the center of curvature of the cell and pore bases. These can be found by measuring the height and width of the pore base cross sections and applying the formula

$$R = H/2 + W^2/8H$$

where R is the radius of curvature, H is the height of the scallop, and W is the width of the scallop (cell size). In the case of the 120-volt phosphoric acid coating, the radius of curvature is found to be about 3000 Å, which places the center of curvature well up inside the pore at the point indicated in Fig. 10. This point apparently represents the hypothetical current distribution point for the pore.

Cell and pore dimensions of coatings formed in 2 per cent oxalic acid, 3 per cent chromic acid, and 15 per cent sulfuric acid electrolytes were also determined. The oxalic acid electrolyte was operated at 75°F and the chromic acid electrolyte at 100°F. The sulfuric acid electrolyte had to be cooled to 50°F to obtain some of the voltages desired.

The relationships between cell size, pore size, and forming voltage in these electrolytes were the same as those observed in the phosphoric acid electrolyte. As would be expected, however, cell size and pore diameter were appreciably different with the several electrolytes. In these electrolytes, pore diameter apparently is determined by the electrolyte and is not affected by forming voltage. Wall thickness is controlled primarily by forming voltage, but is also related to the particular electrolyte by virtue of the different thickness of oxide formed per volt of applied potential. Inasmuch as cell size is equal to the sum of the pore diameter and twice the wall thickness, cell size is determined by both the electrolyte and the voltage employed to form the coating.

The cell and pore structures of coatings formed at several voltages in one of the electrolytes investigated are shown by Fig. 11 and the relation between cell size and forming voltage in the four electrolytes is shown graphically by Fig. 12. The pore diameters and wall thickness values in these same electrolytes are given in Table I. These pore dimensions apply only to pore diameter at the base of the pores and do not take into account any possible widening of the pores resulting from solvent action along the pore walls. Also, the values given apply only to the particular electrolyte concentrations and temperatures, although additional work indicates that changes in concentration and temperature of an

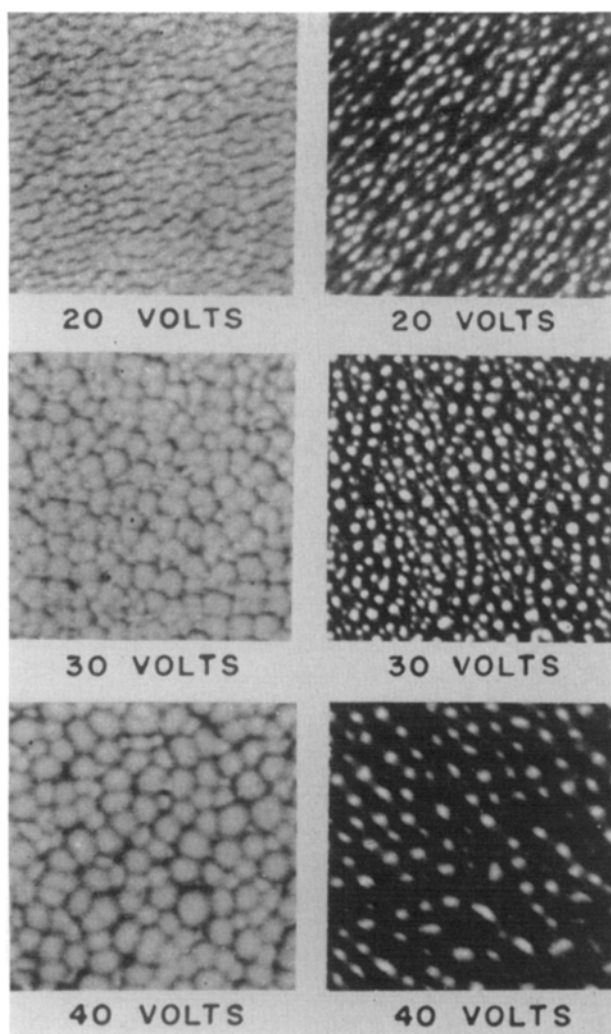


FIG. 11. Cell (left) and pore (right) structures of coatings formed in 4% phosphoric acid electrolyte. Electron micrograph. Oxide film replicas. 35,000 \times .

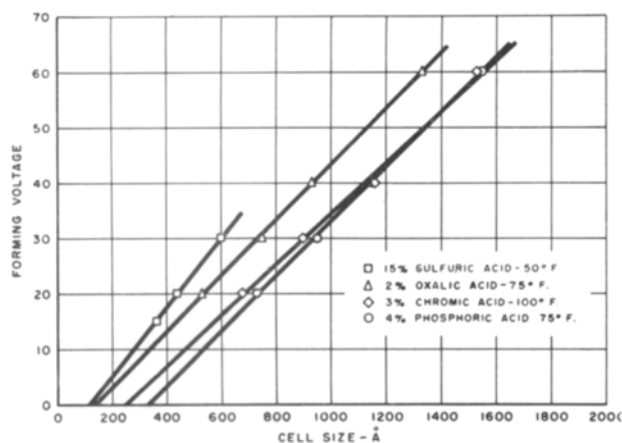


FIG. 12. Relation between cell size and forming voltage in anodic coating electrolytes.

electrolyte may have only a small effect on the pore and cell size.

The cell size of coatings formed at any voltage in

these electrolytes can be calculated from the equation

$$C = 2WE + P$$

where C is cell size, W is wall thickness in \AA per volt, E is forming voltage, and P is pore diameter.

TABLE I. Pore diameter and wall thickness values of oxide coating

Electrolyte	Pore diameter, \AA	Wall thickness \AA per volt
4% Phosphoric acid, 75°F.....	330	10.0
2% Oxalic acid, 75°F.....	170	9.7
3% Chromic acid, 100°F.....	240	10.9
15% Sulfuric acid, 50°F.....	120	8.0

TABLE II. Number of cells or pores in oxide coatings

Electrolyte	Volts	No. per in. ² $\times 10^6$
15% Sulfuric acid, 50°F.....	15	498
15% Sulfuric acid, 50°F.....	20	334
15% Sulfuric acid, 50°F.....	30	179
2% Oxalic acid, 75°F.....	20	230
2% Oxalic acid, 75°F.....	40	75
2% Oxalic acid, 75°F.....	60	37
3% Chromic acid, 120°F.....	20	140
3% Chromic acid, 120°F.....	40	52
3% Chromic acid, 120°F.....	60	27
4% Phosphoric acid, 75°F.....	20	121
4% Phosphoric acid, 75°F.....	40	50
4% Phosphoric acid, 75°F.....	60	27

An interesting feature of the wall thickness data for the various electrolytes is that another investigation, as yet unpublished, has shown that the barrier oxide thicknesses at the oxide cell bases are in the same order in these four electrolytes. The actual thickness of the barrier at the cell bases, however, appears to be greater by a factor of 1.1 to 1.2.

The actual number of cells in anodic oxide coatings can best be appreciated by translating the cell size values to its reciprocal cell numbers, in visible dimensions. The number of cells and, consequently, the number of pores runs into hundreds of thousands per inch and into billions per square inch. The numbers of cells for coatings formed in the four electrolytes investigated are given in Table II.

With values of pore number and diameter available, calculations of pore volume can be made. Pore volume must decrease with increasing formation voltage because cell size is increasing, the number of cells per unit area is decreasing, and the pore diameter remains constant. Assuming that the pores are circular in section, a close approximation

to the star shape as discussed earlier, the pore volume of a coating may be calculated from the equation

$$V = 78.5 P^2/C^2$$

where V is pore volume in per cent, P is pore diameter, and C is cell size. The relationship between pore volume and forming voltage in the electrolytes investigated is shown by Fig. 13. In actual practice, pore volume is generally greater than these calculated values because of solvent action occurring

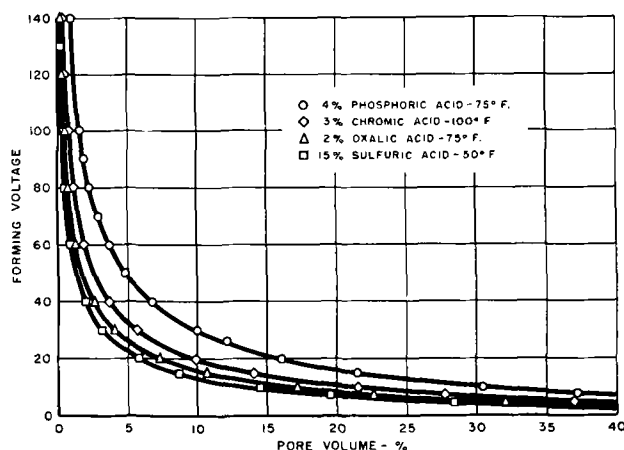


FIG. 13. Relation between pore volume and forming voltage in anodic coating electrolytes.

along pore walls and at the surface of the coating during the time of formation.

Consideration has thus far been given to anodic coating formation where the final oxide layer is the desired end product. Electrobrightening is actually a similar type of anodic coating treatment but, in this case, a final oxide layer is undesirable. Accordingly, the ideal electrobrightening treatment would be one in which the oxide layer was dissolved as fast as it was formed. In commercial treatments, however, this is not practical, and electrobrightened articles have a thin oxide film or "smudge" which must be removed to obtain maximum brightness.

Examinations of electrobrightened surfaces in the manner described prove that this type of treatment actually involves the formation of a porous type of oxide coating. Surfaces brightened by a treatment that operates at 15 volts in a fluoboric acid electrolyte² and by one that is carried out at 20 volts in a phosphoric acid-carbitol electrolyte were examined. In each case, the cell base pattern characteristic of the porous type of oxide coating was apparent.

² Patented process licensed by Aluminum Company of America.

SIGNIFICANCE OF OXIDE CELL DIMENSIONS

The various structures and dimensions of the porous type of anodic oxide coating described are of considerable interest from the theoretical viewpoint. Of even greater importance is the fact that they explain many of the aspects of anodic coating behavior and may be used to formulate combinations of electrolytes and forming conditions to produce anodic oxide coatings having certain specific desirable characteristics.

Basically, the behavior of this type of anodic coating is a function of four variables: namely, pore size, cell wall thickness, the barrier thickness at the base of the pore, and the character of the oxide formed. Investigation of this latter variable is not within the scope of this paper. Of the dimensional variables, wall thickness and barrier thickness are primarily a function of the forming voltage and cannot be greater than 14 \AA times the applied voltage. In all cases investigated, they were less by a factor that was a function of the nature of the electrolyte. Pore size is found to be a function of the electrolyte and is independent of forming voltage.

With these facts in mind, consideration may be given to the relation between electrolytes and forming conditions and the characteristics and performance of the coating. In sealing anodic oxide coatings, pore size is of primary importance. When oxide coatings are sealed in boiling water, some of the oxide comprising the cell wall is converted to a different form of oxide which has a larger volume than the oxide consumed. This tends to seal or plug the pores and prevent access of substances into the coating or to the underlying metal. In sealing an oxide coating, the smaller the pore size, the tighter is the plug created. In a coating of large pore size, the greater volume of the oxide formed during sealing may not be sufficient to fill the pore, and complete sealing in boiling water cannot be accomplished. This is the behavior of coatings formed in a phosphoric acid electrolyte which, as has been shown, have a large pore diameter.

Pore size is of importance when electroplated coatings are to be applied over an anodic oxide coating. In this case, the pore diameter should be large so that as much as possible of the metal to be plated may enter the oxide layer. For this reason, the phosphoric acid coatings with their relatively large pores have been used in this application.

In the matter of hardness and resistance to wear and abrasion, pore volume or, conversely, the amount of massive oxide is of prime importance. Inasmuch as the massive oxide is the material that supports the load and resists the wear, increases in

hardness and wear resistance can be obtained by decreasing the size and number of the pores. This can be done by choosing an electrolyte that develops small pores and by using high forming voltage to increase cell size and cell wall thickness and thereby decrease the number of cells and pores in a given area.

For resistance to corrosion, pore and cell size and, particularly, thickness of the oxide barrier at the pore bases are important. When an oxide coating is used to protect aluminum from corrosion, its primary function is to prevent the corroding medium from coming in contact with the metal. The easiest approach is through the pores and then through the barrier layer at the pore base. Thus, decreasing the pore size by choosing an electrolyte that characteristically develops small pores makes access to the pore base more difficult. Also, if the thickness of barrier is increased by increasing the forming voltage, more time is required for the corroding medium to dissolve through this portion of the coating and come in contact with the metal.

These examples are but a few of the many ways

in which this method of approach may be used to solve anodic oxide coating problems. It can be used to establish the dimensions of the fundamental oxide cell formed in any electrolyte and under any combination of forming conditions. With a knowledge of these dimensions and their relation to behavior, it is then possible to produce coatings specifically designed for particular applications.

Any discussion of this paper will appear in a Discussion Section, to be published in the June 1954 issue of the JOURNAL.

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