Developing a Computer Program for Anodizing Aluminum

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Control of an anodic coating thickness is initially obtained from the number of amp-minutes per ft^2 per mil required for a particular product. The number so determined is used as an empirical constant K for a given component. This takes into account the alloy, temper, and fabrication history. In selecting this method, it is assumed that K is constant for any range of load size. Once determined, the required amp-minutes can be calculated for any targeted thickness and load size by incorporating this constant into a formula. Through this method using standard process cycles, the same statistical average thickness should always be achieved at the same times, for any load sizes.

However, when using this method it was observed that the average thickness was not always statistically constant for products anodized at different load sizes. We noticed small changes in the anodic film thickness, which upon initial review appeared to occur at random and were thought to be statistical “noise”. All readings obtained were within established process control limits and customer specifications. However, after plotting the thickness data against area for several groups of products, we noticed a trend in the readings.

In meeting requirements for closer thickness control demanded by the semiconductor and aerospace industries, we wanted to identify the origin of the variation, determine its cause, and hopefully develop a method to compensate for it. It was found that the anodizing constant varied slightly with load size. The trends identified were product specific, with some products showing no trend at all. These were defined mathematically using a specially developed computer program. This assigned a *trend index* for the trend of a particular product or product group.

This resulted in a new mathematical model to calculate anodizing process parameters, including precise run times corresponding to amp-minutes. The use of the computer program resulted in a reduction in statistical variation of the average thickness and increased the process capability index, Cpk. The following paper reports these findings, which hopefully offers some guidance to others who may encounter similar situations.

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Introduction

Past experience has shown that applying voltage control during anodizing aluminum resulted in anodic film buildup rates that were fundamentally uncontrollable and inconsistent when anodizing machined products made of alloy 6061. So when Semano Inc was formed, we used the fundamental approach of anodizing by current density, and we found the results were much more controllable and more consistent. We recognized that voltage is merely the potential (driving force) to cause anodizing to occur – it does not do any work. What builds the oxide is the actual current flow with its exchange of electrons between the oxygen and the aluminum (as per Faraday's law). If the system resistance varies, including increase in resistance from the coating buildup then the current will vary at a preset voltage.

Others now use this approach which was recently reinforced by author Charles Grubbs (1), wherein he made a compelling case of why *not* to anodize by voltage. In his paper "Anodizing by Current Density – An Update", he stresses the pitfalls of anodizing by voltage: "the voltage will fluctuate according to the needs of the system being anodized: bath temperature, acid concentration, aluminum content, aluminum alloy, temper and many other variables will change the voltage "

Grubbs brought to the forefront the difficulties the anodizer experiences in controlling and reducing what we call the total system noise effects on the anodizing rates and final thickness. Although the anodizer can control all things within his plant to reduce "internal factory noise", he has little control over the influence caused from the "external material noise."

"Internal factory noise" includes contributing such factors such as SPC control of chemical baths, characterization of the anodizing tanks, instrument calibration, and sound process procedures. "Exterior material noise" is meant to include effects from variability of the base material composition and makeup, its' thermal history including any heat-treating, or machining techniques, including milling, diamond turning & scotchbrite finishing.

Understanding that the total noise contributes to the thickness control limits, we began plotting the results of various product runs to understand and quantify the "external noise" effects. The effort was initiated by our ISO-9000 continuous improvement policy, and was driven by our semiconductor manufacturing and aerospace customer base. Anodized thickness control of components used in the production of wafers became essential, as the coating's electrical properties directly influence the plasma performance during deposition and etching of the wafer. Electrical properties of the coating were characterized by a variety of methods including use of electrochemical impedance spectroscopy (EIS)

In the process we discovered two important factors which influenced us to develop a computer program. One was that different thickness readings were obtained on products depending on run load sizes. And two," given the old maxim: "That you should not anodize by time" can be countered with new calculating methods. We could see no specific reason for this limitation, especially since the use of "amp-minutes" has time as one of its components

The first observation led to a new mathematical model formulated to counter the load size effect, and simplifying amp-minute calculations. The second led to incorporating new mathematics into the anodizing ramp system, wherein the final amp-minutes are achieved at a calculated time.

Thus only a load size is now required as an entry into the new computerized ramp. The ramp output provides the operator, or an auto ramp program, with the necessary amp-minutes and precise run times to achieve the set targeted thickness for any load size. With the run times set, an operator is now equipped with a valuable cross-checking signal to end his anodizing run.

Development of new model

Our first step was to take a look at the traditional method of calculating process run parameters, namely the calculation of amp-minutes to obtain the required thickness at a give load size. The formula includes the use of the anodizing constant K (amp-minutes/ft^2/ml). This constant is dependent of the product alloy, temper, fabrication history and anodizing process conditions. Once determined, the required amp-minutes can be calculated for any targeted thickness and load size by incorporating this constant into the following formula:

$$\mathbf{I = K \times A \times th} \qquad \mathbf{(1)}$$

where
I = amp-minutes
K = (amp-minutes/ft^2/mil)
A = load size – ft^2
th= thickness – mls

As shown, the formula requires three variables and therefore makes it cumbersome to use and difficult to analyze. The formula implies directly that the obtained thickness should be the same for any load size, and, indirectly implies that the run times are the same for any given load size. This is, however, not what we found on products investigated in this report, as shown in fig 1.

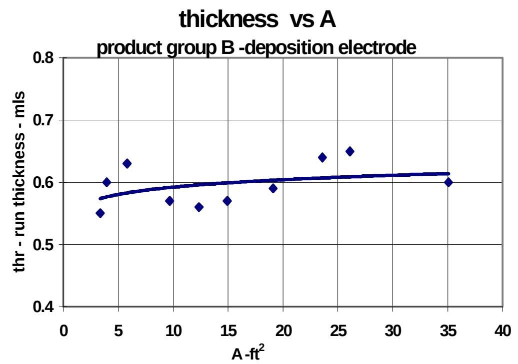

fig 1

Here we see that the anodize thickness decreases as the load size decreases for one product group. Other product groups showed a reverse trend – the thickness increased with decreasing load size.

Anodizing rate equation

Our desire in attempting to develop a new, simpler, and more accurate method of calculating amp-minutes came from the simple analogy a runner. How can I know the distance of a runner given a specified time to run? After all, is that not the same question we are asking ourselves here: how can I determine the thickness of a coating from a specified number of amp-minutes? For the runner, I use the formula: d(distance) = s(speed) x T (time), and to calculate the distance I need to know the runner's speed. I determine the runner's speed by timing him over a particular distance. Graphically I plot this distance vs. time and calculate the speed (s) from the slope of the resultant relationship, or differentiate, as shown in fig 2.

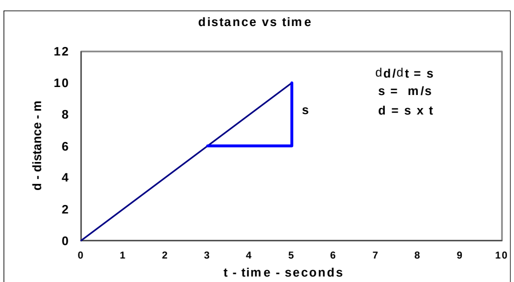

fig 2

The same method is applied to for anodizing. Here I plot the thickness (th) against amp-minutes (I) and calculate the rate (r) from the slope of the curve as in fig 3. The basic premise,(as in the case of the constant speed), that the anodize film build-up is directly proportional to amp-minutes, is assumed, and serves as the underpinning in our development of the following mathematical model. Actual anodizing rates included in this report were calculated from thickness readings and amp-minutes of products process in our plant.

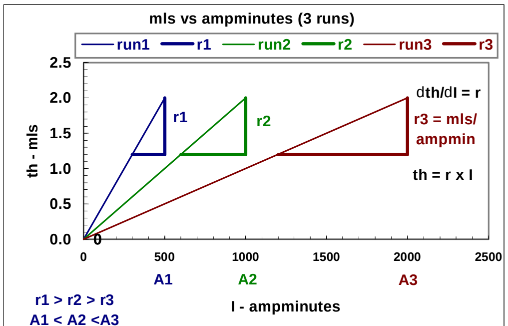

fig 3

For the runner, the units for speed (s) are *m/sec or miles/hour*. The units for the anodizing rate (r) are *mls/amp-min, or um/amp-min,* whichever is appropriate. Now we can use the equivalent "distance" equation, and calculate the anodize film thickness from: th = r x I. Or knowing the rate, set up the formula for calculating the amp-minutes as follows:

$$\mathbf{I = th / r} \qquad \mathbf{(2)}$$

where I = amp-minutes
r = mls / amp-minute

A key feature here is that the load area A is not included in the amp-minute calculation.

To check the units for (r), we compare equation (1) and (2) for the amp-minute calculation, we see that K x A x th = th/r,

$$\mathbf{r = 1/AK} \qquad \mathbf{(3),}$$

Then by eliminating A in the denominator (amp-minutes /A/mls x A) we have the units for (r):

r = 1 / amp-min/mls or mls/ amp-minute.

Thus, we can see that K can actually be calculated from r at a given load size, or vise versa. Since this rate (r) is a relatively small number in absolute terms, we decided to make it more user friendly and made it "larger" by adding the factor 10^{-5}. After all, it's the privilege of even a non-scientist to use scientific notations.

The next task was to define the relationship between the anodizing rate and the load size, so that equation (2) can be used by the computer to calculate required amp-minutes for any given load size.

Actual anodizing rate (r) for each run was calculated by dividing the obtained final thickness (th) by the recorded final amp-minutes (I) by r = th/ I. The rate r was then plotted against run areas. .As shown in fig 3, the slope of the curve (r) decreases as the load size increases.. To find the mathematical relationship between anodizing rates and surface area we plotted the run data, and applied a curve-fitting program as shown in fig 4.

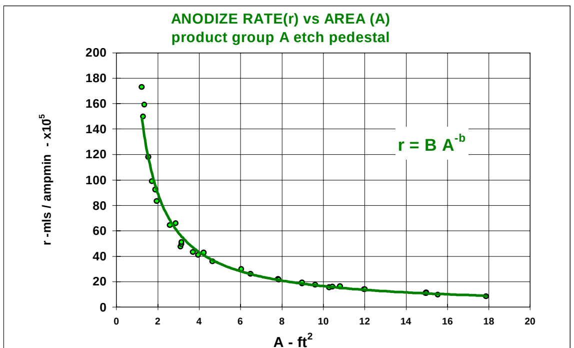

fig 4

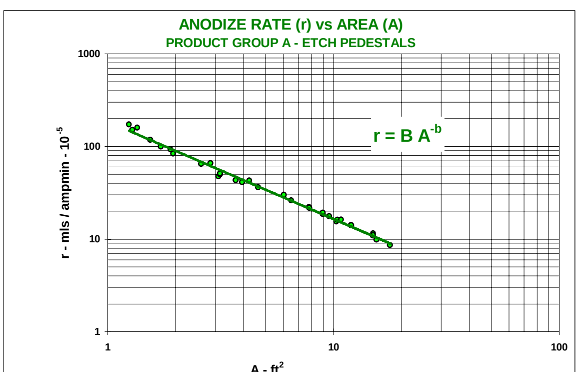

fig 5

The same graph plotted in semi-log format is shown in fig 5. This graph shows a straight-line relationship, between r and A, indicating that the anodize rate function r = f (A) is a 1st order power function.

The resulting fitted equation is :

$$\mathbf{r = B\,A^{-b}} \qquad \textbf{(4)}$$

where
r = anodize rate
B = equation constant
b = equation coefficient

Substituting equation (4) for (r) into equation (2) then yields:

$$\mathbf{I \;=\; th / B\,A^{-b}} \qquad \textbf{(2A)}$$

This is the equation used by the computer to calculate the amp-minutes needed for the run. As a result, at any load size, the obtained anodized thickness should be constant and the curved thickness graph shown in fig (1) will be flat-lined at the target thickness level.

Anodizing constant K equation

Using the same thickness readings, and run surface areas displayed in fig 1, and corresponding amp-minutes, we calculated the constant K for each run using equation (1), and plotted K vs run load sizes. After applying the same curve-fitting program to this data, we obtained the K equation, the mathematical relationship between K and load size. The resulting graph is shown in fig 6. Here we wanted to graphically see any trend in K.

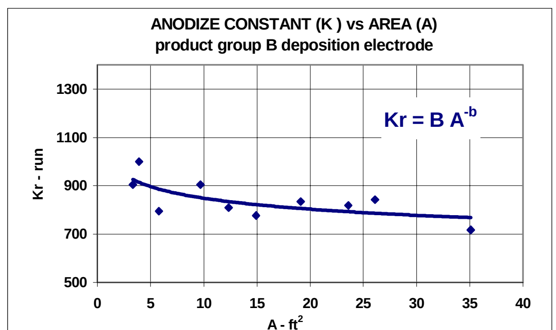

fig 6

The resulting fitted equation is

$$\mathbf{K = D\,A^{-d}} \qquad \textbf{(5)}$$

where
K = anodizing constant K
D = equation constant
d = equation coefficient

Substituting equation (5) for (K) into equation (1) then yields:

$$\mathbf{I \;=(D\,A^{-d}) \times A \times th} \qquad \textbf{(1A)}$$

or

$$\mathbf{I \;=(D\,A^{1-d}) \times th} \qquad \textbf{(1A1)}$$

And we wanted to see graphically how K changes with load size. And if we compare calculated amp-minutes using either equation 1A or 2A, and both yield the same number of amp-minutes, we would gain confidence in our new method through validation. It should be noted that the direction of the

K trend in fig 6 is opposite to the thickness trend shown in fig 1, as expected.

Anodize run time determination

While anodizing to the target thickness utilizing preset amp-minutes set on the rectifier, we wanted to include into the computer program the precise run time corresponding to the preset amp-minutes. Being taught that the anodizer should not anodize by "time", this task became challenging. However, since the time element is part of "amp-minutes", this became relatively easy to achieve..

Our first step was to look at the actual anodizing ramp., Under a current density run for a given load size, the common method is to increase the current either continuously or in specified steps until the final current density has been achieved (ramp). The process then continues at the final current density (dwell) until the required amp-minutes have been achieved. The straight-line ramp rise and constant dwell is graphically shown in fig 7.

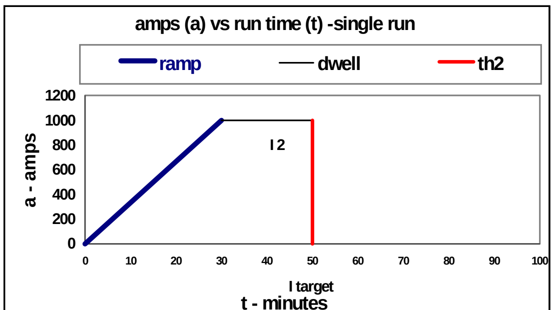

fig 7

Anodized runs of different thickness are represented in fig 8 where the ramp is constant and the dwell times vary.

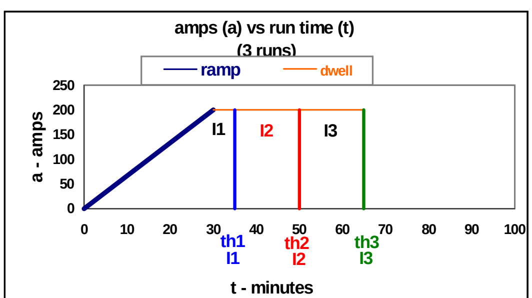

fig 8

From the graph we can see that the ramp rise and ramp time is constant, and what is needed is to calculate the dwell time. This dwell time, when added to the known ramp time, would then give us the desired total run time. We reasoned that if the computer calculated the amp-minutes accumulated during the ramp, then the remaining dwell amp-minutes can be determined by subtracting that number from the total preset amp-minutes. Once the dwell amp-minutes have been determined, the dwell time is then calculated by dividing the dwell amp-minutes by the constant dwell amps.

The ramp amp-minutes can be calculated by finding the area under the ramp curve in fig 7. The area under this curve is found by mathematically integrating the current rise function over the ramp time. For a linear rise in current, this function is expressed as follows:

$$\mathbf{c = mt + b} \qquad \mathbf{(6)}$$

where
- c = current-amps
- m = constant ramp rise rate
- t = time
- b = c intercept = 0

The area under the curve, or amp-minutes, is expressed as follows

$$I_r = \int_{t=0}^{t=tr} mt\,dt \qquad \mathbf{(7)}$$

where
- I_r =ramp amp-minutes
- t =time – minutes
- t=0 =ramp start
- $t=t_r$ =time to final amp-min
- dt =time differential

Resulting integration yields: $I_r = m\,t^2/2$. For example, for a ramp rise of 5 amps/min, and dwell time of 20 min, Ir = (5x400)/2 = 1000 amp-minutes. (If a step ramp, or non-linear ramp is used is used, the above formula needs to be adjusted)

The dwell amp-minutes (Id) can now be determined by subtracting the ramp amp-minutes from the total amp-minutes calculated from prior equations (1A) or (2A); or $I_d = I - I_r$. And then the dwell time (t_d) is readily available by dividing the dwell amp-minutes by the dwell amps (c_d);
or $t_d = I_d/c_d$

For the above example, the dwell amps (c_d) are 100 amps, and if I = 4000 amp-minutes, then t_d = (4000 -1000)/100 = 30 minutes. Adding td and tr then gives the total run time (t_r) of 50 minutes

Incorporating these equations into the program, the computer was able to calculate the precise run time for each run.

Next, we wanted to find out if there exist any trend in run times and compare that trend to the equation K trend. They should be in similar in direction. We selected the calculated run time at target thickness (termed Ts) for the graph.

We used the actual thickness reading in fig 1 to obtain Ts. As shown in fig 9, the expected thickness reading was calculated from the amp-minutes using a calculated anodizing rate (rc). We show this at the intersection of the (rc) line with the target thickness line. However, in the example below, the actual run thickness (x) was below the target thickness. This thickness (x) then determined the actual run rate (rr). Where this (rr) line intersects the target thickness line, the new extended amp-minutes are shown., And from the new amp-minutes at target thickness, the computer calculates the extended time. This new time at target thickness is termed the standardized time or Ts.

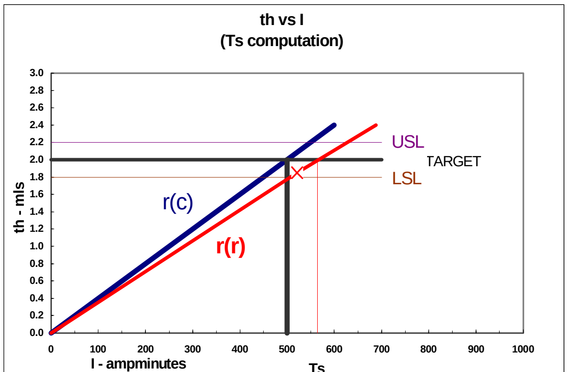

fig 9

The "standardized" run times (run time to target thickness) were then plotted for load sizes of different surface areas and shown in fig 10.

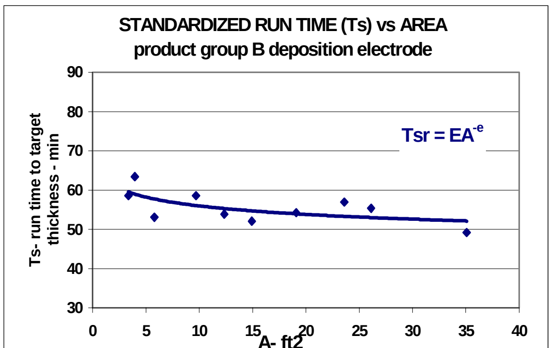

fig 10

The resulting fitted equation is:

$$Ts = E A^{-e} \qquad (8)$$

where Ts = standardized run time to target thickness
E = equation constant
e = equation coefficient

It should be noted that the direction of the Ts trend is opposite to the thickness trend shown in fig 1, and parallel to the equation K trend, as in fig 6, as expected. If run thickness readings were below the target, then it should take longer to anodize to the target and require more amp-minutes.

This Ts equation and the K equation should have similar characteristics: if the constant increases then the run time should also increase. And we wanted to see graphically how Ts changes with load size. And if we compare the Ts trend to the K trend, and they correspond, we should gain confidence in our new method.

Results and Discussion

Four product groups are being presented. A product group is defined a family of similar products exhibiting only minor design differences Three of product groups were fabricated by three different machine shops, each having their proprietary method of machining and finishing their respective parts. Two different suppliers machined the fourth product group. We investigated parts from both suppliers of the fourth group to compare the effects of their different fabrication and finishing methods on the anodize rates. Each product group is considered a critical component used by OEMs in the semiconductor manufacturing business.

Product Group A are etch pedestals made from aluminum alloy 6061-T6 One machine shop produced all products and the general fabrication procedures include rough milling, heat treating, final milling & scotch-brite finishing and were anodized under type III conditions

Product Group B are deposition electrodes made from aluminum alloy 6061 T6 One machine shop produced all products and the general fabrication procedures include rough milling, heat treating and final milling and were anodized under type II conditions. The one noticeable addition to this product group is that they were bead blasted prior to anodizing.

Product Group C are gas distribution electrodes made from aluminum alloy 6061 One machine shop produced all products and the general fabrication procedures included rough diamond turning, heat treating, final diamond turning, and were anodized under type III conditions.

Product Group D are etch chambers made of aluminum alloy 6061-T6. Two machine shops (fab1 & fab2) produced all products under proprietary methods. Chambers were anodized under type III conditions.

Product Groups A, C and D were anodized in one tank while product group B was anodized in a second tank

Resulting equation parameters calculated from the anodizing runs for each product group are summarized in tables 1and 2.

Table 1 identifies the product groups, type of anodizing, load size, and target thickness and summarizes the constants and coefficients for the rate, K, and Ts equations.

For the rate equations, the value of equation constant B is an indication of the degree of the anodize build up: higher numbers indicate faster rates. The equation coefficient quantifies how much the anodize run times to target thickness changes and in what direction, as a function of load size.

The rate equation coefficient b is defined as the anodizing *trend index* of the product. An absolute value of b less than 1.0 implies that the run times to target thickness will *decrease* as the load size increases. We term this a “downward trend”. Conversely, an absolute value of b greater than 1.0 signals that the run times will *increase* as the load size increases; and the *trend index* will be “upward”. The negative or positive values are said to provide the index *direction*.

The difference between 1.0 and the absolute value of b is an indication of the spread in run times to target thickness between small and large load sizes. Larger differences between the two numbers indicate larger run time differences between small and large loads. The magnitude of this difference is said to define size of the *size* of the trend index.

In Table 2 the actual amp-minutes and run times are calculated from the rate (r), K equation (K_e), and from the average constant K (K_a), and summarized for comparison. Included in this table are actual anodize rates and K values obtained from the equations; and actual average K values.

As an example let us look at product group B. As shown in fig 5a and 5b, the anodizing rate r increases rapidly as the load size decreases and steadily declines as the load size increases. Applying equation (4) and inserting actual values for the constant B and coefficient b, (Table 1) the anodize rate equation becomes:

$$r = 98.39\ A^{-0.921}$$

For a load size of 36 ft^2, $r = 3.58 \times 10^{-5}$ as shown in Table 2. The computer then calculates the amp-minutes for 0.60 mls of coating from equation (2A), where

$$I = 0.60 / 3.58 \times 10^{-5}$$

or $I = 16{,}745$ as shown in Table 2 (I_r).

Run times were calculated by applying the integration method described above for each process run (equations 6-8). For the same thickness and load size as above, the run time to target thickness is 51.3 minutes, as shown in Table 2 (T_s). The corresponding values for constant E and coefficient e are listed in Table 1. It should be noted that time equation (9) was not used to set up ramp calculations; it was deployed only as a technique to substantiate the observed trend in r and equation K graphs.

Like wise, from graph 6, and applying equation (5) and using constant D and coefficient d from Table 1,

$$K = 1018.70\ A^{-0.079}$$

or for the same load size as above, K = 766 as shown in Table 2 (Ke). Corresponding amp-minutes for a 0.60 mls thick coating are calculated using equation (1) or (1A), where

$$I = 766 \times 36.00 \times 0.60$$

or $I = 16{,}545$ as shown in Table 2 (I_{Ke}).

The calculated run time to obtain the target thickness here is 51.2 min as per Table 2 (T_{Ke})

The last column in Table 2 (average K_a) shows the run parameters applying the conventional method of calculation. For the load size and thickness specified above, K = 845 as shown in Table 2 (K_a) The corresponding average amp-minutes, as calculated from equation (1), are

$$I = 845 \times 36.00 \times 0.60$$

$I = 18{,}252$ as shown in Table 2 (I_{Ka}) with a run time of 55.6 minutes (T_{Ka})

TABLE 1 ANODIZING PARAMETER EQUATIONS

constants & coefficients

product group	anodize type	run area ft^2	target thick mls	rate(r) eq const B	rate(r) eq coeff b	constant (K_e) eq const D	constant (K_e) eq coeff d	run time (T_r) eq const E	run time (T_r) eq coeff e
A	III	2.00	2.0	179.82	-1.039	555.64	0.039	43.58	0.027
A	III	18.00	2.0	179.82	-1.039	555.64	0.039	43.58	0.027
B	II	4.00	0.6	98.39	-0.921	1018.70	-0.079	63.79	-0.057
B	II	36.00	0.6	98.39	-0.921	1018.70	-0.079	63.79	-0.057
C	III	2.00	2.0	127.77	-1.006	782.85	0.005	63.70	0.001
C	III	24.00	2.0	127.77	-1.006	782.85	0.005	63.70	0.001
D1	III	4.00	2.0	168.01	-1.054	595.59	0.054	52.36	0.039
D1	III	22.00	2.0	168.01	-1.054	595.59	0.054	52.36	0.039
D2	III	4.00	2.0	182.70	-1.031	547.17	0.031	48.25	0.032
D2	III	22.00	2.0	182.70	-1.031	547.17	0.031	48.25	0.032

TABLE 2 ANODIZING PARAMETER COMPARISON

rate equation, equation K, average constant K

product group	run area ft^2	rate equation r: r $x10^{-5}$ mls/ampmin	I_r ampmin	T_s run time min	Equation (K_e): K_e ampmin/ml/ft^2	I_{Ke} ampmin	T_{Ke} run time min	average (K_a): K_a ampmin/ml/ft^2	I_{Ka} ampmin	T_{Ka} run time min
A	2.00	87.52	2,285	44.8	571	2,284	44.8	600	2,400	46.2
A	18.00	8.93	22,396	47.2	622	22,392	47.2	600	21,600	46.2
B	4.00	27.46	2,185	58.9	912	2,188	58.9	845	2,028	55.6
B	36.00	3.58	16,745	51.3	766	16,562	51.2	845	18,252	55.6
C	2.0	63.64	3,143	63.7	785	3,140	63.7	790	3,160	64.0
C	24.0	5.23	38,230	64.3	795	38,173	64.3	790	37,920	64.0
D1	4.00	38.95	5,134	55.3	644	5,136	55.3	682	5,458	57.5
D1	22.00	6.46	30,975	58.9	703	30,970	58.9	682	30,008	57.5
D2	4.00	43.77	4,569	51.3	570	4,560	51.3	586	4,688	52.2
D2	22.00	7.55	26,481	53.1	602	26,496	53.1	586	25,784	52.2

An important feature to observe in this product group is that the exponent (b) in the rate equation (r) in product group B is less than 1. Thus the trend index of –0.921 (Table 1) indicates that the actual run times will decrease as the load size increase. (See fig 10), Thus this product group exhibits a *downward* anodizing trend. The index size of .079 corresponds to a 7.6-min difference in run times between a load size of 4 and 36 ft^2**.**

For group B at 4 ft^2 amp-minutes calculated from the rate equation (I_r) and from the K equation (I_{Ke}) are 2,185 and 2,188 respectively,. with run times of 58.9 and 58.9 minutes (see Table 2) Likewise, for a 36 ft^2 load, corresponding amp-minutes are 16,745 and 16,562, and run times of 51.3 and 51.2 minutes. For both load sizes, either equation provides nearly the same amp-minutes and run times. Thus we feel confident that the mathematical model presented here for the rate equation is sound.

If we compare the amp-minutes and run times calculated from the K equation or the rate equation (Table 2) to the conventional method using an average K, we see the conflicting results. For the same group B as described above, we obtained 2,028 amp-minutes at 55.6 minutes for 4 ft2 using the average K, and 18,252 amp-minutes at 55.6 minutes for 36ft2. The amp-minute difference for 4 ft2 is approximately 7% while the time difference is 6%. Corresponding differences for 36ft2 are 8% and 8%. The effect of these differences is described in the following **applying average constant K to various load sizes** section.

Trend indexes for product groups A, C and D are all positive, as each absolute number is greater than 1, as summarized in Table 2, In each case the run times will increase as the load size increases. A closer look at the group C trend index shows that the number is very close to -1.000, suggesting that there maybe only be a small run time difference between the 2 and 22 ft2 load sizes. This was indeed the case as the smaller load size anodized to target thickness at 63.7 minutes, while at 24 ft2 the time was 64.3 minutes; only a 0.6 minute difference, less than 1%.

Here, the small trend index suggests that the average K method to calculate run parameters may be adequate. Indeed, the run time using the average K was 64.0 min.. Since this product was diamond turned under controlled conditions, we suspect this may be a contributing factor resulting in the small trend index. The above example illustrates that as the trend index approaches –1.000, process times are constant at any load size, and the use of the traditional method of calculating amp-minutes from average K value can be successfully employed

Two point are worth mentioning for product groups A,C and D, which were all anodized to the target thickness of 2.00 mls:

1. process run times varied from as low as 44.8minutes to as high as 64.3 minutes using the r function at various load sizes, while process times using the average K values ranged from 46.2 to 64.0 minutes (see Table 2). Keep in mind that all components were machined from 6061-T6 aluminum. These large variations are partially attributed to the machining methods employed by the machine fab, from use of plate or round bar stock, and to the different current densities applied in the anodizing process.

2. K values ranged from 570 to 912 for the same product group using equation K for calculations. Similarly, using the average K, numbers ranged from 586 to 845. The point here is to demonstrate that not all products machined from 6061 have a uniform K.

Mixed load runs of different anodizing rates

The question arises what would happen, under a time restraint condition, if an urgent request came in and we were asked to anodize one part from group D from each fab at the same time. How should we respond? Given the rate curves as shown in fig 11, can we mix the load, and maintain the thickness within control limits, or, within customer specifications? Which anodize rate do we use to calculate the run amp-minutes?

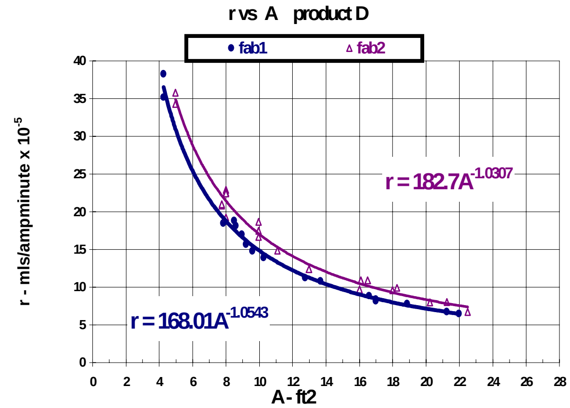

fig 11

A quick process check by the computer reveals that fab1 product group D (D1) achieves 2.0 mls in 56.7 min (assume 8 ft^2 for combined load). Because of the faster rate for fab2 product (D2), D2 will be projected to be at 2.28mls. That is not acceptable given the upper control limits for the product being 2.15mls and the upper specification limit set at 2.0mls. If we use the fab2 ramp calculations, fab2 products take 52.0 minutes to reach 2.0mls. Because of the slower rate for fab1 products, fab1 products will reach 1.75mls. Again this is not acceptable, since our lower control limit is 1.85mls, while specifications allow for 1.80mls. We present this scenario graphically in fig 12.

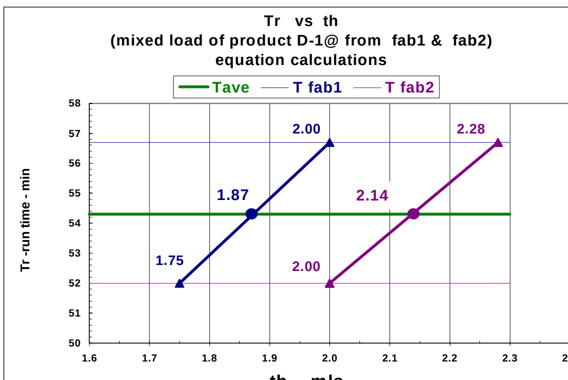

fig 12

The optimum setup would be to average the target times between the two products(the target times are determined from amp-minute calculations). This yields a run time of 54.3 minutes

Via regression analysis, the computer calculates the thickness then from a 54.3 minute run, yielding a coating thickness of 1.87mls for D1 and 2.14mls for D2, as shown in fig 12. Both readings are within upper and lower control limits and the projected calculations indicate that both products can be anodized within the customer specifications. However given a total system noise of about +/-0.10 mls, chances are that 30% of D1, and 60% of D2 product may not anodize to customer specification. So the answer is, if push come to shove, yes it can be reasonably done based on calculations. Would we recommend it? That's another matter. Perhaps the customer can make the call.

Applying average constant K to various load sizes

Utilizing the traditional average K method to calculate amp-minutes may not be the best way to control the anodizing process. Indeed, in applying this method, the target thickness could be missed at either extremes of your load size range. Let me demonstrate this in the following case based on two of the product groups B and D.

For product group B exhibiting a relatively large negative trend index (Table 1), we calculated an average K value of 845 amp-minutes/ft^2/mil for all runs. Applying the equation K, for small areas as low as @ 3 ft^2, the K value was 910, while for areas as large as 36ft^2, the value decreased to 766. This means that smaller loads would anodize for a longer period of time (larger Ts) to reach the target thickness than shorter run large loads. Using the same regression analysis as above, we calculated the Ts at each K value for the target thickness, upper & lower control limits, and customer spec limits. Results are represented in the three Ts vs. th curves in graph form as shown fig 13.

To meet customer specification (0.50 mls and 0.70mls), at the 910 K value, products Ts times varied from 51.3 min to obtain the lower limit of 0.50mls, to 66.4 min for the upper limit of 0.70mls. Like wise, for the mean K value of 845, the respective Ts times were 48.5 and 62.6 minutes. For the low K value of 780, the numbers were 45.8 and 58.8. The Ts times for the corresponding target thickness (0.60mls) were 58.8, 55.6 and 52.3 minutes. So if the anodizer chooses the mean K (845) and the mean Ts (55.6) to run his process, he will statistically anodize to "targeted" thickness of 0.56 for small load sizes of @3ft^2. While, on the other hand, he will statistically obtain 0.65 mls at the larger load size of 35ft^2.

These numbers can be obtained from the intersection of the constant Ts line (55.6 min) with each of the K curves. Yes, these values were within customer specifications and barely within upper and lower control limits (0.55 and 0.65mls). However given the normal exterior material noise and interior factory noise of the system, in this case, approximately 0.10 mls, there is an up to 50% chance that at low load sizes the product will *not* come within the lower control limit. In another words the process is out of control, and the chances are increased that customer thickness specifications may not be met.

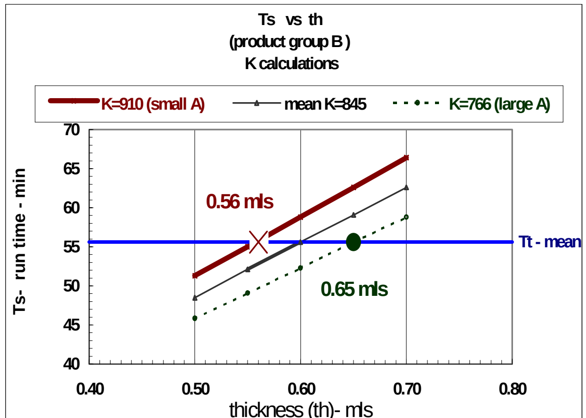

fig 13

Likewise, based on the graph, the same results can be expected from larger load sizes where approximately 50% could be outside the upper control limit, and chances are increased of sending over anodized parts to the customer.

Group D1 products are graphed and presented in fig 14.

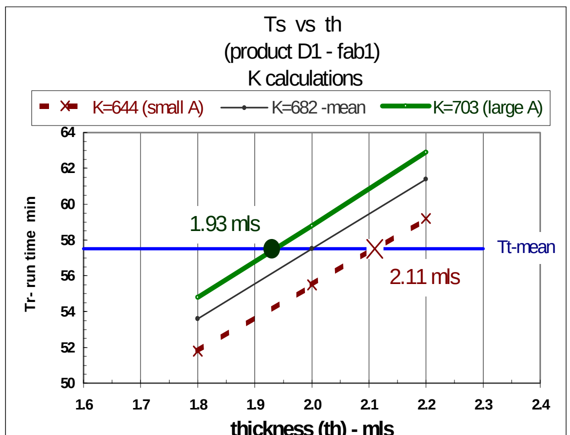

fig 14

In this case just the opposite of product group B became apparent. This group exhibited a positive trend index (see Table 1). Here, lower K values were observed at smaller loads. Larger loads would anodize for a longer (larger Ts) period of time to attain the target thickness. From this graph we see that the average Ts time line intersects the large load K curve (22 ft^2) at 1.93mls and the small load K

(4ft2) curve at 2.11mls. Here, with a combined material noise factor of approximately 0.20 mils, statistically approximately 35% of the larger loads may be under control limits, while approximately 50% of the smaller loads may be outside the upper control limits.

One comment worth mentioning here is that the above scenarios may represent the best case if the anodizer averages the K's from a broad range of load sizes. If he averages K values from primarily large runs and then uses that value to calculate the amp-minutes for a small run, he could grossly miscalculate his required amp-minutes and be even more off his target thickness.

Go back to fig 13 and 14 and move the Ts line in either direction and you can see the effect. In fig 14, if we shift the Ts from 57.5 min to 58.8 min (from the calculated Ts value for the large load K average of 703) and attempt to run a small load, we would target about @2.20 mls, or the upper spec limit. Given the noise factor, this means that in this case @50 % of the products would be anodized above the customer specifications.

Anodizing adds calculations

Some times the anodizer under-calculates the required amp-minutes on first article products or scrap pieces. He now has to add anodize. He sets up his run using a calculated anodizing rate (rc), however he finds he did not reach the target thickness. He can now quickly calculate his run rate (rr) by dividing the run thickness (thr) by the run amp-minutes (Ir), or rr = thr/Ir. By knowing how much thickness he has to add (tha), he determines his add amp-minutes (Ia) from the run rate or: Ia = tha/rr. Dividing Ia by the dwell current then gives the operator a time frame for his add.

The advantage here is that the load size (A) is not needed for the add calculations .The technique is graphically demonstrated in fig. 15.

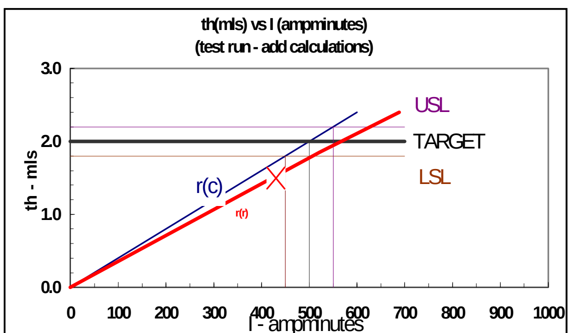

fig 15

Constant load size runs: "sweet spot"

We wanted to explore the reason why anodizers tend to select a constant load size when thickness requirements are critical. And why this selected load size may not be the maximum load size possible? We suggest here that there may be a way of determining this so called "sweet spot". If we intersect the average Ts (Ts=57.5 for fabD1 – Table 2) line with the Ts vs. A curve for this product group, we obtain the optimum run area of 11.2 ft^2, as represented in fig 16. Here the Ts =57.5 minutes represents the time obtained from the traditional amp-minutes calculation using the average constant K method.

He finds himself locked into this load size. If he changes the load size he may not get his targeted thickness, as discussed in the above section **applying average constant K to various load sizes.**

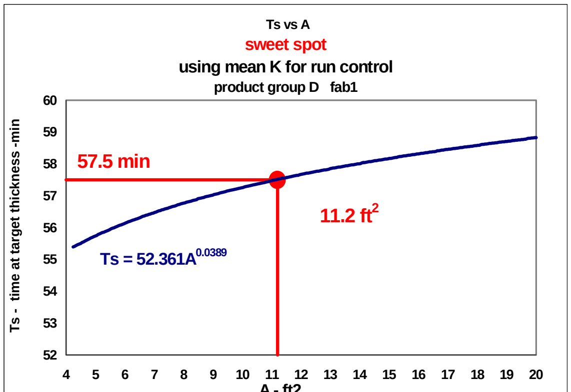

fig 16

Conclusions.

- We have presented 4 anodized product groups that exhibited various degrees of changes of the anodizing constant K (amp-minutes per ft^2 per mil), depending on load size.
- This constant K dependence on load size led to the development of new mathematical model to compensate for this dependence.
- Because the constant K included three variables, (surface area, thickness, amp-minutes), mathematical modeling became cumbersome and complicated. Thus, for simplification, we introduced a new model consisting of only two variable, (thickness, anodize rate)

- An equation was developed defining how the anodizing rate relates to the run surface area (load size). This equation also establishes the relationship between the anodizing rate and the anodizing constant K. Actual rates of products produced at our plant were plotted against load size, and curve fitted to define the function.

- A new mathematical model, applying anodizing rates, was introduced to calculate amp-minutes required for a targeted anodized film thickness at any load size (surface area). Presented equations can be used as the foundation to computerize this process.

- Resulting anodize thickness readings obtained by using this new model should be uniform at all load sizes and reading should show a statistically average flat line when plotted against surface area.

- The coefficient of the “rate vs surface area” equation is defined as the trend index of the anodized product group. This index provides an indication of the different run times (from amp-minute integration) expected to anodize the product to target thickness at different load sizes.

- A new mathematical model, applying amp-minute integration, was introduced to calculate precise anodize run times corresponding to the needed amp-minutes for a targeted anodized film thickness. Suggested equations can be used as the foundation to computerize this process.

- A mathematical relationship was established between the constant K and load size. This was established to verify and substantiate our new model.

- In the new mathematical model using rates, the only data entry required to generate a particular product ramp for a set thickness is the run load size. From there, the computer generates the ramp amps and dwell current, and determines final amp-minutes and run times. The computer displays calculated amp-minutes at any time during the run, which allows the operator to compare this number with those generated by the rectifier amp-minute meter. Any difference between the two alerts the operator to a process deviation or potential failure.

- All products produced in this report were anodized within customer specifications. It is believed that the load size effect on thickness contributed to the range of the upper and lower process control limits, and thereby affecting the process capability index for thickness, Cpk.

- In our plant, the process capability index Cpk for thickness was increased from under 1.3 to near 2.0 as a direct result of applying the new computer model utilizing the rate equation.

- The new mathematical model presented a tool to determine the feasibility of anodizing mixed products each exhibiting a different anodizing rate.

- We postulated an explanation of why an anodizer tends to select a constant load size when thickness requirements are critical; and why this selected load size may not be the maximum load size possible. We presented the potential underpinning for his decision, which may be related to not having a proper tool available to analyze his process. In the past anodizers have been taught that the anodizing constant K does not change with load size.

- Equations presented herein should not be construed to provide any specific formula to set up the process. Equations developed here are product and plant sensitive. If the anodizer were to utilize this method, he must develop his own relationships based on data collected from actual anodizing runs. Nor is it construed that the equations presented here will always be of this type.

References

1. Charles A. Grubbs, *Metal Finishing,* p. 71, November (1999).

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