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ELECTROLYTIC CUTTING OF METALS

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2

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ABSTRACT

The research reported herewith describes a method suitable for cutting cylindrical shaped specimens electrolytically for the primary purpose of securing metallographic specimens of irradiated metals and alloys. The principles involved, and the cell conditions and cathode design established, are directly applicable to general cutting problems where conventional machine methods are inappropriately suited. Little effort was made to investigate cell conditions best suited to produce either an electrolytically polished cut surface or even the best possible smoothness of cut surface. Rather, attention was directed mainly to the most significant variable — cathode design — in an attempt to produce a cut having flat-cut surfaces with little undercutting, and in general one comparable in this regard to that secured by conventional cutting methods. This was achieved.

Data are given on the quality of cut secured on a low carbon steel specimen anode as a function of five different cathode assemblies. Of the five designs, the cathode-auxiliary anode assembly produced the best cut. This cathode assembly is described in detail.

Suggestions are advanced relative to possible modifications of the cathode-auxiliary anode assembly to enable shapes of unsymmetrical cross-sections to be successfully cut.

ELECTROLYTIC CUTTING OF METALS

This report constitutes the outcome of an investigation into the feasibility of, and the most appropriate method for, cutting metals and alloys electrolytically, with particular reference to securing specimens for metallographic examination after exposure to high levels of radiation. For the purpose intended, the securing of electrolytically cut specimens may be considered in terms of either a one or a two step process. In the one step procedure, and this is perhaps the more desirable, the specimen of interest is sectioned electrolytically and the exposed cut surfaces simultaneously electrolytically polished to a perfection appropriate for direct metallographic examination. The two step process consists of sectioning electrolytically in one selected electrolyte and subsequently polishing in a second electrolyte more suited for the purpose. The quality of cut secured by either method is dependent mainly upon cathode geometry and attendant schemes for confining the current distribution on the anode to a narrow band, whereas whether or not polishing occurs simultaneously during sectioning is more directly related to factors such as composition of electrolyte, current density, composition of material to be cut, and others.

The principle of electrolytic cutting is similar to that of electrolytic polishing, and is associated with selective removal of metal from the specimen anode in an electrolytic cell appropriately arranged with respect to cathode and electrolyte. In the cutting process, attention must necessarily be directed to the attendant electrochemical reactions, particularly those occuring at the anode, and to the current distribution on the anode surface.

The anodic process involves an oxidation reaction which, in the case of metals, is the formation of metal ions. It is this reaction that is responsible for metal removal from the anode and which, under controlled conditions, ultimately sections the specimen anode. However, when the limiting current density of the anode is exceeded in an aqueous medium, there is a second reaction involving the evolution of oxygen. This reaction, when it occurs, may cause passivation on the anode surface and attendant lowering of the rate of metal removal and in some cases, severe pitting of the exposed cut surfaces.

Inasmuch as the ideal electrolytically sectioned specimen should be nearly comparable to that secured by more conventional cutting methods, particularly with regard to smoothness and flatness of cut surfaces, and amount of metal removed, it seemed appropriate to study qualitatively the distribution of current over the anode surface as a function of cathode geometry. Of all the variables that would influence quality of cut, it appeared that cathode geometry was by far the most important, since current distribution on the anode was directly related to the perfection of selective removal of anode metal. Having once secured a high quality cut with regard to flatness of cut surfaces through appropriate cathode design, it seemed relatively easy to then adjust the cell conditions — current density, electrolyte composition, temperature of electrolyte, degree of agitation of electrolyte, etc. — to improve the rate of cutting, smoothness of surface in terms of a metallographic polish, etc.

Experimental Arrangements

In an attempt to control the distribution of current on the specimen anode to give a well-defined and satisfactory cut, five significant designs of cathodes to be described were investigated. The performance of these designs was determined against a standard shaped anode, namely, a specimen bar 1 in. in diameter and about 6 in. long. As a first experimental approximation, the qualitative criterion was based upon the shape, width, and character of cut produced on the specimen anode after a cut was secured approximately $\frac{1}{4}$ in. deep.

In operation of the electrolytic cell, it became necessary with the electrolytes used and shown in Table 1, to protect the specimen anode from chemical attack, except that peripheral region that was to be cut. Furthermore, such protection would limit to some extent with appropriate cathode design the electrolytic removal of metal over too large an area. Practically, the specimen anode was protected by binding it with electroplaters tape; this procedure was followed throughout the investigation.

Owing to the presence of the tape binding, there existed a sharp demarcation between the protected and unprotected anode areas that gave rise to a comparatively high current density at the tape edges. Because of this the rate of metal removal adjacent to the edges of the tape was high compared to that nearer the middle of the exposed anode area. As a consequence grooves would be formed locally under some circumstances at the taped edges, and in other cases undercutting or metal removal would occur in varying amounts from beneath the edges of the tape.

Cathode Assemblies.

The first design of cathode assembly investigated, illustrated in Fig. 1, consisted of a bakelite strip into the slot of which was placed a cathode of either copper or platinum wire. The depth of the slot varied from 1/32 to 1/2 in., and the extended bakelite shields were about 1/32 in. thick. The length of the assembly was approximately 4 in.

Fig. 2 illustrates a second design of cathode assembly. The two 4 in. long L-shaped pieces were made adjustable to any distance apart by inserting into the intervening space appropriately sized bakelite spacers. The two small rectangular face-pieces served to locate centrally the cathode wire in the space between the L-shaped sides. The holes in the face plates provided a means of varying the distance between the cathode wire and the edges of the shields.

Cathode designs illustrated in Figs. 3 and 4 represent improvements over that shown in Fig. 2. The former consisted of two 3 in. glass shields placed, with respect to one another, at an angle of 30°. The distance between the leading edges of the shields could be altered by moving the plates within the slotted face pieces. The face pieces were provided with centrally located holes so that the cathode wire could be at various distances from the edges of the glass plate shields.

Fig. 4 illustrates the same design as that shown in Fig. 2 with exception that two 3 in. glass plates, held rigid by the L-shaped pieces, were used as cathode shields.

The cathode assembly illustrated in Fig. 5 represents the most successful assembly design. The principle of this design is based upon the function of auxiliary "robber" anodes which, when appropriately used in a manner to be described, afforded a means of controlling current distribution on the specimen anode to produce a cut of high quality with negligible undercutting.

The assembly consisted of a sandwich, about 1 in. by 3 in., composed of a 0.05 in. thick stainless steel cathode sheet on each side of which was bonded with electrical insulating resins a platinum anode sheet 0.003 in. thick. Owing to the inability to secure a single bonding resin that would adhere to both stainless steel and platinum, it was necessary to use two resins. The assembly was fabricated by heat-pressure molding techniques, and by appropriate adjustment of pressure the excess resin was exuded from the sandwich edges to form a uniform thickness of resin between the metal sheets. A polyfluro ethylene resin, known as Kel-F, adhered well to stainless steel and constituted the resin layer next to the cathode, and General Mills polyamide resin No. 90 adhered moderately well to platinum. No difficulty was experienced in the adherence of the two resins to each other.

Because it is known that some polymerized plastics suffer physical changes when exposed to radiation, attempts were made to fabricate the assembly sandwich with thin glass plates instead of resin to serve as insulation between the metal sheets. Mechanical contrivances to hold such an assembly together, particularly at the leading edge, did not prove entirely satisfactory.

Although it was desirable to maintain the thickness of the sandwiched assembly as small as possible to minimize the amount of metal removed during cutting, it was found practicable, however, to maintain the thickness of resin layers to about 0.003 in. on each side of the cathode. Thinner layers of resin would permit a fluffy deposit of anode metal to bridge over readily from the cathode to auxiliary anodes and thus radically change the current distribution of the circuit. Since the cathode assembly was stationary, it was difficult to keep the assembly free from such deposited metal. However, this could have been easily accomplished by imparting reciprocating motion to the cathode and passing the leading edge of the assembly over stationary wiper pads.

Anode and Electrolytic Cell Arrangements.

Two different anode arrangements were employed in this research. The first of these consisted of a stationary specimen anode wherein the anode bar was merely placed horizontally into the electrolytic cell and supported at the ends. In the other arrangement the anode bar was slowly rotated about its longitudinal axis in a bearing assembly illustrated in Fig. 6. Provisions were made in the form of an insulated flexible drive tube and lead wire, a slip ring and brush assembly, and a drive motor, to rotate the specimen anode and to permit electrical connections to be made.

As described before, the specimen anode in all experiments was bound with electroplaters tape except for the peripheral region to be cut. The precise width of unprotected anode surface depended largely upon the thickness of the cathode assembly being investigated and upon other factors.

The electrolytic cell was cooled by means of a water bath and the electrolyte agitated by a conventional motor stirrer. To provide even more agitation of the electrolyte, and which proved beneficial, the reagent was made turbulent at the area of the anode undergoing cutting by circulating the electrolyte through a rotary laboratory pump and ejecting it from a jet tube.

Suitable manually operated devices were provided to advance the cathode assembly, which so permitted, into the cut portion of the specimen anode as cutting progressed. In all cases the cathode assembly was positioned above and normal to the longitudinal axis of the specimen anode.

Experimental Results

Point-type Cathode.

As mentioned heretofore, the criterion used to judge the performance of any given cathode design and attendant cell conditions was merely comparative, i.e., the quality of cutting and the smoothness and flatness of the cut surfaces was visually adjudged after cutting had proceeded in most cases to a depth of about 1/4 in.

Experiments were first conducted on stationary brass and copper specimen anodes to compare the bahavior of a point-type cathode with a line-type cathode. The expected data indicated that the smaller the point area of the point-type cathode, the greater was the difficulty in attaining desired current densities. It was observed in addition that the point-type cathode characteristically produced an electrolytically polished area at a position on the anode only and directly opposite the point. The amount of metal removed from this area was not significantly greater than that observed elsewhere on the exposed anode surface.

The line-type cathode also produced a polished area on the anode directly opposite the line cathode, as well as a small, but well defined cut. The amount of metal removed elsewhere from the exposed anode surface was, in general, greater than in the case of the point-type cathode.

It was demonstrated early in the course of experimentation that a simple type cathode designed with no regard to geometry, as for example a sheet of copper or stainless steel merely placed in the cell, produced on a taped anode specimen an extremely poor cut and a large amount of undercutting.

Owing to the outcome of these initial experiments, the simple - and point-type cathodes were abandoned and all subsequent experimentation was conducted with various designs of line-type cathodes. Only one anode material was subsequently used, namely, low-carbon steel bar stock, since efforts were directed mainly to studying qualitatively current distribution on the specimen anode, and not to determining appropriate cell conditions for different anode compositions.

Line-type Cathode.

Data concerning the effect of cathode shielding, its extent, and distance from the specimen anode are shown in Tables 2 and 3, and Fig. 7.

It was observed that some form of shielding was necessary in simple-type cathode assemblies to confine the distribution of current on the specimen anode to a somewhat narrow band. If the shielding, however, was made too extensive, gas formation associated with the cathode reaction could not escape. Attending this situation the current flow was sufficiently disrupted so the cut produced on the specimen anode was considered quite unsatisfactory.

With an appropriate design of cathode assembly to allow for gas escapage, and with the edges of the shields out of contact with the specimen anode; the mere presence of gas was found not to be exceptionally deleterious on the quality of cut. These circumstances are indicated in the data of Table 4. It is to be noted that the best quality of cut was secured when the cathode designed permitted effective gas escapage and within limits the best quality of cut was obtained the closer together were the shields, provided they were not so close so as to inhibit the dissipation of gas.

It was the general observation that if the edges of the cathode shields touched the specimen anode, the cut produced was quite irregular and particularly so on that part of the anode making contact. This was probably attributable to the inability of the evolved gas to escape at the area of contact and the attendant disturbance of current flow.

With regard to quality of cut as influenced by the width of exposed peripheral area of specimen anode, defined by the distance between the tape edges, it was generally observed with all designs of cathode assemblies except that illustrated in Fig. 5, that the percentage of undercutting increased as the width decreased. This is illustrated quantitatively by some of the data in Table 5. In a sense, this existing circumstance is opposed to what is highly desirable in a cut of good quality, namely, one as thin as possible with little or no attendant undercutting.

From the data presented heretofore, it is evident that the shielded-type cathode assemblies -- Figs. 1, 2, 3 and 4 -- have many advantages over unshielded designs, but as a group they are deficient in ability to control undercutting to a degree considered satisfactory. This deficiency, however, has been practically eliminated through the use of the cathode-auxiliary anode assembly illustrated in Fig. 5.

As described before, the principle of the cathode-auxiliary anode assembly is based upon the function of auxiliary "robber" anodes wherein the distribution of current on the specimen anode can be controlled to such a nicety that the quality of cut is nearly comparable to that secured by rough machining methods.

By adjustment of the resistances in the electrical circuit described in Fig. 8, it is possible to vary independently the current flowing between the cathode and specimen anode, and the cathode and auxiliary anodes. As a consequence, a part of that current flowing between cathode and specimen anode, particularly the divergent current causing undercutting, can be diverted to the insoluble auxiliary platinum anodes.

The date in Table 6 — a part of which is illustrated in Fig. 9 — indicate that within limits a deeper and better quality of cut was produced with less undercutting the greater the ratio of current flowing between cathode and auxiliary anodes (I_p), and between cathode and specimen anode (I_s). It is to be noted, however, that the quality of cut was dependent upon the values of I_p and I_s , even at the same current ratio. As indicated in Table 6, items 4, 5, and 6, it is evident that at the same current ratio of 23:1, the quality of cut improved as the value of I_s decreased, even though the same electrochemical equivalents were passed in each case.

If the value of I_s does not exceed the limiting current density of the specimen anode, and if the value of I_p is of such order that the rate and volume of gas evolution does not seriously disturb current flow between the cathode and specimen anode, then the cathode-auxiliary anode assembly will function best and the quality of cut will leave little to be desired.

The sectioned specimen anode, illustrated in Figs. 10 and 11, represents the best achievement in electrolytic cutting with any of the cathode assemblies described. The undercutting was uniform, as indicated by the flatness of the cut surfaces, and amounted to about 1/16 in. total. The cut surfaces, although not entirely suitable for direct metallographic examination, were nevertheless surprisingly smooth in appearance. The center projections evident in the illustrations were the natural consequence of the specimen anode breaking before the cathode assembly had passed through the cut and beyond the longitudinal axis of the bar. In the experimental arrangement no provision was made to support and rotate the specimen halves to accomplish removal of the projections. The asymmetry of the cut noted in Fig. 10 is attributable to restrictions of the manually-operated device for supporting the cathode. It was impossible to advance steadily the cathode assembly into the cut at a rate commensurate to the rate of metal removal, and to advance it without some slight lateral misalignment of the assembly relative to the exposed cut surfaces.

Summary

It has been demonstrated in this research that electrolytic cutting is a feasible process for sectioning cylindrical shaped specimens, and that with attention directed to those variables associated with cell conditions, other than cathode design and geometry, a cut surface comparable in smoothness to that secured by conventional cutting procedures can undoubtedly be obtained. The latter has significance insofar as direct metallographic examination of the cut surface is concerned.

The cathode auxiliary anode assembly is the best possible arrangement yet devised for the prupose of electrolytic cutting. By appropriate adjustment of the current distribution in the electrical circuit, the cut surfaces can be made flat, and the little amount of undercutting that occurs can be made uniformly so over the entire cross-section of the exposed surfaces.

Because of the demonstrated uniformity of undercutting secured with the cathode-auxiliary anode assembly, it is suggested that it may function equally as well on an uninsulated specimen anode as on one taped and insulated except for the peripheral region to be cut, provided the electrolyte composition is of such character that it will not chemically attack the specimen.

For unsymetrically shaped sections that cannot be rotated, it is believed that the cathode-auxiliary anode assemble would function satisfactorily in the form of a rotating disk with the material to be cut held stationary within the cell. This arrangement would allow for wiping away metal deposit from the edge of the disk during rotation, and thus eliminate the difficulties in this regard and as described with stationary assembly. Consequently, the cathode assembly could be made thinner than the one described in this research.

Although inconclusive at this time, it appears that a high conductivity, low polarizing-type, electrolyte is superior with regard to cutting than most of the conventional, low conductivity reagents employed for electrolytic polishing. This circumstance suggests that a two-step procedure - cutting in one electrolyte and subsequently polishing in another - may be more feasible than cutting and simultaneously polishing the cut surfaces in the same electrolyte.

References

1. Electrolytic Cutting of Metals, K. Ya Shornyakov, Promyshlennaya Energetika, Vol. 3, 1946.

Table 1. Composition of Electrolytes

Electrolyte	Composition by Weight
1	85% Orthophosphoric acid
2	1 N. Sulphuric acid
3	96% Sulphuric acid - 41.8% 85% Orthophosphoric acid - 54.2% Dextrose - 4%
4	85% Orthophosphoric acid - 41.2% Ethyl alcohol-31.4% Ethylene glycol - 27.4%
5	96% Sulphuric acid - 40% 85% Orthophosphoric acid - 46% Water - 10% Dextrose - 4 %
6	1 N. Sodium sulphate

Table 2. The Effect of Cathode Shielding and Distance from a Stationary Low Carbon Steel Specimen Anode on Quality of Cut Using Cathode Assembly Illustrated in Figure 1.(1)

Item	Current Density,(2) amp.per dm^2	Cathode Assembly Data		Distance of Shield Edges from Anode, in.	Remarks
		Depth of Shielding, in.	Diameter of Pt Cathode Wire, in.		
1	6.9	1/2	0.020	Touching	Rounded cut opposite cathode, matte surface, grooves next to anode tape insulation.
2	6.9	1/32	0.020	1/2	Only grooves next to anode tape insulation.
3	6.9	1/2	0.050	Touching	Similar to 1, but in general inferior.
4	6.9	1/32	0.020	Touching	Well defined cut, better than 1, somewhat irregular where shields touched anode.
5	6.9	1/32	0.050	About 1/16	Only grooves next to anode tape insulation.
6	6.9	1/32	0.020	About 1/16	Same as 4, but no irregularities.

(1) Electrolyte: 96% sulphuric acid - 41.8%
85% orthophosphoric acid - 54.2%
dextrosw - 4%

Average temperature of electrolyte - 80°F.
Duration of cutting - 3 hours.
Diameter of specimen anode - 1 inch

(2) Current density based upon exposed anode surface area.

Table 3. The Effect of Cathode Shielding and Distance from a Rotating Low Carbon Steel Specimen Anode on Quality of Cut Using Cathode Assembly Illustrated in Figure 4(1)

Item	Current(2) Density, amp. per dm^2	Cathode Assembly Data		Distance of Shield Edges from Anode, in.	Remarks
		Depth of Shielding, in.	Diameter of Cu Cathode Wire, in.		
1	22.8	3/16	0.050	About 1/16	Very deep cut, but rough. Grooves next to anode tape insulation.
2	22.8	3/8	0.050	About 1/16	Surface roughened, but no significant cut. Grooves next to anode tape insulation.

(1) Electrolyte - 1 N. sodium sulphate.
Average temperature of electrolyte - 80°F.
Duration of cutting - 3 hours.
Specimen anode rotated at 10 rpm.
Diameter of specimen anode - 1 inch.

(2) Current density based upon exposed anode surface area.

Table 4. The Effect of Separation Distance of Cathode Shields and Improved Method of Cathodic Specimen Gas Escapage on the Quality of Cut on a Rotating Low Carbon Steel Specimen Anode.(1)

Item	Current Density,(2) amp. per dm^2	Cathode Assembly	Cathode Assembly Data: Depth of Shielding, in.	Cathode Assembly Data: Diameter of Pt Cathode Wire, in.	Cathode Assembly Data: Distance Apart of Shields in.	Time of Cutting hr.	Remarks
1	31.3	Figure 2	3/16	0.050	0.24	6	No significant cut, but large amount of undercutting. Exposed anode surface highly polished.
2	31.3	Figure 2	3/16	0.050	0.15	4-3/4	Similar to 1, except slight cut.
3	16.6	Figure 2	3/16	0.050	0.79	7	Definite cut despite low current density. Better in quality than 2.
4	31.3	Figure 3	3/16	0.050	0.79 at leading edges of glass plates	6	Grooves next to anode tape insulation and opposite edges of cathode shield. Highly polished.
5	31.3	Figure 3	3/16	0.050	0.02 at leading edges of glass plates	6	Almost complete mergence of grooves at edges of anode tape insulation to form a single cut. High degree of undercutting.

(1) Electrolyte: 96% sulphuric acid - 41.8%, 85% orthophosphoric acid - 54.2%, dextrose - 4%.
Average temperature of electrolyte - 80°F.
Specimen anode rotated at 10 rpm.
Shields of cathode assembly maintained approximately 1/16 inch from specimen anode.
Diameter of specimen anode - 1 inch.

(2) Current density based upon exposed anode surface area.

Table 5. The Effect of Width of Exposed Peripheral Surface of a Low Carbon Steel Specimen Anode on the Quality of Cut.(1)

Item	Current Density,(2) amp. per dm^2	Width of Exposed Peripheral Surface of Anode, in.	Cathode Assembly	Cathode Assembly Data		Distance Apart of Shield Edges, in.	Time of Cutting hr.	Total % of Undercutting(3)	Remarks
				Depth of Shielding, in.	Diameter of Pt Cathode Wire, in.				
1	31.3	1.2	Figure 3	3/16	0.050	0.02	6	17	Some degree of undercutting. Nearly complete mergence of cathode cut and grooves at edges of anode tape insulation.
2	31.3	0.4	Figure 3	3/16	0.050	0.02	6	20	Nearly one cut as compared to 1. Greater amount of undercutting than 1.
3	31.3	0.02	Figure 3	3/16	0.050	0.02	6	200	One cut. Greatest percentage of undercutting compared to 1 and 2.
4	31.3	1.2	Figure 4	7/16	0.050	0.08	2¼	—	Well defined polished cut. Grooves at edges of anode tape insulation.
5	31.3	0.4	Figure 4	7/16	0.050	0.08	6	—	Similar to 4 except no significant cut.
6	31.3	0.04	Figure 4	3/16	0.050	0.08	6	—	Similar to 5.

(1) Electrolyte: 96% sulphuric acid - 41.8%, 85% orthoshosphoric acid - 54.2%, dextrose - 4%.
Average temperature of electrolyte - 80 °F. Specimen anode rotated at 10 rpm.
Shields of cathode assembly maintained approximately 1/16 inch from specimen anode.
Diameter of specimen anode - 1 inch.

(2) Current density based upon exposed anode surface area.

(3) Percentage of undercutting based upon original width of exposed peripheral surface.

Table 6. The Influence of Some Operating Variables of the Cathode Assembly Illustrated in Figure 5 on the Quality of Cut Produced on a Rotating Low Carbon Steel Anode.(1)

Item	Current Between Cathode & Specimen Anode, (I_s), amp.	Current Between Cathode & Pt Auxiliary Anodes (I_p), amp.	$\frac{I_p}{I_s}$	Voltage Between Cathode &		Time of Cutting hr.	Remarks (See Figure 9)
				Specimen Anode	Pt. Anodes		
1	0.15	0	0	1.0- 0.57	0	12	Shallow cut with fair amount of undercutting. Cut surface very rough. Similar results with or without the presence of the auxiliary anodes.
2	1.5	3.5	2.3	7.1- 5.3	7.2- 5.4	12	Shallow cut with little undercutting.
3	0.4	3.5	8.8	3.6- 4.0	6.6- 5.9	12	Deeper cut than above with less undercutting than 2.
4	0.15	3.5	23	2.5- 2.3	6.8- 6.2	12	Deeper cut and less undercutting than in 1, 2, and 3.
5	0.40	9.1	23	5.2- 3.0	9.6- 6.4	12	Cut about the same as 4, but somewhat more undercutting.
6	0.55	12.9	23	9.0- 7.0	15.0-11.5	3	Cut much shallower than 4 with same electrochemical equivalents passed.
7	0.075	3.5	47	6.6- 2.0	11.2- 5.3	24	Deeper cut than 4 with about same amount of undercutting.
8	0.15	9.1	61	13.5- 2.9	19.0- 6.2	12	Depth of cut intermediate between 4 and 7 with about same amount of undercutting.

(1) Electrolyte: 1 N. sulphuric acid. Average temperature of electrolyte - 80°F. Specimen anode rotated at 5 rpm. Diameter of specimen anode - 1 inch.

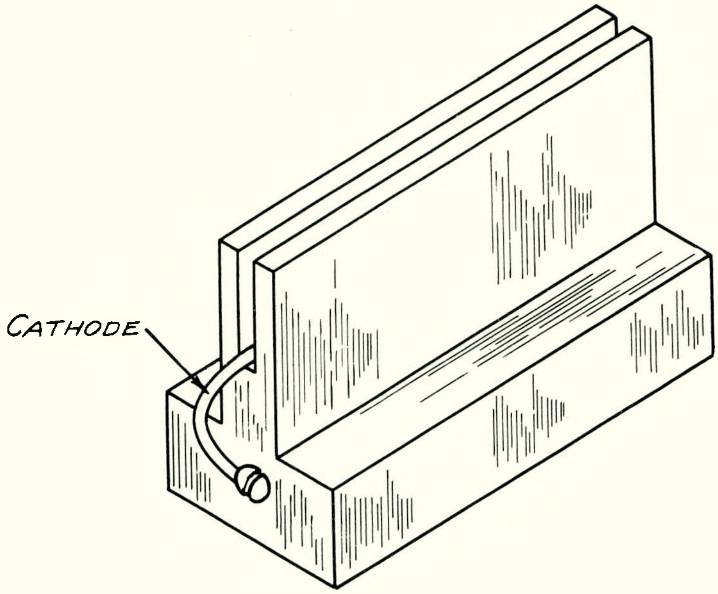

Figure 1. Line-Type Cathode Assembly With Extended Side Shielding.

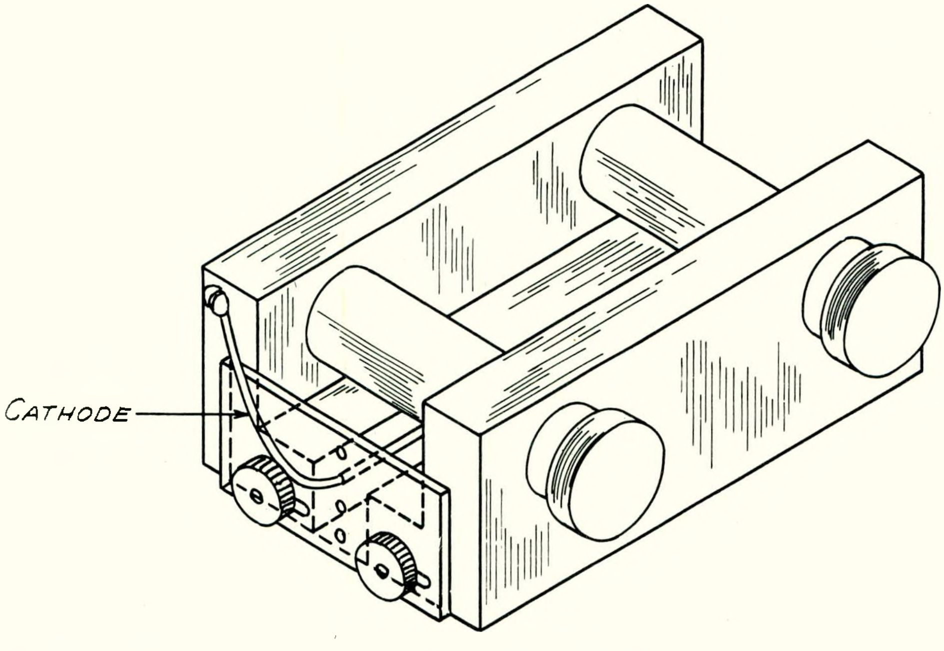

Figure 2. Improved Design of Cathode Shielding to Provide for Ready Escapage of Evolved Gas.

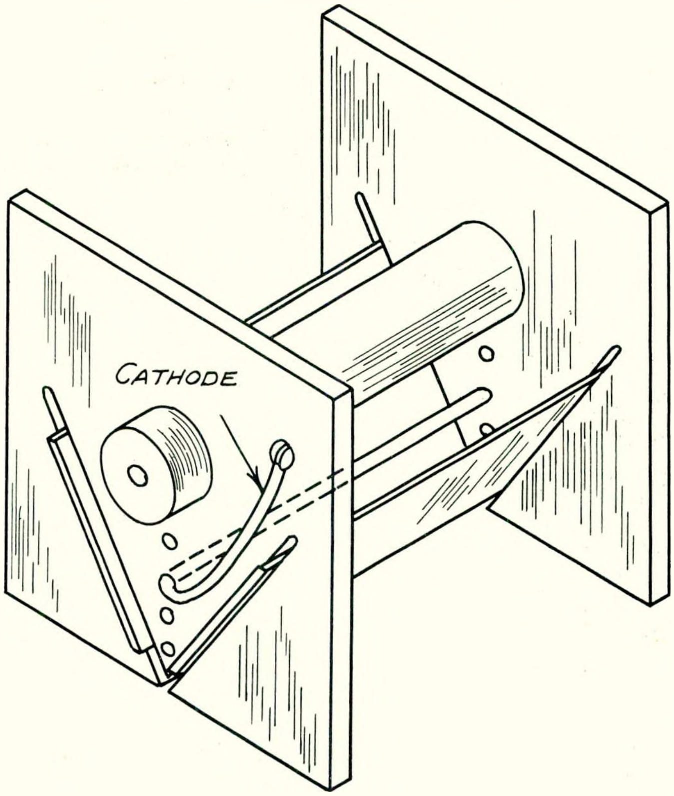

Figure 3. Line-Type Cathode Assembly Provided With Adjustable Glass-Plate Shields.

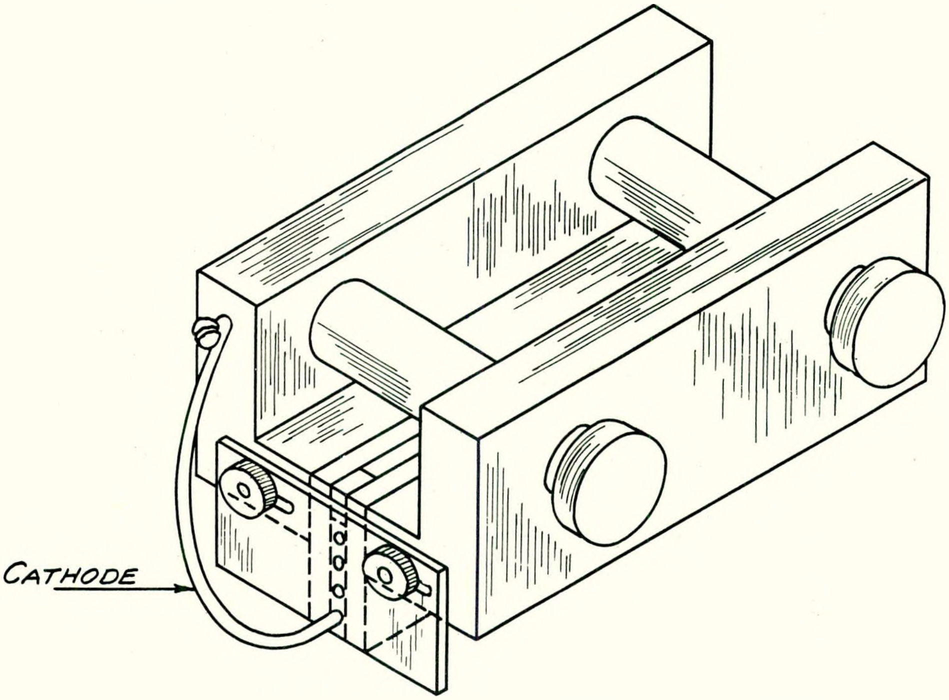

Figure 4. Line-Type Cathode Assembly, Similar to Figure 2, But Provided With Extended Glass-Plate Shields.

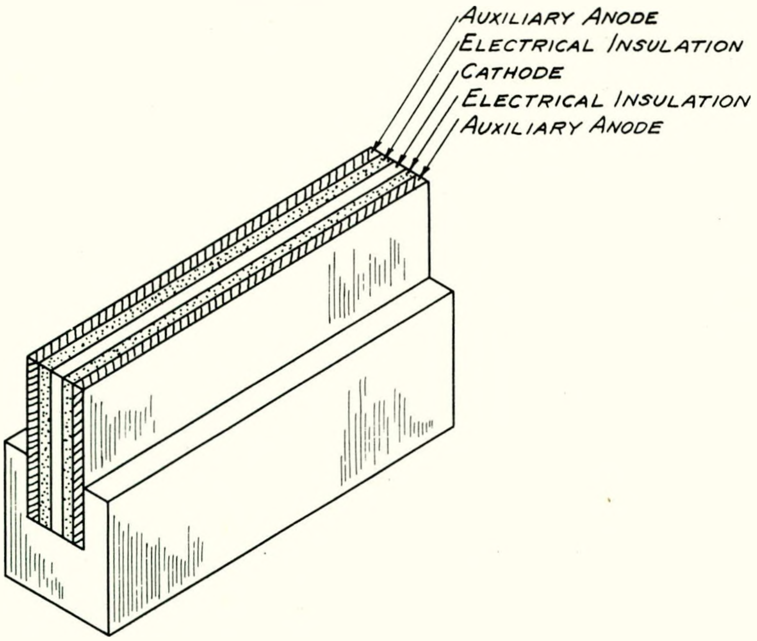

Figure 5. Line-Type Catnode-Auxiliary Anode Assembly.

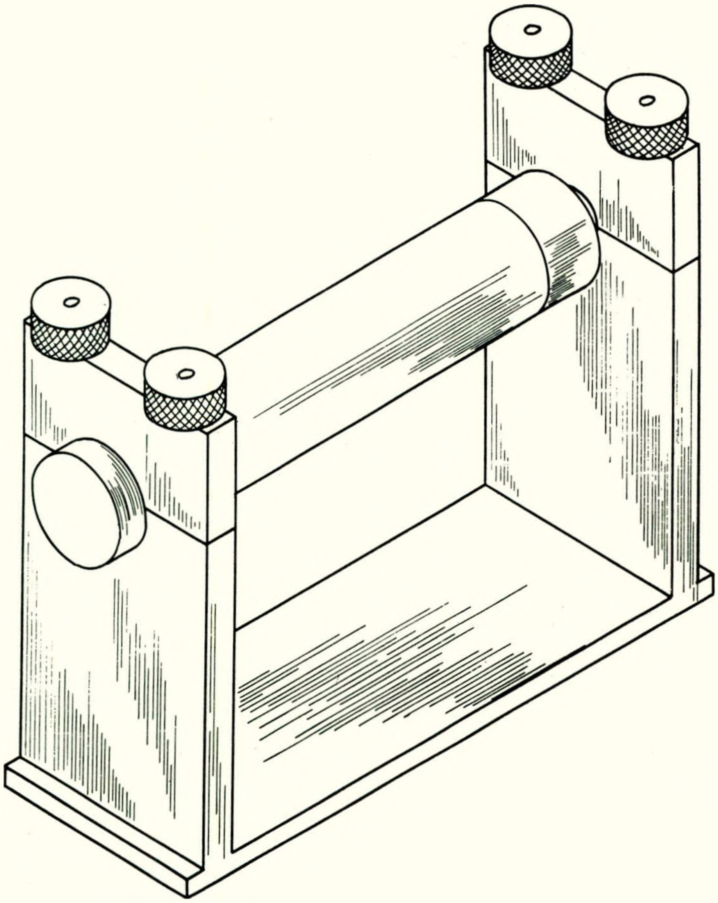

Figure 6. Assembly Contained Within the Electrolytic Cell To Permit Rotation of the Specimen Anode.

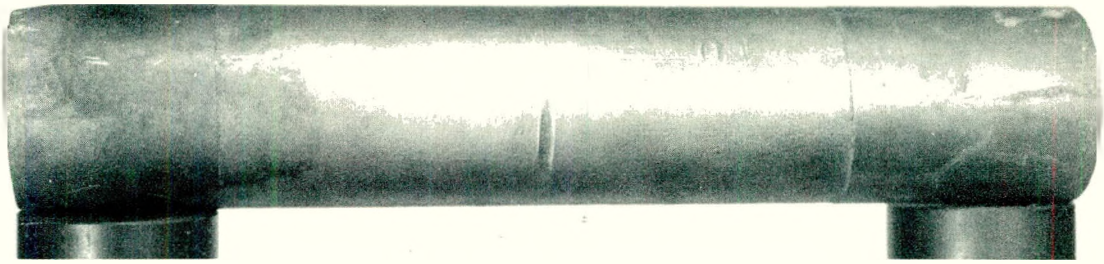

Figure 7. Illustrating the Best Concentrated Current Distribution Secured On a Stationary Specimen Anode as a Function of Cathode Shielding and Distance. 1X. For Technical Data, See Item No. 6, Table 2.

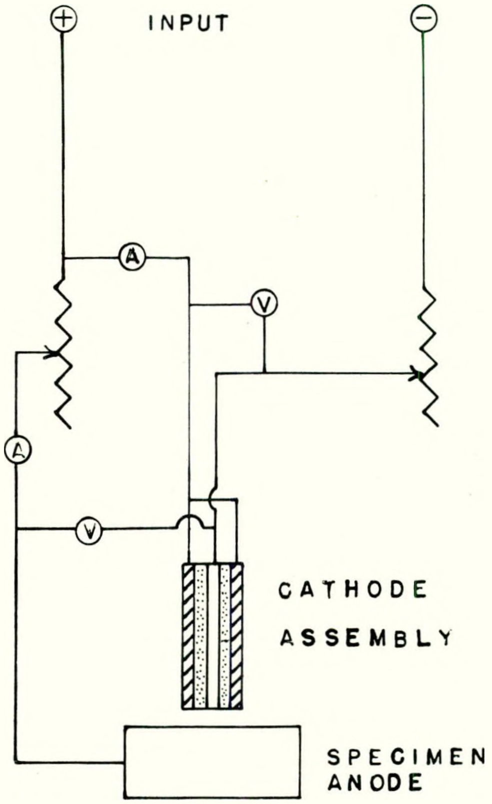

Figure 8. Electrical Circuit Including Specimen Anode and the Cathode-Auxiliary Anode Assembly Illustrated in Figure 5.

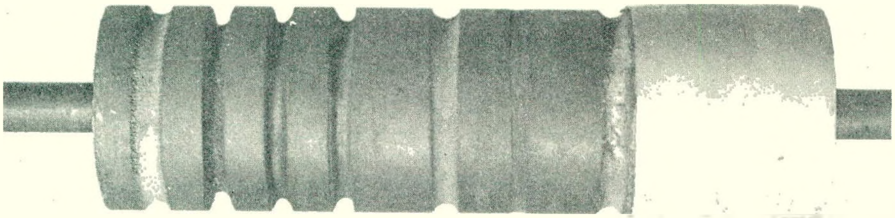

Figure 9. Partial Cuts on a Low Carbon Steel Anode Produced with the Cathode-Auxiliary Anode Assembly Using Different Values of I_s and I_p. 1X. From left to right, with reference to Table 6; items 1 (with platinum anodes not present in circuit), 7, 4, 8, 1 (with platinum anodes present in circuit), and 2.

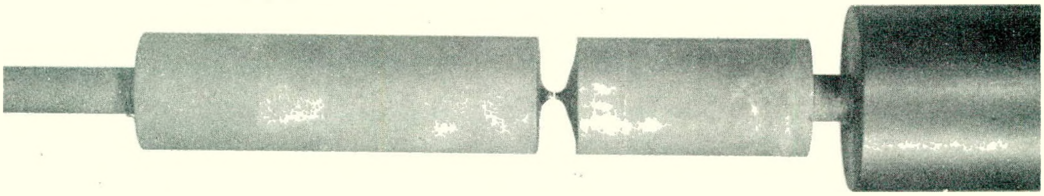

Figure 10. Completely Sectioned Bar of Low Carbon Steel, Using the Cathode-Auxiliary Anode Assembly. 1X. Technical data: anode rotated 5 rpm; electrolyte, 1 N. sulphuric acid; I_p, 9.1 amp.; I_s, 0.15 amp.; time of cutting, 26 hours.

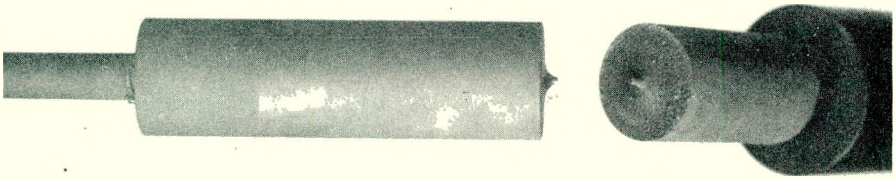

Figure 11. The Electrolytically Sectioned Bar of Figure 10, Illustrating the Quality of Cut Surface. 1X.

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