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PROCEEDINGS OF SECOND SYMPOSIUM ON ELECTRON BEAM PROCESSES

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EDITOR - R. BAKISH

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Proceedings of the Second Symposium on Electron Beam Processes

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R. Bakish
Editor

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THE ALLOYD CORPORATION
35 Cambridge Parkway
Cambridge, Massachusetts

ELECTRON-BEAM MELTING SYMPOSIUM

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PREFACE

The belief of the Alloyd Corporation in the future of electron beam processes has been well substantiated by the growth of the field. At last year's symposium, discussion of electron beam work was concerned largely with melting and refining. Today, the additional fields of welding, recording, machining and evaporating have assumed definite positions as areas from which we derive benifits from electron beam techniques. These are, however, only a beginning. We most likely shall see before long their application to the solution of problems in microelectronics. Their role in space propulsion has yet to be evaluated.

We interpret the overwhelming response accorded our symposia as an endorsement of our judgement to organize and carry out scientific meetings of this type. We have attempted to select the speakers from those who are working in the forefront of electron beam technology. We have endeavoured to limit attendance in order to prevent sheer numbers from defeating the purpose of close and informal exchange of information between engineers and scientists. Thus we hope to serve the cause of electron beam technology in the future also.

I wish to take this opportunity to express once again the Alloyd Corporation's appreciation to those who have helped contribute to the success of this meeting. In particular, thanks are due to the speakers and their organizations for making the information here contained available. Mention must be made of the Institute of Physics'cooperation in granting permission to reprint Dr. Glenn's article from the Journal of Applied Physics. We regret National Electrona's decision to withhold the talk presented by Mr. Tesman from publication. Although we did record the complete talk, as was done with all Symposium proceedings, we are honoring their request not to publish. We trust the readers will appreciate our position.

It is hoped that these proceedings, as well as those of the first symposium, will be of help to both the participants and those who are interested in electron beam processes in general.

For the Management of the Alloyd Corporation
R. Bakish, Editor
2nd Symposium on Electron Beams

INTRODUCTORY REMARKS

By

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2 Park Square
Boston Massachusetts

In the year that has elapsed since the first symposium on electron-beam melting we have experienced a tremendous growth of interest in the electron-beam processes. As a result of the increased interest it was felt that the second symposium program should emphasize the equipment as well as the process results. This position has proved itself valid, for most of those who were in attendance and most of those who will read the proceedings do not yet own electron beam equipment, but are interested in either purchasing or designing such apparatus in the near future. It is hoped that the symposium and proceedings will be helpful in either case.

It is always interesting to look at the history of a technique, and to this end I have reproduced a patent No. 848600 to M. von Pirani by the U.S. Government in 1907. When one notes the electron guns, power supplies and objectives of von Pirani and compares them with our present state of the art one can only pay tribute to a great scientist working many years in advance of this field.

THERMOPLASTIC RECORDING

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INTRODUCTION

A WIDE band width recording technique will be described in this paper in which an electron beam is used to cause deformations in the surface of a thermoplastic film. These deformations can be detected optically, and by using a special optical system described in a previous paper,[1] full color images can be projected from the film. The film requires no chemical processing and can be erased and reused. The resolution is comparable to that of photographic film and the bandwidth capability is well in excess of that required for video-recording.

RECORDING TECHNIQUE

The recording principle is illustrated in Fig. 1. The film used consists of a high-melting base film coated with a transparent conducting coating with a thin film of a low-melting thermoplastic on its surface. An electron beam is used to lay down a charge pattern on the surface of the thermoplastic film in accordance with the information to be stored. The film is then heated to the melting point of the thermoplastic. Electrostatic forces between the charges on the film and the ground plane depress the surface where the charges occur until these forces are in equilibrium with the surface tension restoring forces. The film can now be cooled below its melting point and the deformations will be "frozen" into the surface. With some materials the charge pattern will persist for days. It is usually not necessary to develop the deformations immediately after charging the film; however, this is usually done so that the recorded information can be monitored as it is being recorded.

The time required for the deformations to form depends on the viscosity of the film when it is melted but is usually of the order of a few milliseconds.

To erase the film the charge pattern must be discharged by heating the film well above its melting point so that its conductivity will increase. Surface tension will then smooth out the deformations and the film is ready for reuse. The film is usually heated for developing the deformations in a vacuum. It must also be cooled back below the melting point before it can be rolled up. A practical way to do this is to heat only the top surface of the film by inducing current in the transparent conducting coating for about 0.01 sec. This is ample time for the deformations to form. The heat will then diffuse into the film base and the surface will cool. By confining the rf fields, local erasure of areas a few mils square is possible if desired.

A recorder was constructed as illustrated in Fig. 2. The film plays off a reel, is driven at constant speed by a drive capstan and is charged by the electron beam. The electron beam is modulated by the signal to be recorded. The charge pattern is laid down in a television-type raster. The electron beam sweeps across the film, providing the horizontal sweep of the raster. Vertical sweep, along the film, is provided by the tape motion. As the film passes over the pair of rf electrodes, the surface is heated to the melting point of the thermoplastic, allowing the deformations to form. As the film moves on, the heat diffuses into the film base and the deformations are frozen into the surface. A small optical system, to be described later, is placed just after the rf electrodes (not shown in Fig. 2) so that the recorded information can be monitored. The entire device is in a continuously pumped vacuum chamber at a pressure of about 0.1μ.

The charge pattern has been laid down successfully in air simply by dragging a fine wire, with the voltage to be recorded applied to it, across the surface of a thermoplastic film. However, recording in a vacuum seems to be much more practical since it permits higher writing density and speed, and is more reproducible.

READINGS

(a) Color Images

For color imaging the deformations are impressed on the thermoplastic surface in the form of phase diffraction gratings. The optical system described in a previous paper[1] permits projection of a color image from such a pattern of gratings. This system is illustrated in Fig. 3. In this projector a condensing lens near the film images an array of line light sources on a set of opaque bars in front of the projection lens. Where the film is smooth, these bars

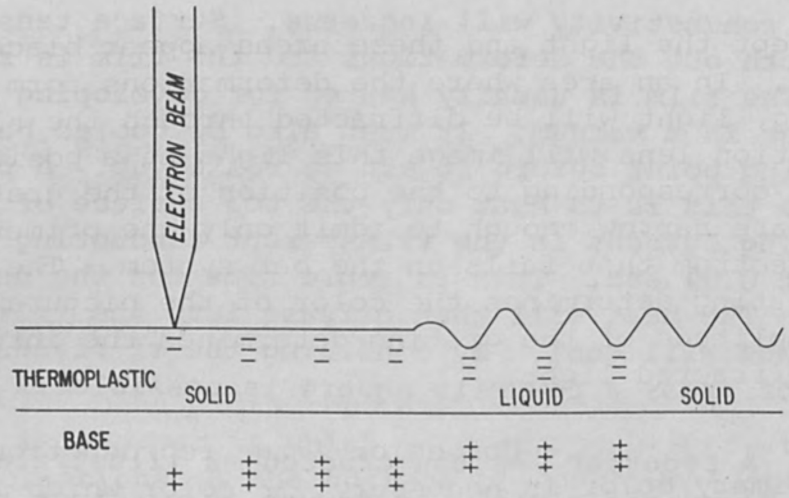

FIGURE. 1

BASIC MECHANISM OF THERMOPLASTIC RECORDING.

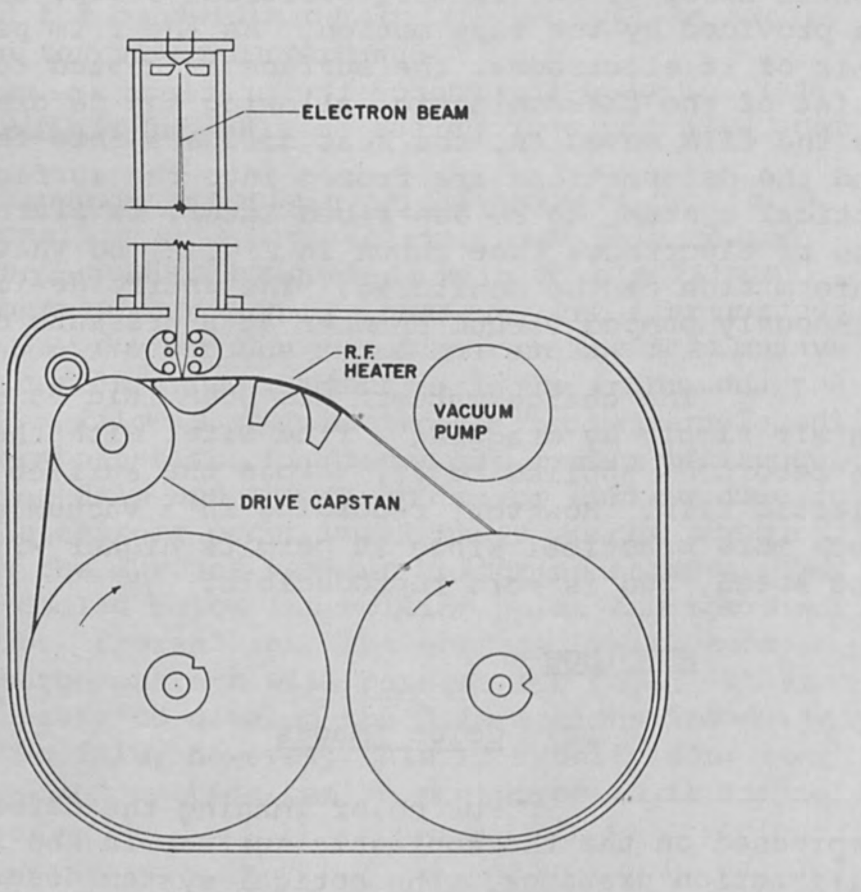

FIGURE. 2

EXPERIMENTAL THERMOPLASTIC TAPE RECORDER intercept the light and these areas appear black on the screen. In an area where the deformations form a diffraction grating, light will be diffracted through the slots and the projection lens will image this light at a position on the screen corresponding to the position of the grating. The slots are narrow enough to admit only one primary color of the spectrum that falls on the bar system. The spacing of the grating determines the color of the picture element. The amplitude of the grating determines the intensity of the diffracted light.

For color image reproduction more than one primary color is necessary. A color which is the sum of two or more primary colors can be formed by simply superimposing two or more gratings, each with a spacing corresponding to a primary color. A new primary system[1] using one fixed and one variable color is found to have many advantages over a system of three fixed color primaries.

A special electron gun, to be described later, is used to produce the gratings in each picture element with the appropriate spacing and amplitude.

(b) Black and White Images

The optical system employed for projection of black-and-white pictures is a modified Schlieren system. The slots and light sources are made wide enough for the entire spectrum to be passed by the optical system. The electron beam simply scans a normal television line, depositing charge in accordance with the light intensity of each picture element. The amount of charge will govern the depth of the resulting deformation, and upon projection the light intensity of the picture element will depend upon this depth.

(c) Resolution

The electron beam size can resolve wavelengths smaller than the wavelength of light. However, the resolution of the system is limited by optical considerations. For the black-and-white system each line can be resolved by the optical system. For color, narrower slots and light sources are used. Because of diffraction from these narrower slots, about four grating lines are required to produce a resolvable picture element in color. This means that a picture element recorded in color requires about four times the area of the corresponding element recorded in black and white.

As the grating spacing is narrowed, the diffraction angle of course increases. When the diffraction angle is large, the optical system of Fig. 3 simplifies to that shown in Fig. 4.

(d) Electrical Signal Output

To read the film to produce an electrical output, a flying spot scanner or camera tube may be used with the optical system described above. A simple version of a flying spot scanner reading system is shown in Fig. 5. Here the film is scanned with light of a single color from the flying spot scanner. Photoelectric cells are placed at different angles to accept light diffracted by gratings of different spacing.

(e) Analog or Digital Data

To record electrical signals in analog form, the electron beam is modulated by the signal to be recorded. For a single beam, the intensity can be modulated. When the split beam is used, both the grating spacing and the intensity can be modulated.

For binary digital data, a single split beam may be used. In this case, it is desirable to use only two colors, one for the 0's and another for the 1's. In this way all data bits appear as the presence of a single color. Since a dust speck scatters light randomly, it appears as white light. A coincidence in the zero and one detectors can thus be made to reject dust. Coordinate data can be recorded as the absence of a color. Since coordinates can be recorded in with the data, high mechanical tolerances are not required to realize the high resolution of the system.

ELECTRON GUN DESIGN

A special electron gun was designed which lays down a charge pattern that will form a diffraction grating of appropriate amplitude and spacing in each picture element.

For recording color pictures on film, the electron beam is split into several beamlets, whose amplitude and separation can be determined by potentials applied to appropriate electrodes in the electron gun. This split beam

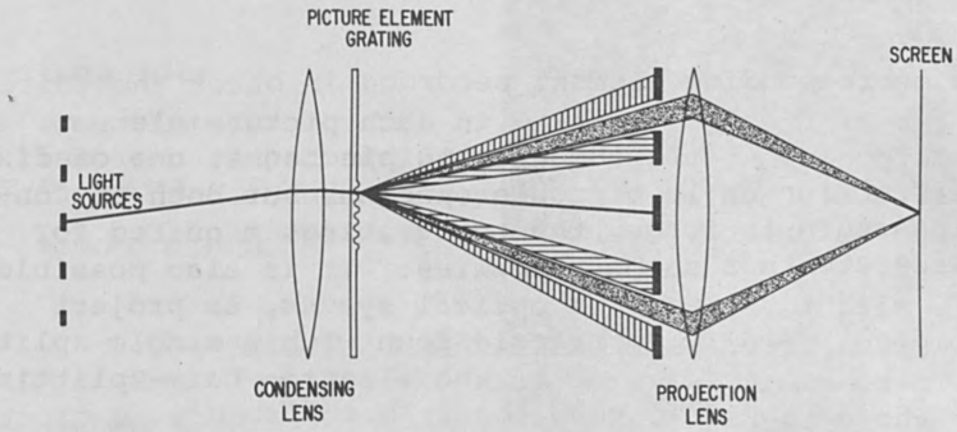

FIGURE. 3
OPTICAL SYSTEM FOR PROJECTION OF COLOR IMAGES FROM DEFORMED TRANSPARENT MEDIUM.

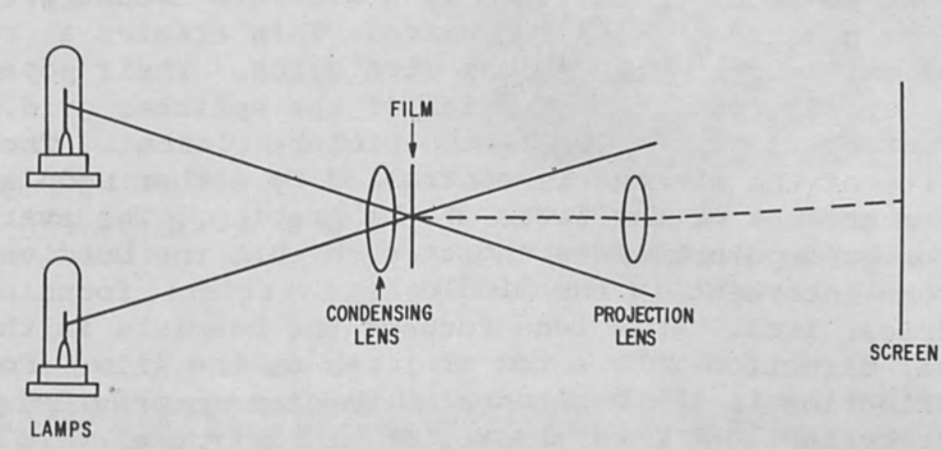

FIGURE. 4
SIMPLIFIED OPTICAL SYSTEM FOR CASE OF SMALL GRATING SPACING (LARGE DIFFRACTION ANGLE).

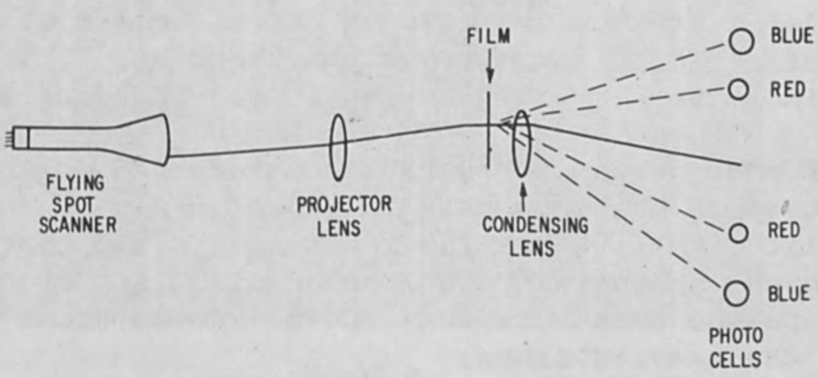

FIGURE. 5
FLYING SPOT SCANNER OPTICAL SYSTEM FOR CONVERTING RECORDED IMAGE TO ELECTRICAL SIGNAL.

forms the diffraction grating in each picture element. The superposition of two such multiple beams, one of fixed spacing, the other of variable spacing, but both of controllable intensity, creates the gratings required for fixed and variable color primaries. It is also possible, using a slightly different optical system, to project color images from patterns laid down with a single split beam. A schematic drawing of the electron beam-splitting gun is shown in Fig. 6.

The beam emerges from the point of the hairpin cathode, and is accelerated by the field between cathode and anode. A fine wire splitter grid, slightly positive with respect to the anode, is placed in the electron beam. Electric field lines terminating on the grid wires deflect different portions of the beam by a discrete amount for all electrons passing between two wires. This creates a row of apparent sources back of the wire grids. Their separation depends upon the potential of the splitter grid, thus controlling the color of the picture element. The intensity of the element is controlled by either modulating the beam current or the focus of the grating. The average splitter grid potential is chosen such that the bundles of electrons intersect in the middle of a vertical focusing cylindrical lens. This lens focuses the beamlets in the vertical direction into a row of lines on the film. Focus and deflection in the horizontal direction is provided by another cylindrical lens and set of deflection plates. Since high resolution but no deflection is required in the vertical direction there is a considerable advantage in focusing in the two directions separately.

For alignment and focus of the gun a transparent phosphor plate replaces the film. A photograph of the split beam trace on the phosphor is shown in Fig. 7. In the photograph the defocusing at the ends of the trace was due to curvature of field of the microscope objective. The split trace was in focus for a deflection length of about 1 1/2 in.

A photograph of raster lines recorded on thermoplastic tape with a split electron beam is shown in Fig. 8. Each raster line is split into five grating lines spaced 10μ center to center. In the photograph the last grating line of one raster line overlaps the first grating line of the adjacent raster line to produce the heavier lines.

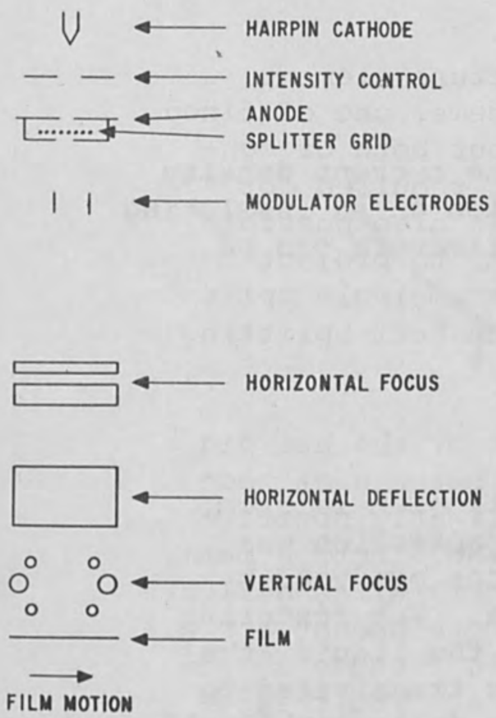

FIGURE. 6
SCHEMACTIC DRAWING OF ELECTRON BEAM SPLITTING GUN.

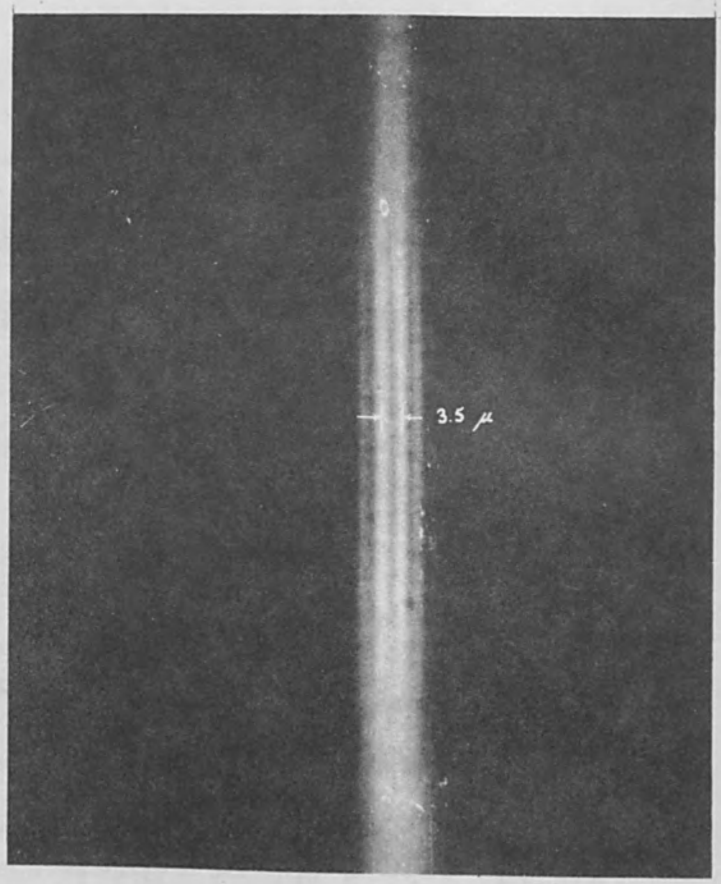

FIGURE. 7
PHOTOGRAPHIC IMAGE OF SPLIT BEAM ON PHOSPHOR.

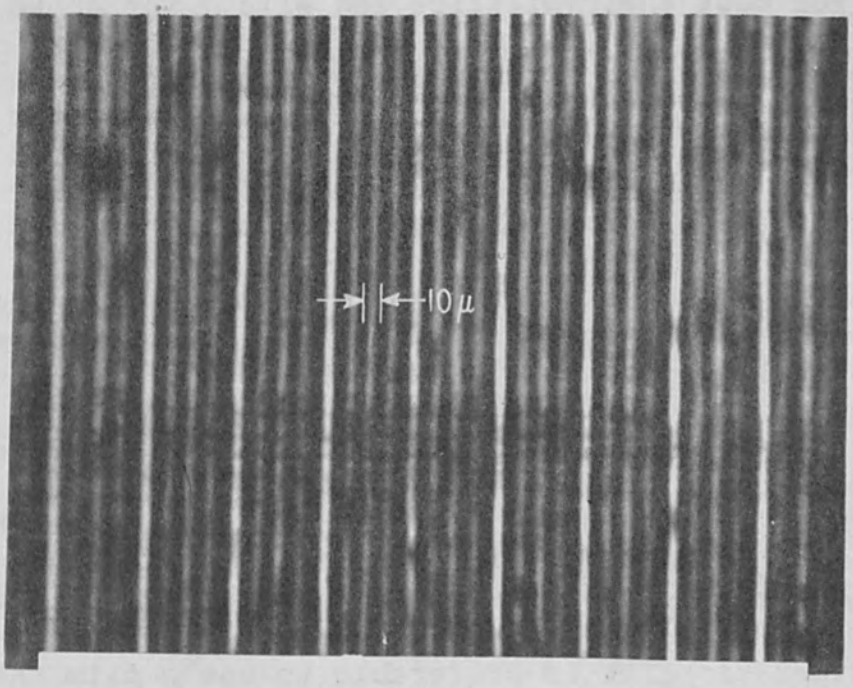

FIGURE. 8
PHOTOGRAPH OF RASTER LINES, RECORDED ON THERMOPLASTIC TAPE, WITH SPLIT ELECTRON BEAM.

SENSITIVITY

An approximate expression for the current density in amp/cm^2 required to produce a deformation on an insulating liquid of wavelength W and depth A in centimeters can be derived as

$$i = \frac{8 \times 10^{-10}}{Wt} (\epsilon TA)^{1/2}$$

where ϵ=dielectric constant, T = surface tension in d/cm, t = dwell time of spot in seconds. This expression was derived by equating the electrostatic forces produced by the charge pattern to the restoring forces. The restoring forces consist of hydrostatic pressure in the liquid (the means by which the force on the surface is transferred to the base) and surface tension forces. The following simplifying assumptions were made (see Fig. 9): (a) The profile of the ripple can be represented by a pair of parabolas; (b) the charge is deposited on the surface in a square wave of wavelength W; (c) the field lines are essentially parallel. To diffract maximum light of wavelength λ into the first order the approximate value for $A = (\lambda/2(n-1))$ where is the index of refraction. If visible light is used, the product ϵTA is about 25×10^{-4} for most thermoplastics and oils. The above expression is then typically $i = (4 \times 10^{-11})/Wt$. This expression has been confirmed experimentally for both oils and thermoplastics and found to be correct within a factor of two. About 1/2 amp/cm^2 is required to write video band widths with a 10-μ grating spacing. This is far below the current density available from the electron gun.

When the depth of penetration of the writing electrons is an appreciable fraction of the wavelength W, the expression is not believed to hold. At 15-kv beam energy the grating amplitude drops rapidly below 10μ even though the electron beam resolution is much better than this. To reach the ultimate resolution limit of the optical system with reasonable current densities the depth of penetration of the electron beam must be reduced. The foregoing expression does not depend markedly on the wave shape of the deposited charge pattern, or film thickness. However, because of several practical considerations it is preferable to use a film thickness of about one-half the grating spacing.

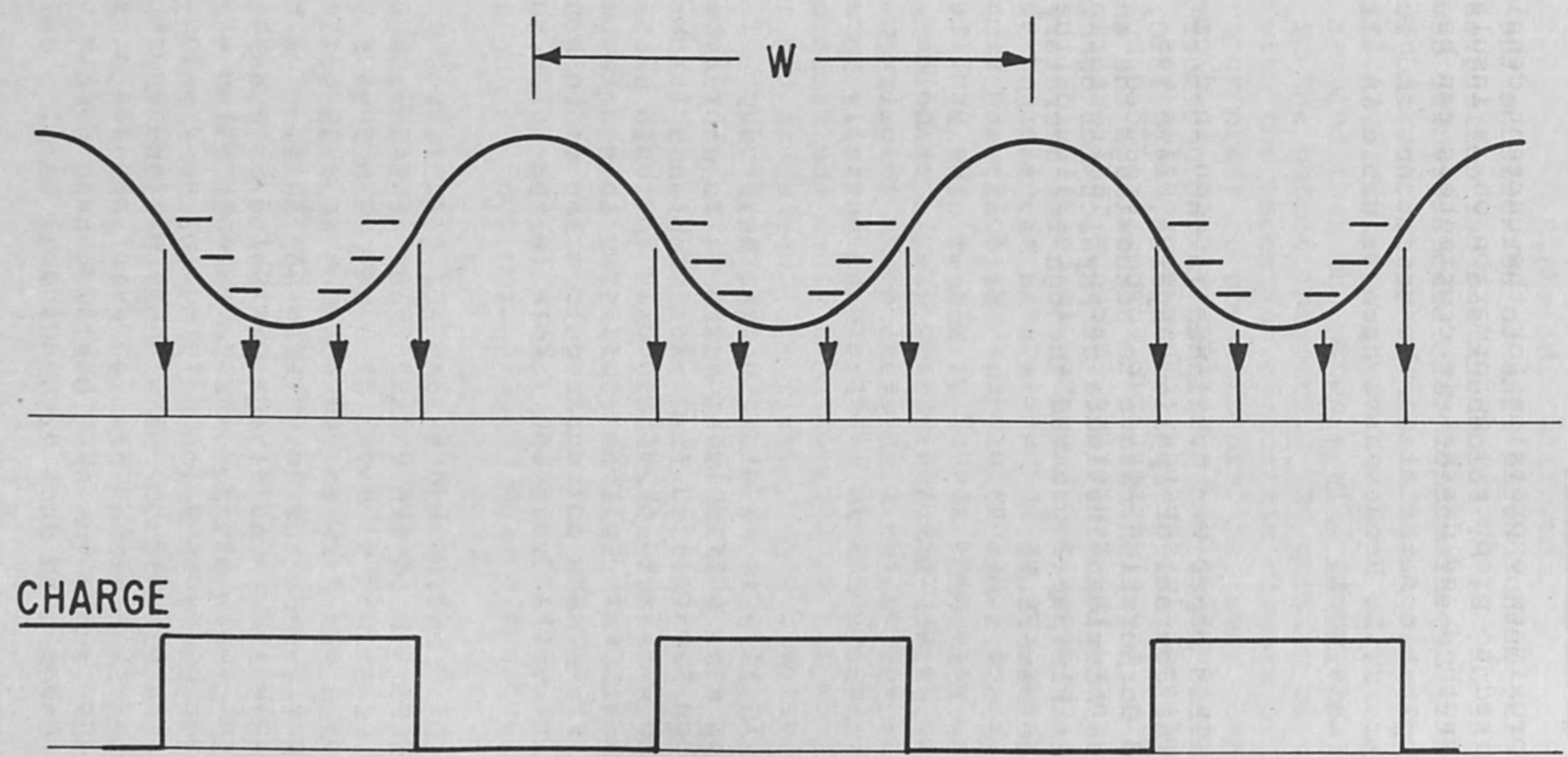

FIGURE. 9

ASSUMED DEFORMATION OF THERMOPLASTIC SURFACE (UPPER) AND DISTRIBUTION OF CHARGE ON SURFACE (LOWER)

ACKNOWLEDGMENTS

The author would like to acknowledge the contribution of Dr. E. M. Boldebuck and her colleagues of the Chemistry Department of this Laboratory for developing thermoplastic materials. The assistance and suggestions of Mr. J. L. Henkes have been valuable in all phases of this work.

N. B.

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THE ECONOMICS OF LARGE SCALE ELECTRON BEAM MELTING

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Considerable attention in the last several years has been directed to progress in the technology of electron beam melting. This progress has been substantial and little doubt remains that the process will occupy a significant place in the metals industry. The quality of the melted product, with the exception of certain classes of alloys with high vapor pressure constituents, has been generally superior to equivalent material processed by other means. In certain cases, particularly the melting of some of the refractory metals, the melt product is uniquely superior. However, from a business point of view, electron beam melting at the present time is in a rather awkward stage of development. As a process it has not yet been scaled up to a level of operation which matches the unit capacity of other vacuum melting processes. For this reason it is not competitive pricewise on a broad product base. This financial limitation to the applicability of the process is a major factor in the economics of electron beam melting at the present scale of operation.

The first part of this paper will discuss economic considerations of electron beam melting in a general way. The general considerations will be followed by the specifics of present electron beam production furnaces which are mainly melting expensive refractory metals. The discussion will then be extended to the coming situation when a six-fold scale up will process special nickel and steel alloys under competitive conditions.

Virtually the entire production of electron beam melted material in this country has been produced in furnaces typified by the 250 KW unit shown in Figure 1. The production capability of this furnace varies with the material being melted as well as the quality of the material particularly with respect to volatile impurities. Melt stock that is clean from the point of view of atmospheric melting is literally filthy from a vacuum melting point of view. The actual mechanism of the purification is not completely understood; however, results consistent with certain theoretical postulations (Ref. 1) have been obtained. In any event, the volatile impurities emitted from the melt must be removed. These are

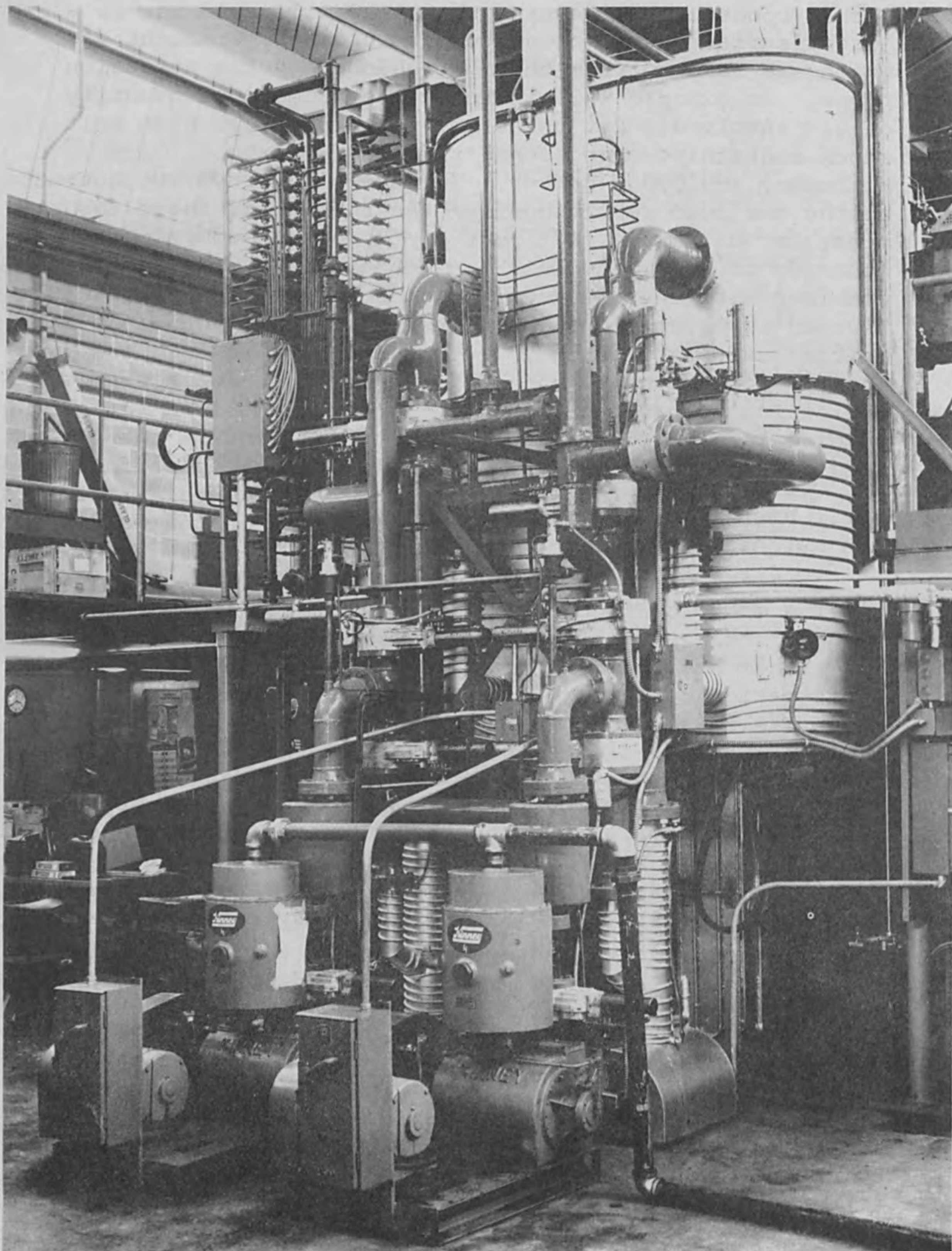


Figure 1
250 KW Production Furnace

either condensable (meaning that they will condense or adjacent surfaces at ambient temperature) or permanent gases which are removed from the melt chamber by the diffusion pumps. An example will indicate the tremendous quantity of gas involved. Let us assume a typical columbium melt stock containing among other things 0.2% oxygen, 0.05% nitrogen, and 0.03% carbon. To make a conservative estimate of the gas load resulting from the removal of these impurities, let us assume that most of the oxygen comes off as the monoxide of columbium which is condensable. The remainder combines with the 0.03% carbon to form CO. The nitrogen is assumed to be completely removed as permanent gas. At an initial melting rate of 10 pounds per hour we are thus pumping .006 pounds of CO and .005 pounds of nitrogen per hour. Neglecting temperature effects which are small as far as the pumping load is concerned, we must then remove a total gas load of about 12,000 liters per second at an operating pressure of 7.6×10^{-5} mm Hg in the melt tank. Figure 2 indicates the actual degree of purification attained in the columbium.

It has been suggested that, to avoid the large pumping capacity required to carry this gas load, the pressure be increased in the melt chamber. Unfortunately, experience has shown that as the pressure is increased, the purification rate decreases, and there is a net loss in the melt rate to reach a prescribed end point. This is in addition to the difficulties encountered in maintaining high electron beam efficiencies at the higher pressures. The effects of increased pressure on the purification reaction kinetics, the diffusion rate of the gases from the melt, and the back reaction rate have not, as yet, been separated. It has been observed, however, that to obtain really high quality material with, for example, total impurity content of 100 ppm, it is necessary to maintain the furnace at even lower pressures, i.e. 10^{-5} mm, and to ensure that total furnace in-leakage is extremely low. Figure 3 shows the extensive purification of tantalum under these conditions.

These examples show that to reach a specified purity, the melt rate is dependent on the composition of the feed stock. Obviously, decreases in impurity content are reflected linearly in the pumping rate at a constant pressure. It has been demonstrated that, to achieve rates of commercial significance, very high pumping capacities are required to maintain suitably low pressures for melting and purifying the typical product of current practice in reduction reactions.

Another consideration that enters into the economic picture is the cost of research in this new field. As more and more experience is obtained, additional interesting avenues of investigation open up. Very often these yield improvements which pay for the cost of the research in terms of lowered production costs in a few months of operation. However, long range research on the fundamentals of electron beam melting and associated phenomena, by its very nature, cannot provide a predictable return on the research investment. These costs must be expensed along with direct production costs if the business is to be profitable. The effects of expensing the research effort depend on the type of business. If electron beam melting is used as the final processing stage in integrated ore-to-metal production, the research effort will probably be a minor item. For custom melters and/or equipment producers, this is apt not to be the case.

In establishing any business depending on a new technology, there are usually major fluctuations in activity. This has been, and will probably continue to be, the case in establishing electron beam melting as a commercial venture. In addition to the cyclical effects on the over-all business, such as variation in work force, adjustment in inventories, etc., there are other factors which affect operational costs. One of the most bothersome, and most necessary, items is the wide variety of small job lots which must be performed as back-up for the developmental sales activity. Many of these small lots require special furnace set-ups and very few of them use identical furnace facilities.

This requirement for flexibility in furnace facilites is not restricted to small experimental lots. In production, different configurations are required not only for different materials, but also at various stages in processing the same material. A real production furnace must possess this operational flexibility. Figures 4 through 7 illustrate a few of the variations in production melting configurations.

The per cent of actual furnace melting time decreases in changing among the various configurations. The result is, of course, that the cost per pound of melted material rises. Conversely, considerable cost savings are effected when there is sufficient business volume in any one metal to run a furnace on that material alone for an extended period. It has also been found more efficient to

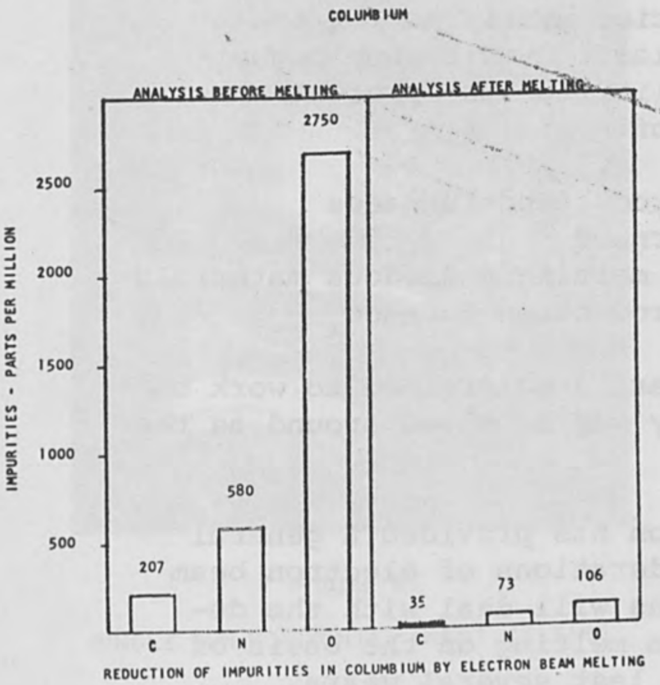


FIGURE. 2

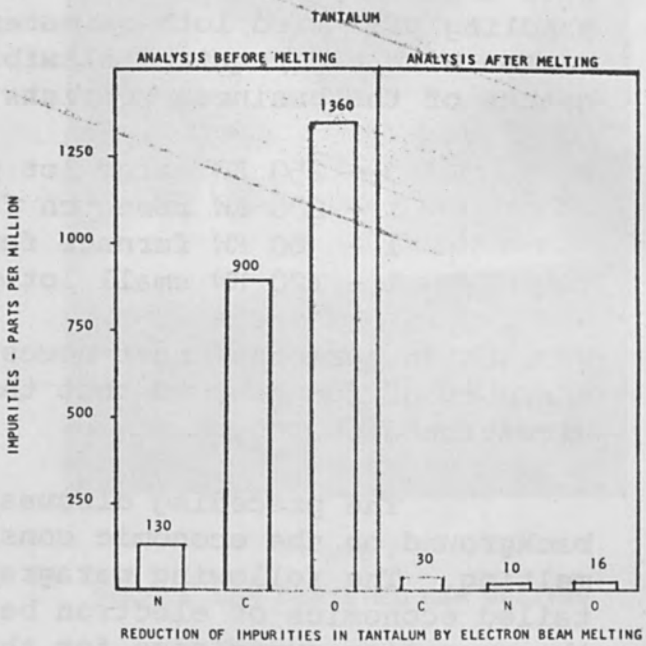
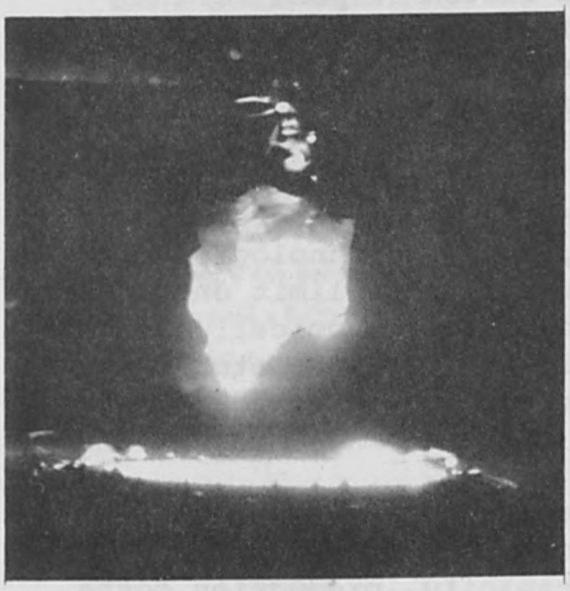


FIGURE. 3



SCRAP REGULAR MELTING

FIGURE. 4

SINGLE GUN VERTICAL INGOT MELTING

FIGURE. 5

have a variety of melting facilities available for the handling of varied lots of material. A melt shop organization with the required flexibility for the present nature of the business consists of:

- 3 - 250 KW large lot production furnaces
- 1 - 200 KW research furnace
- 1 - 60 KW furnace for melting hazardous materials
- 1 - 120 KW small lot production furnace.

Production personnel must necessarily be trained to work on a number of furnaces so that they may be moved around as the situation dictates.

The preceding discussion has provided a general background on the economic considerations of electron beam melting. The following paragraphs will deal with the detailed economics of electron beam melting on the basis of the operation experience for the last several years.

Figure 8 shows the basis of established costs for a 250 KW furnace. Several of the listed items bear further elaboration. Note that the furnace cost reflects that of an operating production unit with proven capabilities, not a laboratory unit which can melt a button of pure feed stock. Operators are non-professionals, but with definite technical aptitudes. Furnace personnel include operators, material handlers, and maintenance men.

In reaching the present level of operation, considerable data on scale-up factors have been generated. It has been clear for some time that, from a technological point of view, there was no foreseeable size limit on electron beam furnaces. Data justifying scale-up economically are now equally conclusive. Figure 9 indicates the estimated costs for the operation of a 1500 KW furnace scheduled for construction.

Figure 10 shows the effects of scale-up on monthly production costs. An important point here is that for at least a six-fold increase in the capacity, production costs increase by slightly more than a factor of two.

The actual melting costs per pound of metal depend, as indicated previously, on the kind and quality of the material. Some cases in point will illustrate actual cost figures.

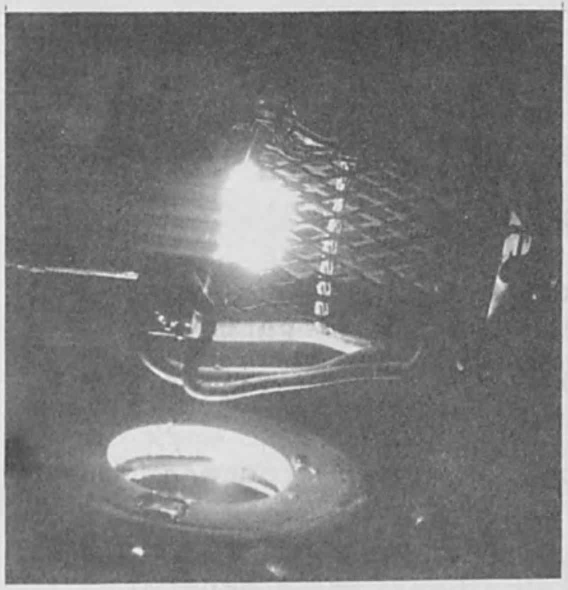


FIGURE. 6

SINGLE GUN HORIZONTAL INGOT MELTING

FIGURE. 7

DOUBLE GUN CENTERED BAR MELTING

BASIS OF ESTABLISHED COSTS
250 KW FURNACE

1. A years production of 5" diameter columbium and tantalum-tungsten alloy ingots.
2. 60% on stream melting time.
3. 15 man days per day on furnace operations
4. 24 hour day, 6 day per week operation
5. Labor + overhead = $1000 per month per man.
6. Capital cost of furnace is $175,000.
7. 5 year amortization period.
8. Utilities at $0.01 per KWH of power.

FIGURE. 8

BASIS OF ESTIMATED COSTS
1500 KW FURNACE

1. Operating experience on 2 250 KW furnaces.
2. 70% on stream melting time.
3. 21 man days per day on furnace operations.
4. 24 hour day, 7 day per week operation.
5. Labor + overhead = $1000 per month per man.
6. Capital cost of furnace + building is $600,000.
7. 5 year amortization period.
8. Utilities at $0.01 per KWH of power.
9. Linear rate of ingot production same as 250 KW furnaces.

FIGURE. 9

EFFECTS OF SCALE UP ON PRODUCTION

COSTS PER MONTH

	250 KW FURNACE	1500 KW FURNACE
Labor	$15,000	$21,000
Maintenance Materials	1,500	5,000
Utilities	1,000	7,500
Taxes and Insurance	300	1,500
Laboratory	500	1,000
Shipping	500	1,000
Supervision and Administration	2,000	3,000
Amortization	3,000	10,000
TOTAL COSTS	$23,800	$50,000

Figure 10

In melting columbium initially containing:

0.2 weight % oxygen
0.05 weight % nitrogen
0.03 weight % carbon

to a desired analysis of:

150 ppm oxygen
70 ppm nitrogen
75 ppm carbon

a production rate of about 6,000 pounds per month can be obtained in a 250 KW furnace.

The cost per pound is then:

$$\frac{\$23,800}{6000 \text{ lbs.}} = \$3.97 \text{ per pound}$$

A production rate of at least six times this is reasonable to expect in the 1500 KW furnace. The costs per pound then become:

$$\frac{\$50,000}{36,000 \text{ lbs.}} = \$1.39 \text{ per pound}$$

Actual charges for melting columbium on a custom melting basis contain not only the basic costs above, but research expense, overhead, depreciation, and profit. Thus the charges are generally of the order of twice the base costs at the present level of operation. When the 1500 KW furnace comes on stream, this pricing factor should decrease appreciably.

The scale-up offers some interesting possibilities in extending electron beam melting to a much broader product base. For example, melting rates for high nickel super alloys have been determined. These indicate present costs for the refinement of these materials to be as follows:

250 KW furnace ------- \$ 1.32/pound
1500 KW furnace ------- \$ 0.46/pound

These costs appear to be competitive in present markets, especially in view of the improved qualities and properties of the resulting ingots.

This single example points up the tremendous potential in the electron beam melting process. As melting facilities are scaled up to production capacities now possessed by other vacuum melting processes, some very interesting economic developments should take place.

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1. Bunshah, R. F. Vacuum Metallurgy, Chapter 14, Reinhold Publishing Corp. New York, 1958

A COMMERCIAL ELECTRON BEAM LABORATORY FACILITY

by

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In this presentation I will briefly mention the aims of L. R. Industries prior to proceeding to describe the Electron Beam equipment which we use and the type of work that we perform. I will show you a short moving picture of the cutting of a hole with the Zeiss machine.

L. R. Industries Inc., was formed a little over one year ago with the intention of going into business cutting small holes using the Zeiss Electron Beam milling machine. We received our equipment last June and it became operable during the early part of July. Since that time we have been performing various tasks for a number of customers.

The Zeiss Electron Beam milling machine is manufactured by the Carl Zeiss Corporation of Oberkochen, West Germany and is shown in Figure 1.

From left to right one can see the high voltage source, the oscilliscope, the work chamber surmounted by the electron beam column, the cabinet containing the electronic circuits and in the far right corner, the edge of the mechanical vacuum pump. Not shown in this picture, but located in back of the work chamber are the isolation transformers. The high voltage source gives us a voltage of from 25 kvs. to 150 kvs., though at the present time we seldom operate above 110 kvs. This unit is capable of giving a beam current of 50 watts continuous power or approximately 500 watts short time pulse power. Looking at the electronic circuits panel (Figure 1) and reading from bottom to top,the function is as follows: bottom panel, mainbreakers and voltmeter. The next panel upward, the vacuum controls. The next panel upward, the circuits used for mechanically centering the beam in the column and for controlling the astigmatism of the beam. The next panel controls the filament voltage and the gun bias. It also holds the vacuum meter. The next panel contains the circuits which generate various wave forms which are used for programming various shapes.

Figure 1

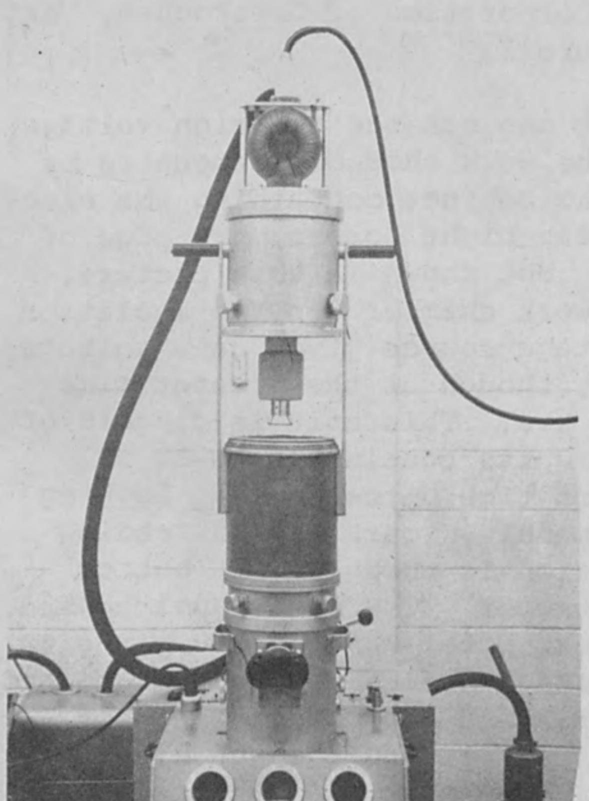


Figure 2

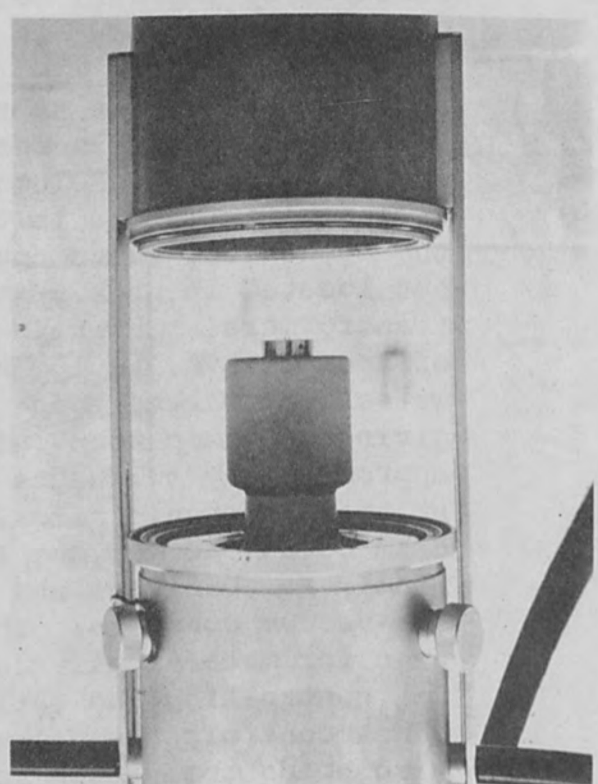


Figure 3

This programming is done by imposing various wave forms on a set of deflection coils located at the foot of the electron beam column and a short distance above the work piece. As an example of how this is accomplished, imagine a 4-pole deflector with the 4 coils arranged 90 degrees apart with their axis pointing inward at a common center. If we now consider two of these coils, 180 degrees apart connected in series and a sawtooth voltage applied to these coils, the electron beam which passes thru the common intersection of the axis will then be deflected at right angles to the field and be swept back and forth in a straight line at a speed determined by the frequency of the sawtooth wave. If we now impose on the other set of coils a square wave, the resultant field from this wave form will deflect the beam back and forth across the straight line formed by the sawtooth wave. If the two wave forms are not synchronized, the beam will eventually pass over all points of a rectangle bounded by the length of the deflection given by the sawtooth voltage and the width of the deflection given by the square wave voltage. If an automatic relay system is now connected in such a manner that the wave forms are interchanged, between the sets of coils (say at 1-second intervals), the rectangle will be turned 90 degrees each time and a simple cross will be generated.

All the figures automatically programmed by the equipment are made in a similar fashion using sawtooth, square wave, and sign wave forms and utilizing a 4-pole and 6-pole deflector system. With this system a number of figures can be cut including "Y's", 6-leg stars, triangles, squares, plain crosses, maltese crosses and plain crosses with superimposed bars at the ends. Many patterns of dots, such as 6 dots in a circle, 4 dots at the corner of a square, etc., can also be made. The next panel is the electron lens control and the two top panels are the pulsor control. The pulsor control pulses the beam OFF and ON with a controllable rate of from 50 cycles to 5,000 cycles and with a pulse duration of from 100 microseconds to 5 microseconds. Due to the characteristics of the pulse transformer it is not possible to cover all the extremes of the frequency and pulse width combinations. This pulsing of the beam is one of the most important characteristics of the equipment since this enables a very high intensity beam of short time duration to be used for cutting. This fact allows the cutting of material without heat seriously effecting the zones immediately adjacent to the cut.

Returning to Figure 1, observe again the work chamber and the column. From the top of the column downward the first grey section contains the pulse transformer, the second is the oil immersed connector chamber which has mounted on its lower end the electron gun. The next dark grey section is the anode chamber. The next short section is the diaphragm chamber and the last section above the work chamber contains the light and electron optics as well as the deflector mechanism. Figure 2 shows the entire cathode head raised on its elevating rails exposing the electron gun. The high voltage insulator can be seen with its lower skirt, and the control electrode can be seen below the insulator skirt. The pulse transformer can be seen mounted on top of the cathode head. The circuitry associated with the pulse transformer is located behind it. Figure 3 is a close up of the gun assembly and shows the control electrode removed and the cathode holder and cathode projecting below the insulator skirt. The cathode is the small hairpin wire projecting below the cathode holder.

Figure 4 (upper left) is looking down into the dismounted anode chamber, and the anode pin can be seen in the center pointing almost directly out of the picture. Figure 4 (upper right) shows the diaphragm holder with the diaphragm and the associated lead shielding. Figure 4 (lower left) shows the top of the viewer section displaying the arrangement of the light source and microscope eye pieces. Figure 4 (lower right) shows the bottom of the viewer chamber giving a view of the bottom of the electron lens with the deflector system mounted on it. Figure 5 is a view of the work chamber showing the arrangement of the carriage supporting the work. A number of the connecting leads and a vacuum valve and connecting leads are also visible in this photograph.

Some of the specifications of the equipment are as follows: depth of drilling, approximately 1/16" smallest diameter hole approximately .00075", tolerance in hole width and smoothness of hole wall .0002". Round holes can be drilled from approx. .00075" to .002" in diameter. It is of course possible to build equipment which would program round holes up to the region of .100".

Most of the work performed by L. R. Industries is drilling through sections under .040" in thickness. The machine is capable of welding in light gages, (say somewhere

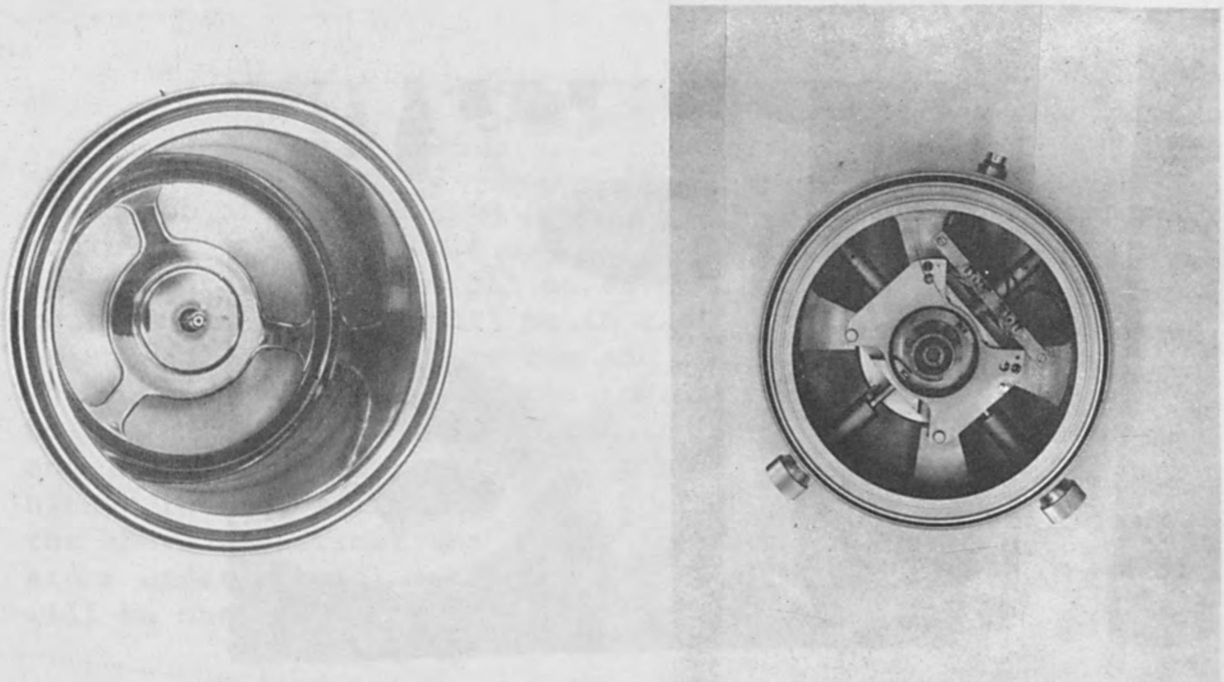
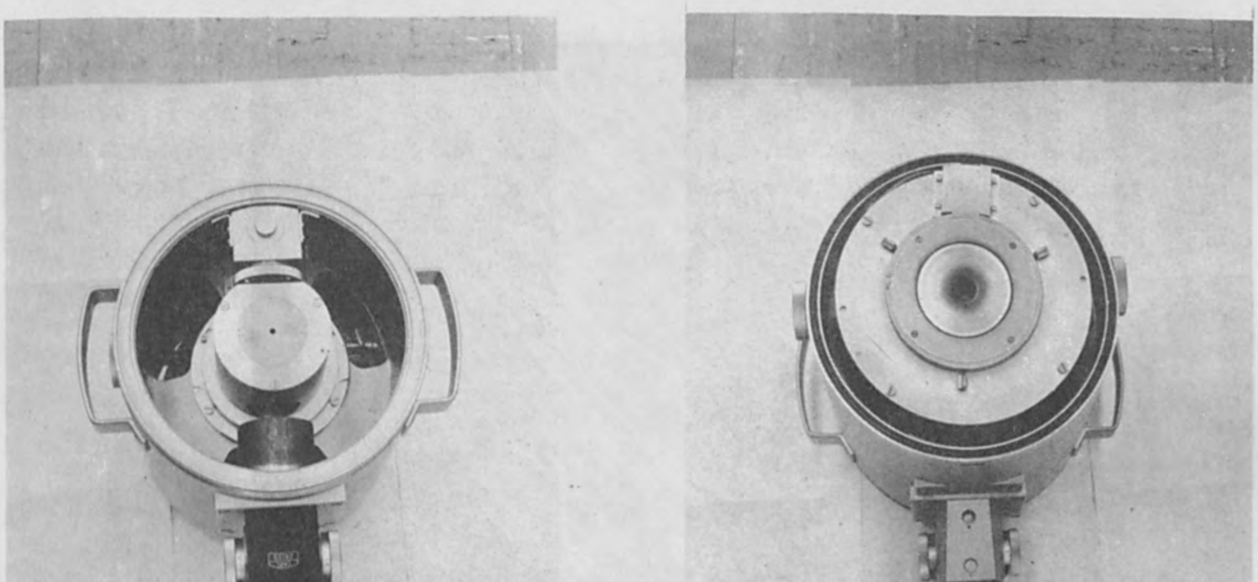


Figure 4



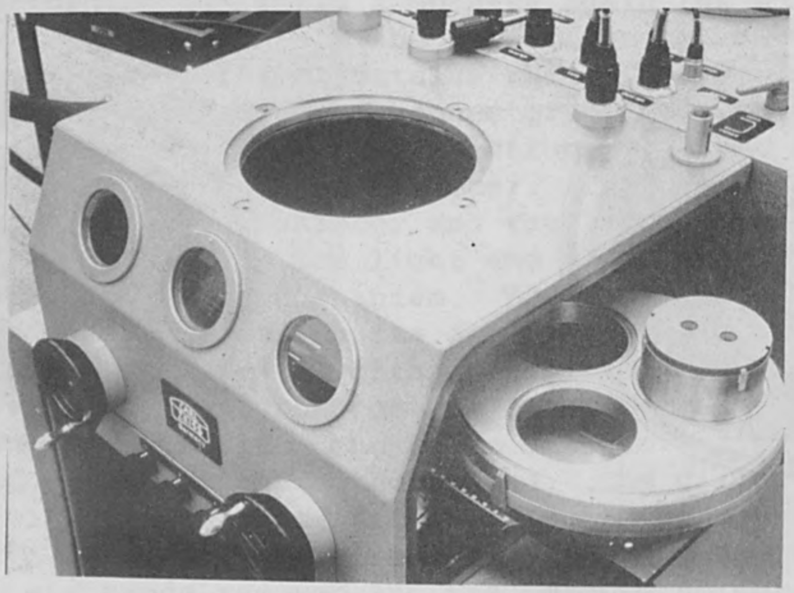


Figure 5

Figure 6

in the neighborhood of .010"), and it will do a relatively crude job of slot cutting or blind hole drilling. The present equipment is not capable of drilling blind holes with square bottoms Almost all holes drilled have a bell mouth entrance and a bell mouth exit, and a sloped side at an angle of about 1 degree and 30 minutes. In general, the machine will drill in the region of 10-to-1 depth-to-hole diameter. It is true that in very small hole diameters and in certain materials it is possible to drill much higher ratios, even as high as 20-to-1. In fact, all of the above specifications can be considered only as guides since under special conditions somewhat different results will be obtained.

Unfortunately, we do not have a large collection of samples or photographs of work, but **Figure 6** is a picture of holes in a spinnerette. The most satisfactory applications of the machine to date have been in the field of microminimization of electronic components. Most of this work is confidential and cannot be discussed here. One of the more interesting applications is the use of the equipment to apply intense local heat to very small areas of semiconductor devices.

I would like to now show you a moving picture of a hole actually being drilled by the machine. This picture was taken through the microscope viewer of the equipment and is the drilling of a spinnerette hole. The material being drilled is No. 300 series stainless, about .025" thick; the voltage is 100 kilovolts; the current is 160 micro amperes; pulse frequency is 1000 cycles and the pulse duration, 20 microseconds.

The moving picture clearly illustrated the pulsating technique used. (Editor)

Electron Beam Machining Laboratory Developments

By
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Carl Zeiss
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This paper gives a more detailed description of the electron beam machining process, of recently developed applications, and of the electron beam machining equipment designed in the laboratories of the Carl Zeiss Company in Western Germany.

Description of the Machining Process

The effects produced by an electron beam of the usual energy level are generally of a purely thermal nature. Only in a few cases radiation damage effects are also important (irradiation of plastic material, processing of semiconductor parts). The thermal energy delivered to the work piece by the electron beam produces structural and chemical changes (e.g. surface hardening, electron beam writing), melting effects (melting, zone refining, welding, soldering, alloying), evaporation effects (cutting, depositing). The properties of a well concentrated electron beam as a versatile tool have been studied systematically during the last 10 years. It was found that by adequate controls of beam generation, shaping and guidance the beam can be adapted to a wide variety of different operations. A result of this comprehensive study was for example the discovery of electron beam deep welds. The surprisingly deep penetration of the beam results from a combination of electron beam drilling and welding features. For electron beam machining it is required to heat the material to be removed to a high temperature above the melting point in order to achieve rapid evaporation. In spite of this there should be only little thermal effects on the adjacent area in order to avoid melting, structural changes or other undesired effects. In most cases these requirements can not well be met by the steady action of a continuous beam. Much better results are obtained with a pulsed beam using short powerful pulses and relatively long pulse intervals. A similar effect is obtained by sweeping a continuous beam rapidly across a wide enough area on the work piece. In the case of a pulsed beam the high working temperature is only reached during a part of the pulse time. For most of the rest of the cycle the temperature is much lower. If the whole cycle time is short the heat conduction in a short distance from the working area is determined essentially by the average temperature of this area which can be kept well below the melting point by using a low duty ratio of the pulsed beam.

In addition small droplets of material are often ejected. In typical operation the relatively low average power of no more than 100 watts of an electron beam accelerated by a voltage of 100 - 150 kv is concentrated into short powerful pulses of only a few microseconds duration. Since the effective diameter of the impinging beam pulses is smaller than 0.001 inch a power density of more than 1 million kilowatts per square inch is obtained.

The Carl Zeiss Electron Beam Milling Machine

The name milling machine was chosen to indicate the application of cutting profile shaped holes or surface contours. The machine shown in fig. 1 consists of 1. the milling unit with the electron beam column, the vacuum chamber, the vacuum system and most of the controls in the lateral parts of the desk, 2. the high voltage supply (a closed loop feedback stabilized RF cascade generator), 3. the deflector control (which controls the shape cut by the deflected electron beam into a fixed work piece). The high voltage parts of the machine are completely shielded, accidental touching of disassembled parts is prevented by safety interlocks. The electron beam column and the vacuum chamber are completely lead lined on the inside for X-ray protection; all windows are made of lead glass. A detailed schematic of the electron beam column together with the supplies is shown in fig. 2. The electron gun is located in the top section

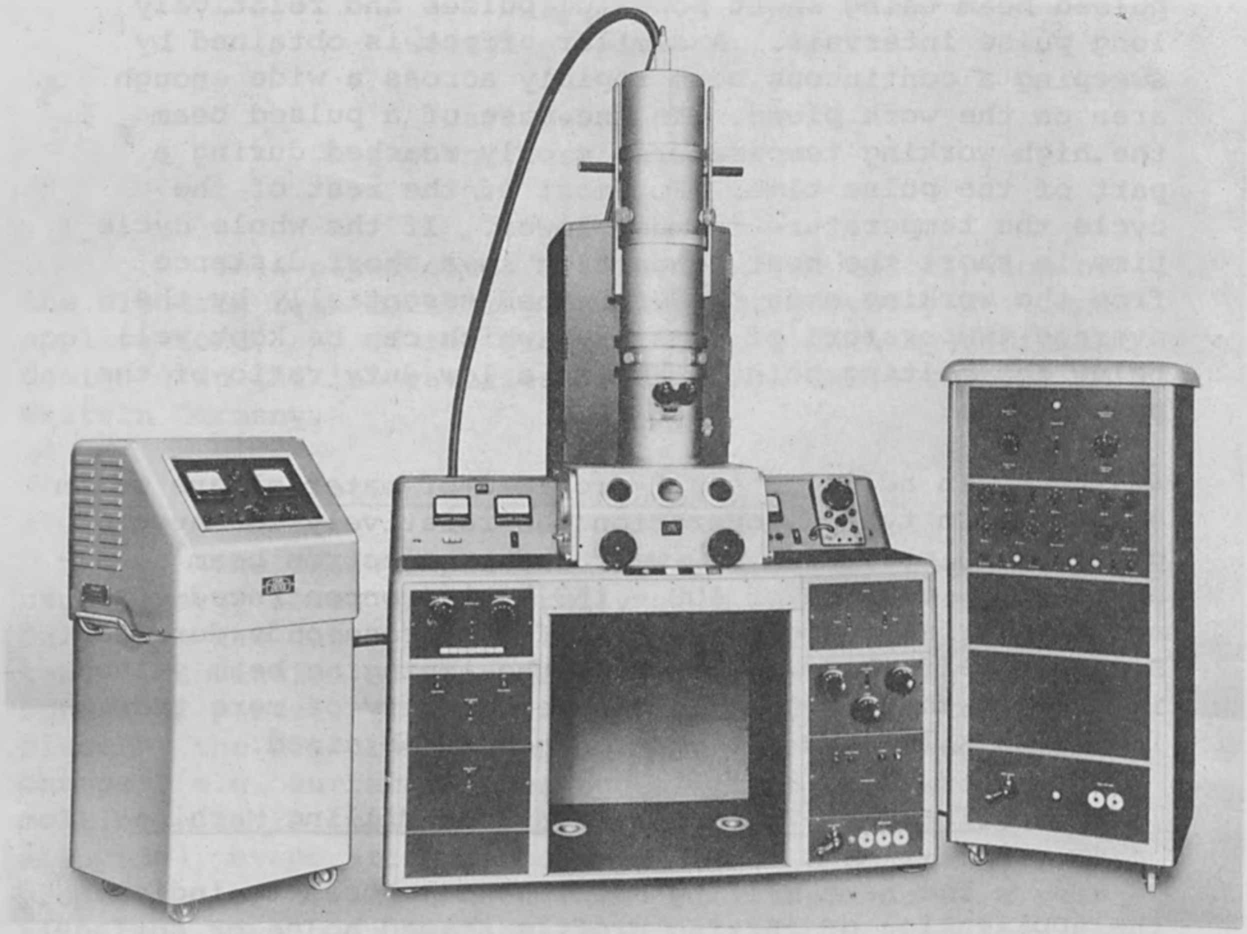

Fig. 1 Electron Beam Milling Machine

Left to right: High voltage supply unit, milling unit, deflector control unit.

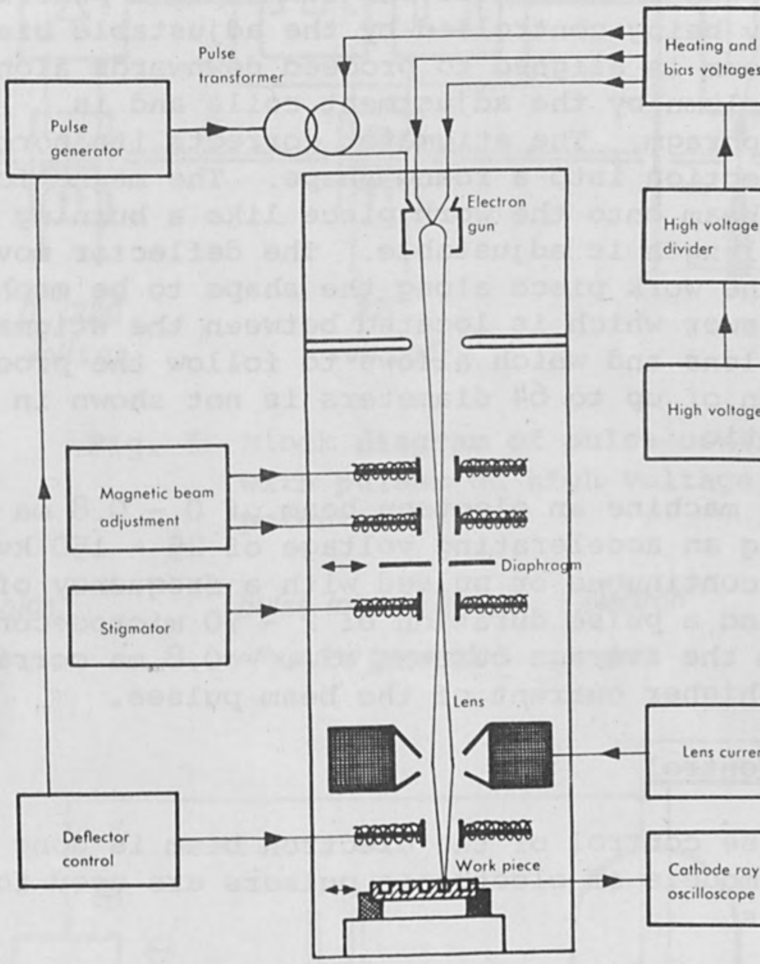

Fig. 2 Block diagram of electron beam generating column and electrical supplies.

of the column. It consists of a hairpin filament,a control electrode of a special shape and a grounded anode. Underneath the gun are two pairs of coils for electromagnetic beam adjustment, a mechanical diaphragm, and a stigmator, and further down the magnetic lens, the deflector, and the work piece mounted on a movable stage. The specially designed electron gun concentrates the beam into a pencil, the beam intensity being controlled by the adjustable bias potential. The beam is aligned to proceed downwards along the axis of the column by the adjustment coils and is shaped by the diaphragm. The stigmator corrects its normally oval cross section into a round shape. The magnetic lens focuses the beam onto the work piece like a burning glass; its focal length is adjustable. The deflector moves the beam across the work piece along the shape to be machined. The microscope viewer which is located between the stigmator and the magnetic lens and which allows to follow the process at a magnification of up to 64 diameters is not shown in this electrical schematic.

In this machine an electron beam of 0 - 0.8 ma can be generated using an accelerating voltage of 25 - 150 kv. This beam can be continuous or pulsed with a frequency of 50 - 10,000 cps and a pulse duration of 2 - 70 microseconds. For a pulsed beam the average current of 0 - 0.8 ma corresponds to a much higher current of the beam pulses.

Pulse Control

The pulse control of the electron beam is done electronically. Two models of electronic pulsers are used for different purposes.

1. Pulser on High Voltage Potential

This method of pulse control is shown schematically in fig. 3; The electron gun in the upper part of the electron beam column is shown at the right together with the high voltage and heater current input leads. Between the heater and the control electrode the d.c. bias and the pulser are connected in such a way that the positive pulses partly counteract the high negative bias potential thus raising the potential of the control electrode from cut-off to the level

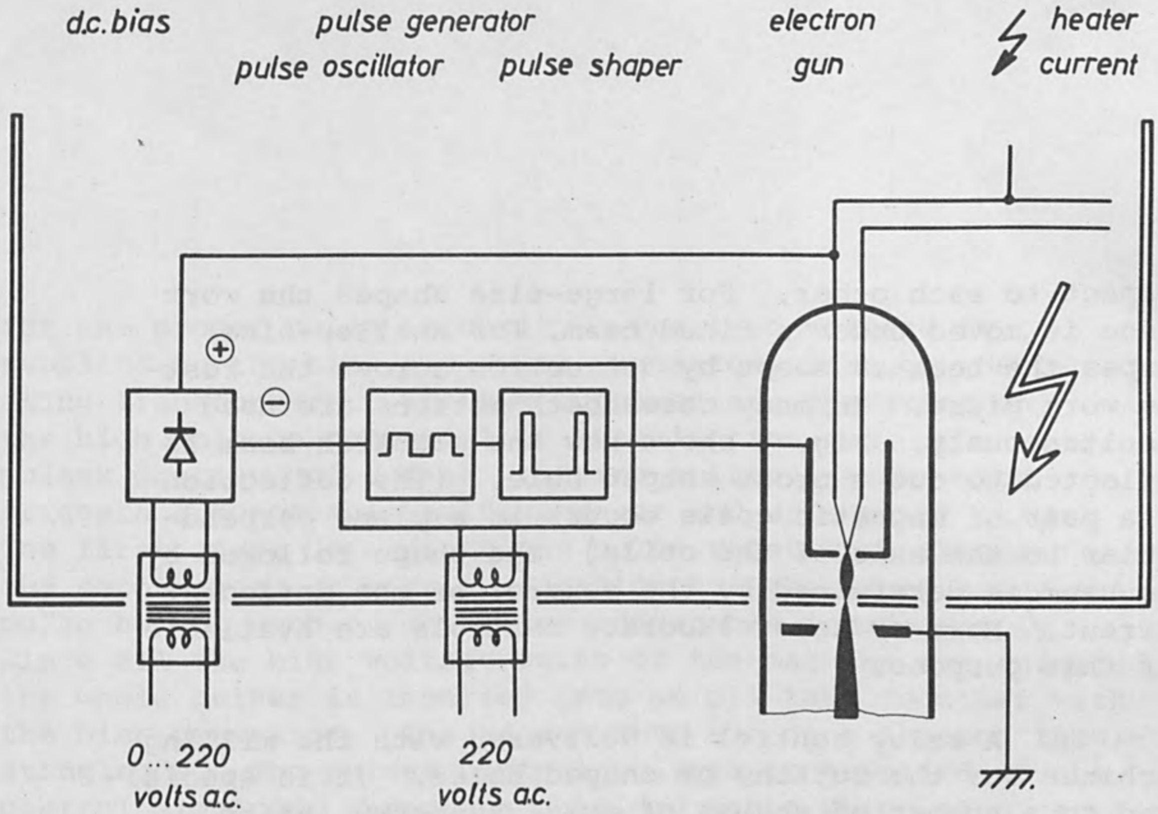

Fig. 3 Block diagram of pulse control with pulser on high voltage potential.

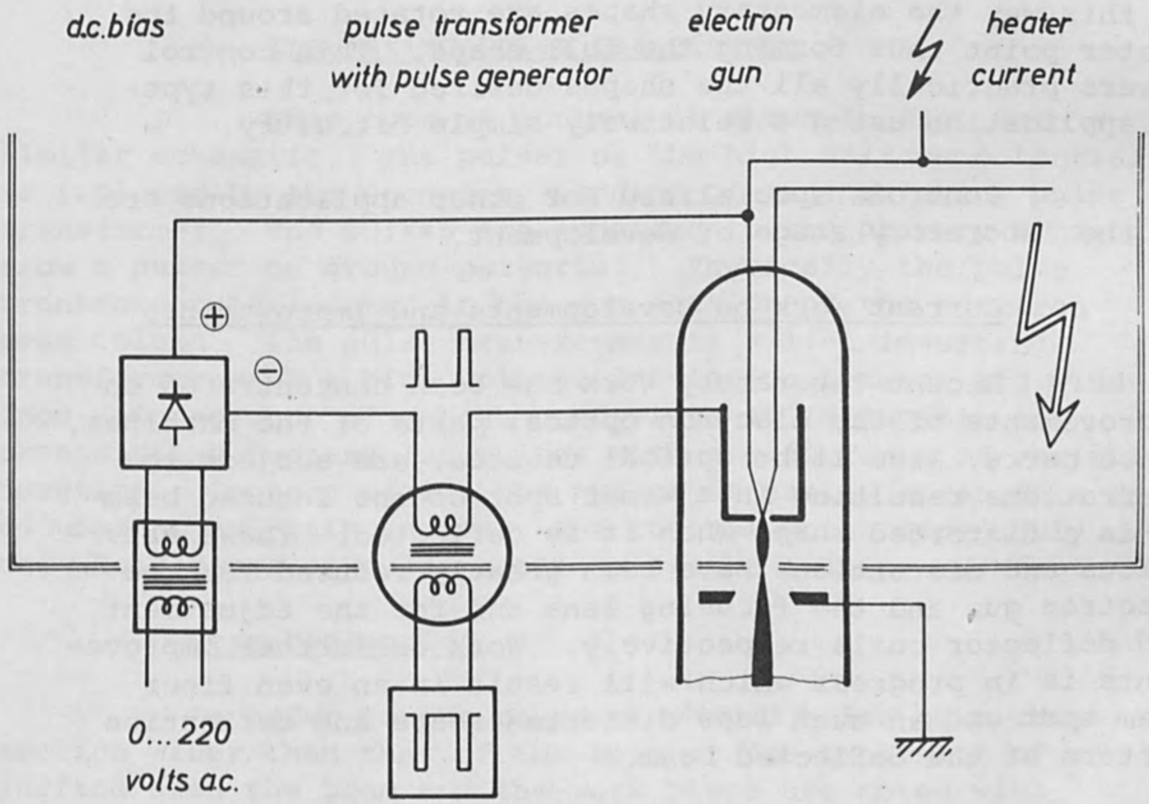

Fig. 4 Block diagram of pulse control through insulating pulse transformer.

respect to each other. For large-size shapes the work piece is moved under a fixed beam, for smaller-size shapes the beam is swept by deflection across the resting work piece. In many cases both motions are used simultaneously. Fig. 5 shows how the electron beam is deflected to cut a cross shaped hole. (The deflection by a pair of magnetic coils occurs in a plane perpendicular to the axis of the coils) The shape followed by the beam is determined by the control of the deflector current. More or less elaborate controls are available for this purpose.

A relay control is delivered with the milling machines for the cutting of shaped holes. It is specialized to a number of shapes of axial symmetry (stars, crosses or multiangular shapes). The shapes are composed of their elementary parts such as rectangular slots or hour glass shapes. These basic shapes are generated by electronic circuits which are connected to the deflector coils by a number of relays operated in succession by a master relay. In this way the elementary shapes are rotated around the center point thus forming the full shape. This control covers practically all the shapes desired for this type of application using a relatively simple circuitry.

Controls specialized for other applications are in the laboratory stage of development.

<u>Current Work on Developments and Improvements</u>

Recent laboratory work has been concentrated on improvements of the electron optical parts of the machines. These parts, like light optical devices, are subject to aberrations resulting in a wider spot of the focused beam or in a distorted shape when it is deflected. These aberrations and distortions have been greatly reduced for the electron gun and the focusing lens and for the adjustment and deflector coils respectively. Work on further improvements is in progress which will result in an even finer beam spot and an even less distorted shape and deflection pattern of the deflected beam.

for the proper pulse intensity. The line voltage is supplied to the bias and pulse generators through insulating transformers. The two supplies are operating on the high voltage potential of the electron gun. The pulser consists of a free running multivibrator which triggers a monostable multivibrator and of a power stage. The first stage determines the pulse repetition frequency, the second stage the pulse duration and the power stage the pulse height, each of which are adjustable independently. Since all the high voltage parts of the machine are shielded, the whole pulser is immersed into an oil tank together with the bias generator. The adjustments are done through insulating rods. The pulsed control voltage is supplied to the control electrode through a shielded cable which also carries the heater current (and the high voltage). This arrangement is used in electron beam welders. However, for the short pulses of the milling machine, the capacitive load of the cable is too high. Therefore another way of pulse control was chosen.

2. Insulating Pulse Transformer

This type of control is shown in fig. 4 in a similar schematic. The pulser on the high voltage potential is replaced by the secondary winding of an insulating pulse transformer. The pulses are supplied to the primary winding from a pulser on ground potential. Physically the pulse transformer is located in the top section of the electron beam column. The pulse transformer is a 1:-1 inverting transformer with a high voltage insulation between its windings. On account of a high band width it is capable of transmitting rectangular pulses with a wide range of variable duration. In this design the pulser is easily accessible for adjustment and maintenance. The control works dependably over the whole range of pulse settings of the milling machine.

Beam Deflection

In order to cut round or shaped holes of a cross section wider than that of the beam or for treatment of a surface area the beam and the work piece are moved with respect to each other. For large-size shapes the work piece is moved under a fixed beam, for smaller-size shapes the beam is swept by deflection across the resting work piece. In many cases both motions are used simultaneously. Fig. 5 shows how the electron beam is deflected to cut a cross shaped hole. (The deflection by a pair of magnetic coils occurs in a plane perpendicular to the axis of the coils.) The shape followed by the beam is determined by the control of the deflector current. More or less elaborate controls are available for this purpose.

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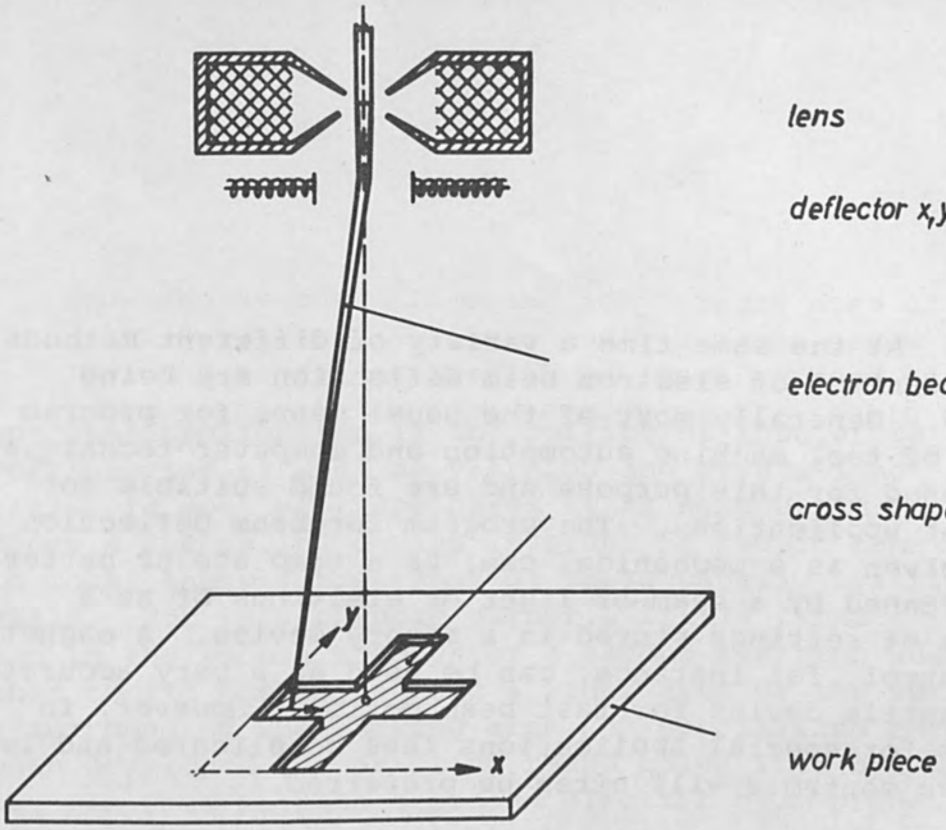

Fig. 5 Cutting of a shape with a deflected electron beam.

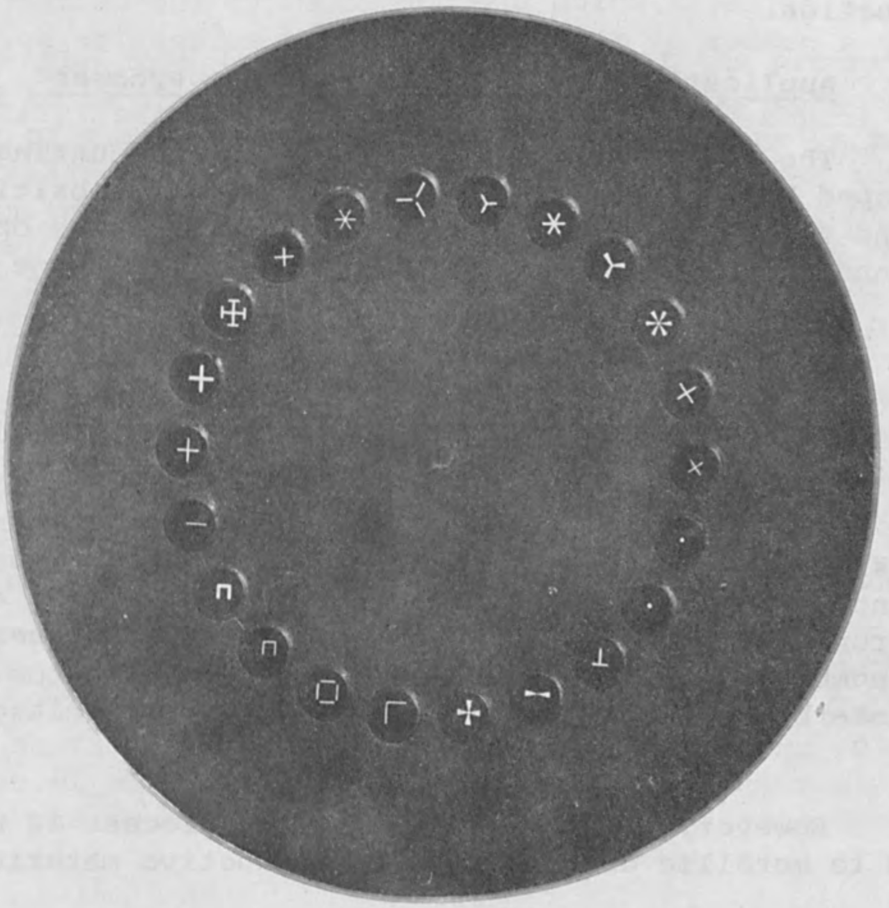

Fig. 6 Model spinneret with a number of holes of different shapes.

At the same time a variety of different methods for the control of electron beam deflection are being reviewed. Generally most of the usual means for program control of tool machine automation and computer technique can be used for this purpose and are found suitable for different applications. The program for beam deflection can be given as a mechanical cam, as a template or pattern to be scanned by a beam of light or electrons or as a sequence of settings stored in a memory device. A magnetic tape control, for instance, can be used as a very accurate and versatile device for fast beam motion. However, in machines for special applications less complicated and less expensive controls will often be preferred.

In addition, general work is being done on further improvements of accuracy, reproducibility of operation and operational comfort as well as automation for efficient use in production.

Applications of the Electron Beam Process

The most advanced application is the cutting of fine shaped holes in metal for nozzles, dies, deposition masks and for spinnerets for synthetic fibres. The optimum performance of the standard equipment is in the range of:

round holes	0.002 - 0.008" diameter
slots	0.002 - 0.004" by 0.040 - 0.080"
depth of the cut	0.020 - 0.040"
accuracy of shape up to ± 0.0002"	

The operating range of the equipment extends to either side of this optimum range with a slightly lower efficiency. The smallest holes which can be drilled are a few microns in diameter. Fig. 6 shows a model spinneret with a number of different shapes cut into the bottom of its counterbores. One of these shapes is shown enlarged in Fig. 7.

However, the application of the process is not limited to metallic or electrically conductive material.

An important application is the cutting of insulators and refractories as well as vitreous and crystalline material. In most of these cases it is helpful to introduce a preheating device in order to reduce tensions due to local thermal treatment of these usually brittle materials. For this purpose either a little furnace can be used in the vacuum chamber or a second electron gun is attached to its bottom, heating a wider area of the work-piece surrounding the working area. A specialized machine has been developed for drilling round holes into bearing jewels. In this machine a second electron beam preheats and anneals the entire jewel blank, usually of synthetic sapphire. A watch stone drilled in this way is shown in fig. 8. Fig. 9 shows a number of trupet shaped holes drilled into a disc of Corning vycor glass.

The most important application of the process is expected to be in the field of small electronic components. A number of successful experiments have been done on machining and processing semiconductor material. Among these applications were the dicing of wafers, the cutting of contours or fine lines into the surface, the alloying by melting metal into the surface from a foil or a deposit, the introduction of structural changes (dislocations) and the welding of small containers with low heating of the encased semiconductor element. Other experiments have been done on machining (shaping as well as cutting of holes) of ferrite material especially for memory units. In the production of micro-miniature components the process can be used for shaping deposited films on a substrate, for shaped depositing by disintegration from a gaseous compound or for the production, machining or porcessing of evaporated semiconductor elements. Fig. 10 shows a micromodule resistor produced by cutting a meander pattern into a deposited film on a ceramic substrate.

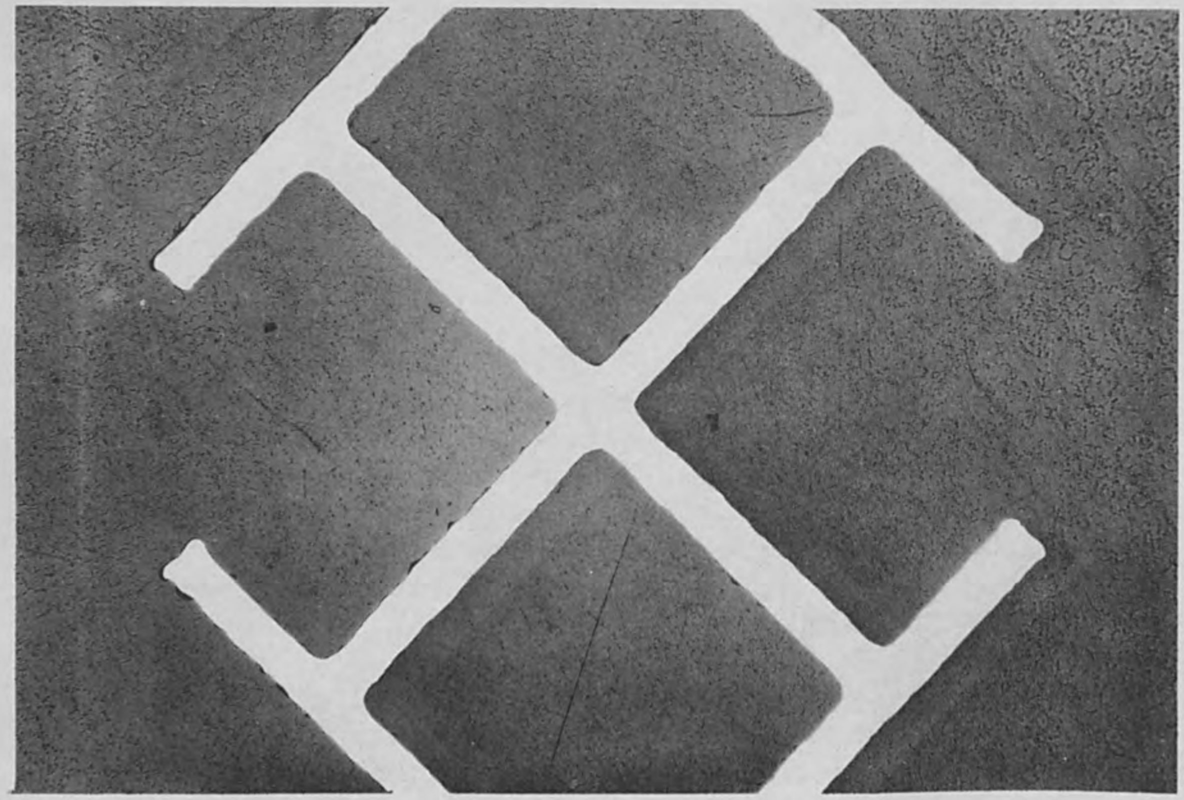

Fig. 7 Enlarged view of a single shaped hole of a spinneret
Main slots: 0.0028 by 0.040"

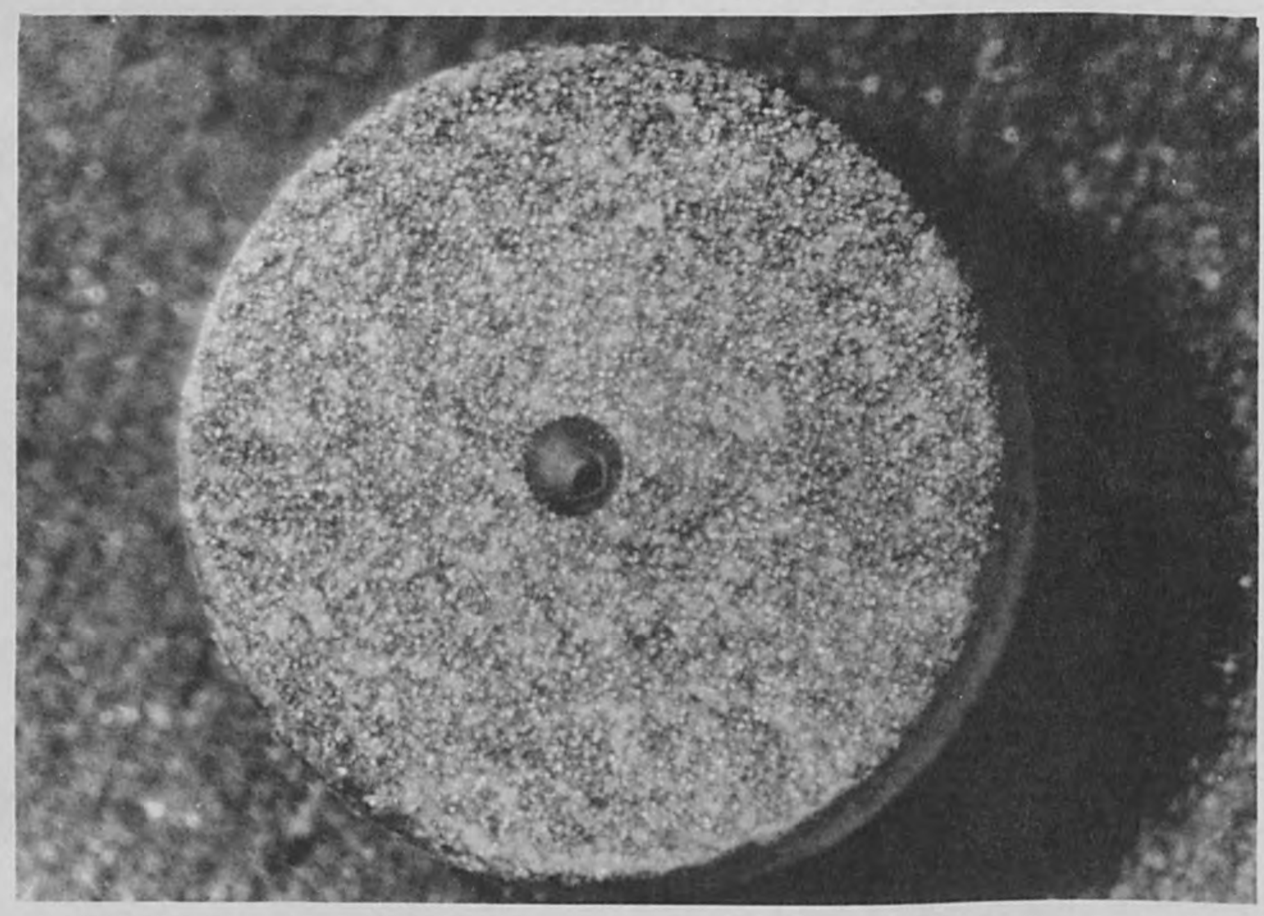

Fig. 8 Watch stone with electron beam drilled hole of 0.002" diameter.

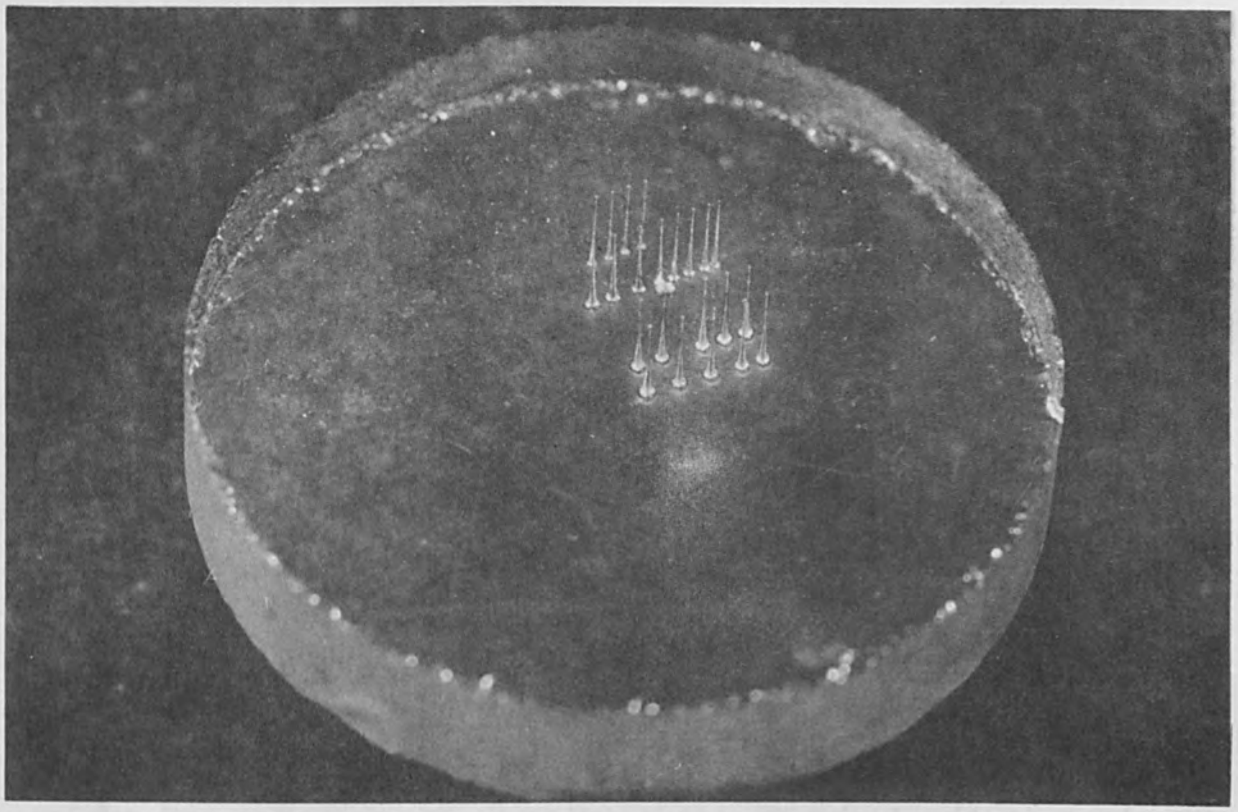

Fig. 9 Trumpet shaped holes in a 0.4" thick disc of Corning vycor glass.

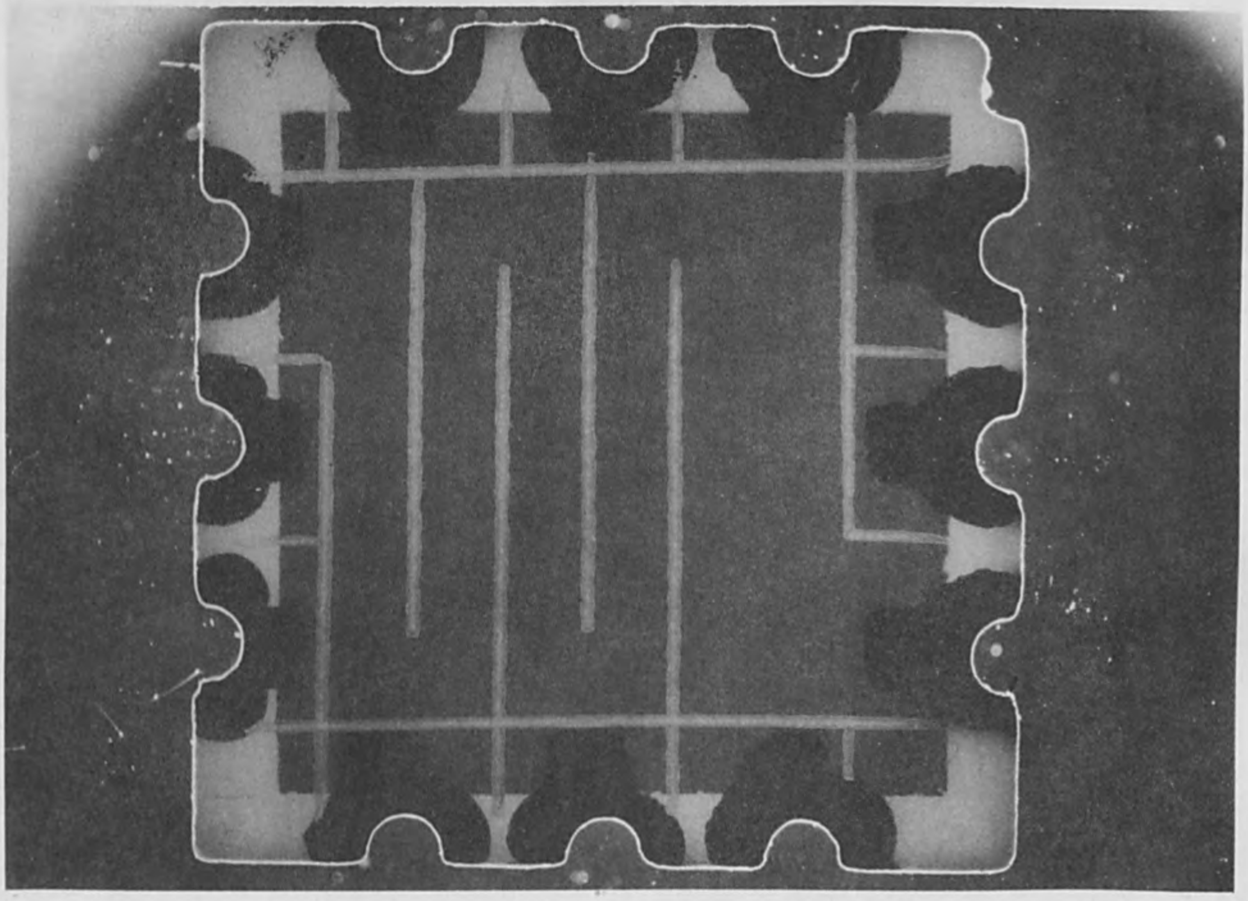

Fig. 10 Micromodule resistor element with a meander shaped pattern cut into a deposited metal film.

A VERSATILE ELECTRON BEAM LABORATORY FACILITY

By;
R. Bakish

THE ALLOYD CORPORATION
Cambridge 42, Massachusetts

I. INTRODUCTION

As result of research projects at The Alloyd Corporation and research ideas of the staff, the need of a versatile laboratory facility using electron beams as heat sources was indicated. A careful study of the problems in the light of needs existing at the time and anticipated future needs resulted in the designing and building of a facility. This modular electron beam laboratory unit is the topic of this presentation.

This facility in its present scope is capable of performing a number of functions and yet has enough versatility built in it to allow future modifications as these are indicated. It is a unit, most timely today but with built-in protection from obsolescence.

Figure I shows an overall view of the system. Ease of operation, modification and service has been a guide throughout the development. The pumping system consists of a 10 inch diffusion pump backed up by a roughing pump, a holding pump and a refrigerated cold trap.

The main chamber is 24 inches in diameter and 24 inches deep, water jacketed at the front flange and on the door. It has flanged ports diametrically opposed every 90 degrees so that electron guns, actuators and windown can be attached as desired. Around the bottom, at the rear of the chamber are eight tubes capped with "O" ring seals for introducing high voltage insulators, thermocouples, vacuum gauges and other leads into the chamber.

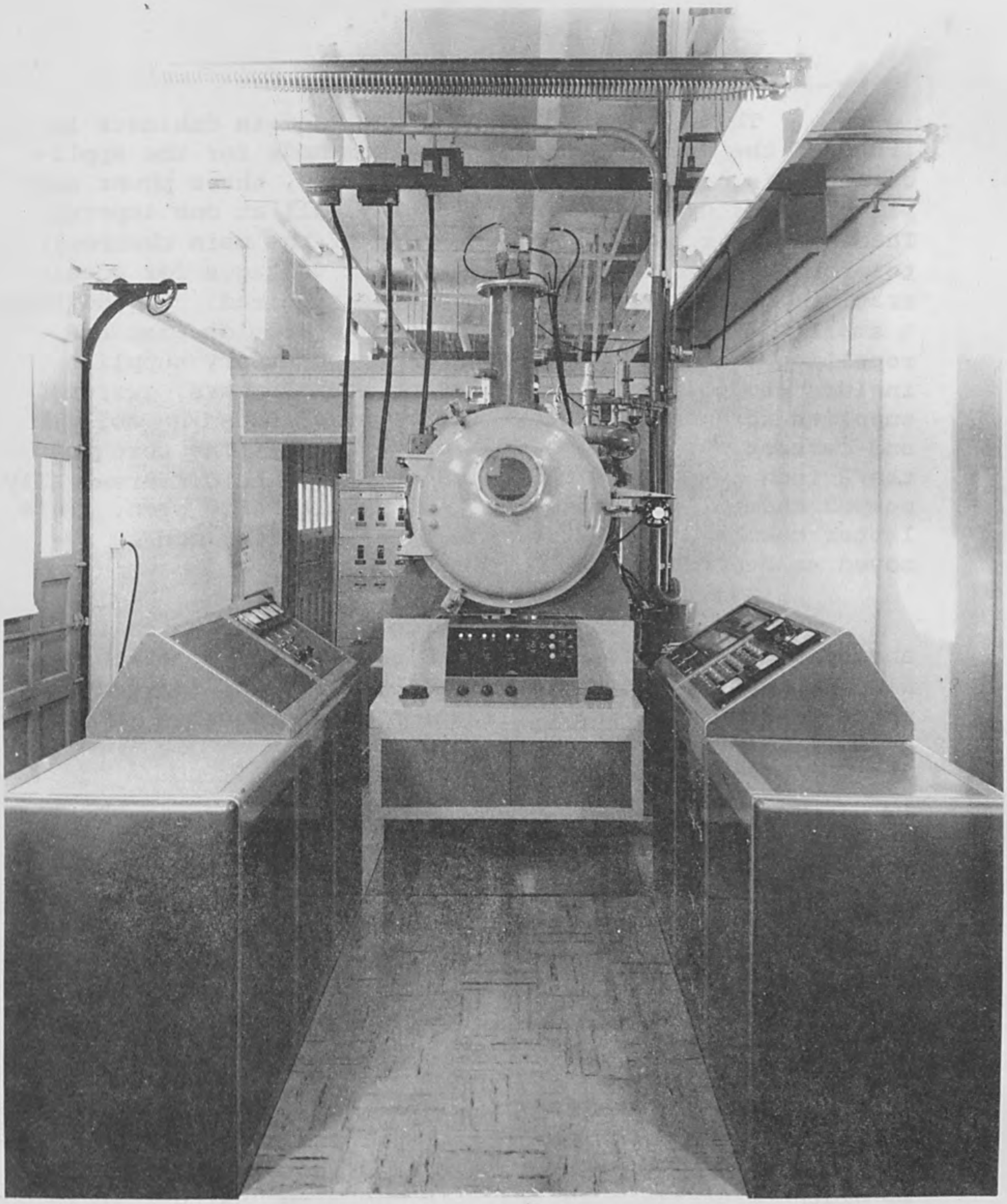

Figure 1 Alloyd's Modular Electron Beam Apparatus

The power supplies are enclosed in cabinets in front of the chamber, and were custom made for the application. In order to achieve flexibility, three power supplies are used, one 12KV and two 5 KV, all at one ampere. These can be connected (at the rear of the main chamber) to provide any desired combination of voltages for acceleration, deflection or power that is required. In addition, a small 1 KV supply is incorporated to provide bias and repelling voltages as needed. Other accessory supplies include properly isolated filament transformers, current supplies for magnetic and electrostatic focussing coils, and current supplies for deflection coils. The fore pump, the 2 inch air-cooled diffusion pump and the differentially pumped chamber for one of the guns can also be seen. This latter chamber, similar to the other modules, can be removed as a package.

Having introduced you to our AMEBA, which is an abreviation for Alloyd Modular Electron Beam Apparatus, I will proceed to discuss its applicability to different operations through the utilization of its several modules.

II. ELECTRON BEAM WELDING

The AMEBA is readily adaptable to welding studies, both of a fundamental and prototype nature. In order to develop optimum mechanical properties in butt welds, very thin, very deep welds are necessary and these must have minimum heat-affected and fusion zone widths. Such weldments have, to date, been produced only by high voltage equipment.

The exact reason for obtaining such thin beads coupled with deep penetration from high voltage equipment, rather than from the more common voltage range of 10 to 30 KV, is unknown. However, a prerequisite for high depth-to-width penetration is very fine beam focussing. It is generally thought that the problem is associated with focusing in the presence of space charge and it is easier to overcome the space charge at higher voltages and thus focus to a finer point. It would, of course, be desirable to obtain narrow beads at low voltage, thereby reducing

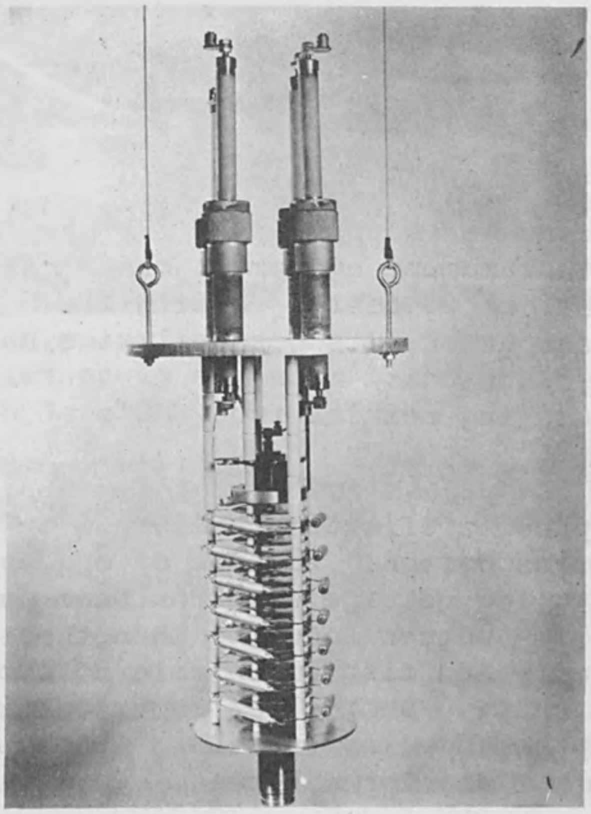

Figure 2

Gun Prototype

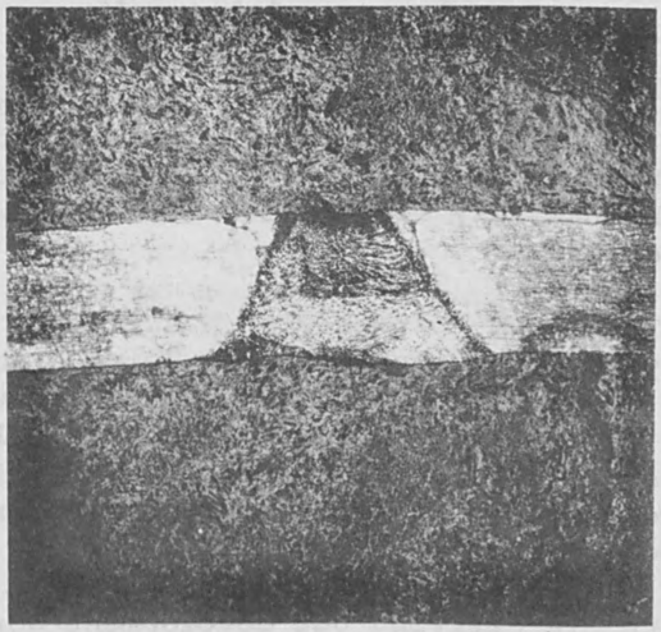

Figure 3

Weld in a 1/16" type 301 stainless by an early prototype of gun seen in Fig. 2

both the x-ray hazard and equipment cost. It is our opinion that while low voltage welding has been given a great deal of attention, its possibilities have not been fully realized. Hablanian[1] in his presentation indicates some very encouraging results from NRC's studies with low voltage guns.

Our present efforts are divided on two programs of electron optics design. The aim of one approach has been to evolve a low voltage electron beam welding gun with substantially better focusing than those available commercially today and also a gun able to produce the desired nugget shape. Because of lower costs and the shorter anticipated development times involved, the low voltage system was developed first.

We have investigated a variety of gun designs and one of the guns is shown in Figure 2, it features the linear accelerator type of beam collimation with magnetic focusing. A cross-section of a weld made in 1/16" type 301 stainless steel by an early prototype of this gun in shown in Figure 3.

It is of interest to compare this weld to earlier welds made with other equipment of comparable voltage, shown in Figure 4. A much more straight-sided weld of substantially less fusion structure was obtained in later weldments.

That high voltage also has a place in welding has already been mentioned, and the Zeiss electron beam welder has very dramatically proven the virtues of this approach. Our staff also feels that high voltage sources are a necessity for certain welding applications. As a consequence, then, this defines the second program in electron beam optics.

We are carrying out development work with higher voltage guns, using a 75 KV x-ray power supply, and utilizing the gun principle of the already mentioned lower voltage gun with needed modifications. We have completed

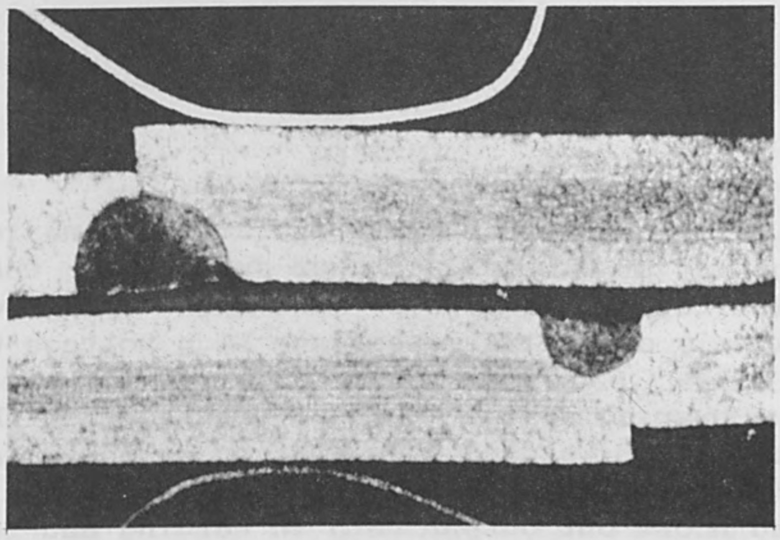

Figure 4

Early weld made on same material with other equipment of comparable voltage.

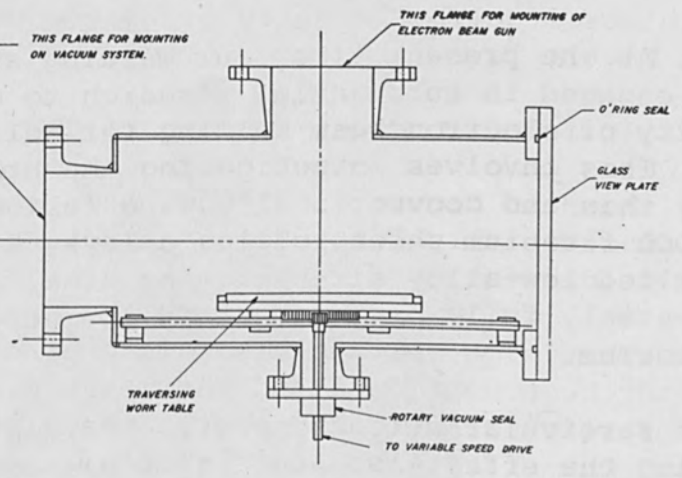

Figure 5

Electron beam welding chamber

installation of control circuits and are getting ready to install the 125 KV 0.025 m.a. power supply for, what we believe will be, the first U.S. made high voltage welding gun. Similarly an entirely separate high voltage welding chamber, Figure 5, is soon to be delivered for addition to the present pumping system. Linear actuators in this system will permit welding speeds of up to 150"/min. With completion of these modifications we shall be in a position to boost our output both in welding and in gun design since we will then be able to weld with some of our present guns while working on further gun refinements.

Thus the laboratory electron beam welding facility will shortly have a high voltage gun and an advanced low voltage gun both of which will perform butt, lap, pierced spot, plug or edge welds of desired size and shape. In addition The Alloyd Corporation has a separate electron beam facility which is used exclusively for beryllium welding. All welding will be controlled by radiograph carriage, the filler being fed automatically as desired.

At the present time, our welding staff is actively engaged in substantial research to determine the feasibility of electron beam welding for solid rocket motor casings. This involves investigating the properties of both very thin and conventionally wide fusion zones in several DOD titanium sheet rolling alloys, air-melted and vacuum-melted low-alloy air-hardening steel and H-11 hot-work die steel, fully hardened stainless steels, tungsten and molybdemum.

Particular attention will be directed toward determining the effect of joint thickness and metallurgical cleanliness on strength increases in joints which would normally be undermatching, i.e. weldments that would when welded with conventional are techniques exhibit a reduction of tensile strength in the welded area. Advantages in resistance to impact will be determined by means of specially designed crack propagation specimens. Cooling rates, heat flow characteristics, chemical changes resulting from evaporation, etc. will also be investigated as will porosity formation, hardness, and metallographic changes.

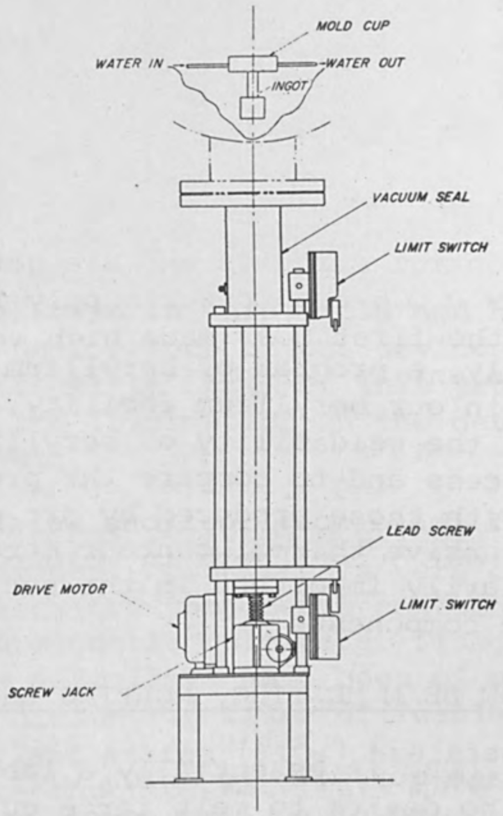

Figure 6 Ingot withdrawel mechanism

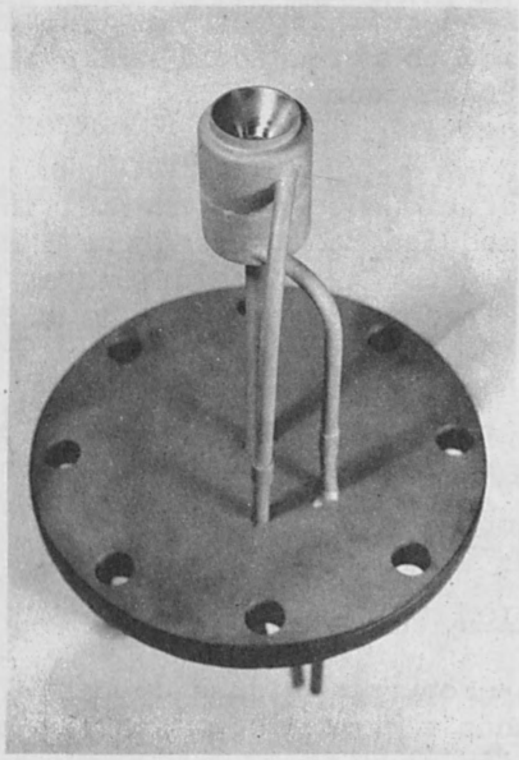

Figure 7 Water cooled button melter

Similarly, a program of beryllium welding is being undertaken in our beryllium facility. This program aims to establish the weldability of beryllium by the electron beam process and to compare the properties of these weldments with those produced by arc processes. This work involves extensive thermal contour determination which is particularily important in the sealing of epoxy potted electronic components.

III. ELECTRON BEAM HEATING, MELTING and ZONE REFINING

As the AMEBA is essentially a laboratory facility, we have had no desire to melt large quantities of material. Our melting module, the ingot withdrawal mechanism of which is shown in Figure 6, permits drip melting of ingots of up to 1 inch in diameter and up to 15 inches in length for research purposes. This module can also be utilized for zone refining applications and has been used at Alloyd for the zone refining of Tantalum and Tungsten. The reader is advised to refer to Alloyd's First Symposium Proceedings for data on zone refining utilizing the electron beam technology.

These operations concern the melting process, however, the same modules can be used for lower temperature electron beam heating for such operations as heat treating and sintering. A fine example of this is shown in the Hayashy[3]. paper.

Figure 7 shows a button melter which can quite advantageously and rapidly be used for special alloy operations. It is, as are most others of similar construction, made of copper and is water cooled.

IV. EVAPORATION

With the great new vistas opening for thin film work, we believe that electron beam sources have a great future in evaporation studies.

Our efforts in this field had been directed to a study of the performance of our devices. These were placed on the market in April of this year. Detailed specifications and information on the devices are available upon request.

Among other performace criteria for the evaluation of our devices, measurements were conducted on printed microcircuitry components containing resistive, capacitive, and magnetic elements. Tungsten, tantalum and some of the permalloys have been of particular interest. Preparation of dielectric films of insulators such as alumina (Al_2O_3) and silica (SiO_2) has also been made possible. Simi-conductor materials have not been overlooked in our studies and silcion films have been produced, although as yet no property measurements have been made. In general it can be stated that electron beam evaporation permits substantially higher rates of deposition than do more conventional techniques and also makes possible the evaporation of substances impossible to evaporate by other means.

Acknowledgements:

The Ameba is truly a team undertaking and, indirectly, all of Alloyd's staff members have in some way contributed to it. The author himself joined this team at a late date and his contributions are most likely lesser than other members of the team.

References:

1. Hablanian, M., this symposium
2. Smith, H., this symposium
3. Hayashy, C., et al, this symposium

PROPERTIES OF ELECTRON BEAMS AT HIGH ENERGY AND POWER

by

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As the energy of an electron beam is increased, the most obvious effect is the increased range of the electrons in air and materials. For electrons of 1-Mev energy the range in air is approximately 13 feet, and this allows the irradiation of a great variety of materials divorced from a vacuum environment.

Electrons at high energies are of great interest in many fields. In general the energy of the beam may be imparted to the bombarded substance by three methods of general interest: - inelastic collisions with valence electrons, by atomic collisions causing displacements of the atoms in the crystal matrix, and by radiative processes; i.e., the production of Bremsstrahlung radiation.

In the first of these processes the average energy loss is 30 to 100 ev. per ion pair. In organic materials permanent rearrangements are formed. These are of great interest to the radiation chemist studying the free-radical type of reaction; i.e., polymerization, cross-linking, and cracking. Examples of these processes are: (1) the great change in the properties of polyethylene by cross-linking under electron irradiation where its "memory", mechanical strength, and melting points are markedly increased; (2) the curing of polyesters in the absence of catalyst; and (3) the change in surface properties of polymer fibers or films by grafting with inorganic materials, and especially in crystalline structures the population of the energy levels are altered by bombardment and although this is only a transient effect it forms a useful tool for research. Metals, except at extremely low temperatures, are not significantly affected by electron bombardment. Insulators may exhibit large changes in electrical conductivity.

In the second type of interaction, atomic collisions resulting in displacement of atoms to another site in the structure, minimum beam energies of approximately 300 kev are required. With electrons, these are usually single displacements. The changes in electrical properties of semiconductors under electron bombardment is of great interest to solid state research and may be of great practical importance for the manufacture of semiconductor devices. Carrier lifetime can be reduced so that faster switching times or higher frequencies can be used.

The third interaction - the production of secondary radiation - is generally undesirable in working with high energy beams due to the massive personnel shielding required. A typical installation operating at 1.5 Mev with a beam power of 2.5 kw. for industrial processing will require concrete walls 42" thick to adequately shield operating personnel. As the energy is further increased the percentage of beam power that appears as Bremsstrahlung radiation increases, (Fig. 1). For electron beam energies greater than 2 Mev the energetic radiation produced is capable of rendering a few specific materials slightly radioactive by photonuclear reactions and by the production of isomeric states in certain elements. The activity is slight and almost completely negligible at energies to 6 Mev, but increases rapidly with energy and probably places an upper limit on useful energies at about 10-15 Mev for certain applications - for example, sterilization of foodstuffs and pharmaceuticals.

These brief remarks should indicate the potential usefulness of energetic electron beams, especially in certain rather specialized fields - chiefly in radiation chemistry, solid state device fabrication, and the cold sterilization of foodstuffs and pharmaceuticals. Present commercially available equipment has power ratings in the 1 - 10 kilowatts region and engineering extrapolation will make available equipment in the hundreds of kilowatt region as the need arises.

The electron stream is generated in a highly evacuated region and must be passed through a "window" into atmosphere in general to be useful. Electron beam welding at super voltages has been experimentally carried out in vacuo; however, this is one of the few exceptions and most processes are carried out in atmosphere. While it is possible in principle and in practice to convey the electrons from vacuo to atmosphere by traversing a differentially pumped small aperture canal,the great scattering and high pumping capacity needed makes this method of limited utility. In general thin metal foils are used as windows.

The electron beam,in passing through the window, loses a small fraction of its energy to the window. This energy loss goes through a minimum with increasing energy (Fig. 2) and is a function of the density and atomic number of the material. This energy loss, coupled with the required mechanical and thermal properties of the window, severely limit the choice of available materials. Required properties are: - low atomic weight and low density to minimize the energy loss; high heat conductivity, and high melting point to dissipate the absorbed energy; and an easily fabricated material available in thin uniform foils that are vacuum tight; i.e., high mechanical strength. Additionally the material should be corrosion resistant to the complex and highly active compounds and ions formed in the atmosphere by the ionizing radiation. Table I lists the properties of two materials that are eminently suitable for use as window materials. These two materials are almost the only materials available for this use.

In application of electron beams the relative ionization in depth is not uniform but has a maximum at approximately one-third of the range of the particle, (Fig. 3). The optimum energy required is usually that

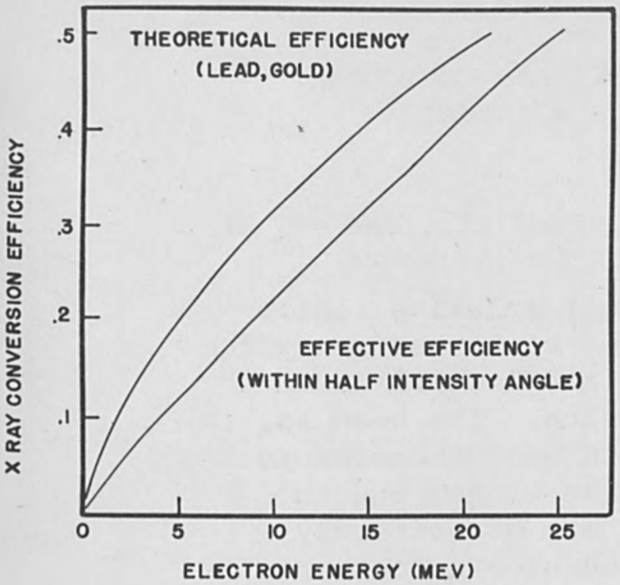


FIGURE 1

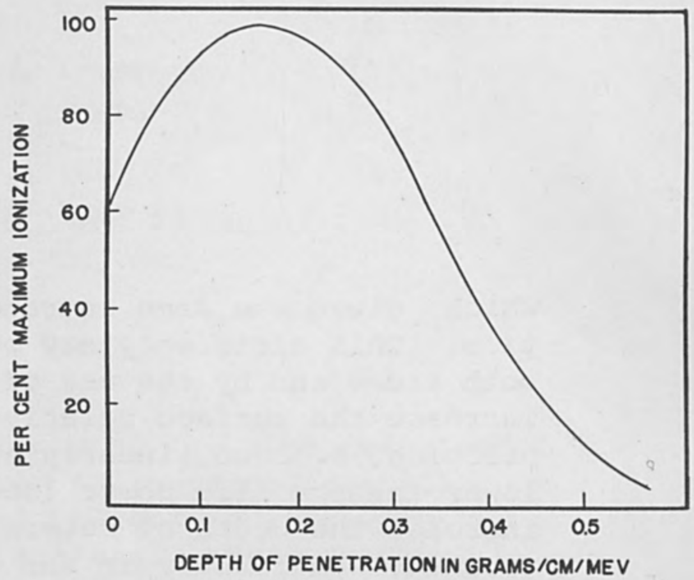
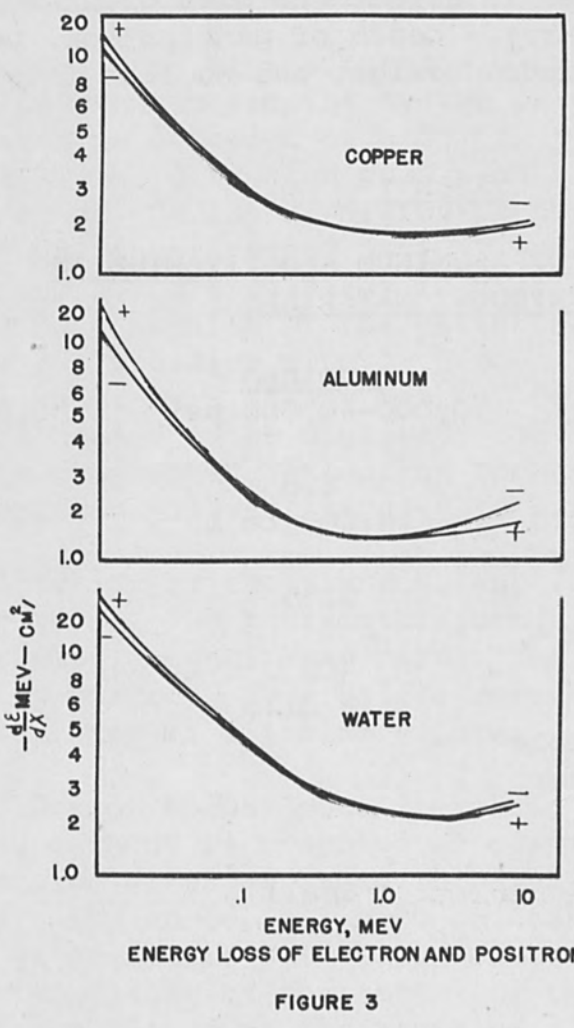


FIGURE 2



ENERGY LOSS OF ELECTRON AND POSITRONS

FIGURE 3

which gives the same entrance and exit relative ionization. This efficiency may be improved by bombardment from both sides and by the use of appropriate filters that increase the surface relative ionization. The beam is, in practice, scanned linearly at least in one dimension to lower the specific power loading of the window and to increase the width of material which may be uniformly treated. Uniformity in the other dimension is obtained by integration through movement of the material under the beam.

The factors, then, which are of importance in using electron beams in air at energies greater than a few hundred kilovolts are: - depth of penetration, beam handling, shielding, window design, and nuclear interactions in some few cases.

TABLE I

PROPERTIES OF ALUMINUM AND TITANIUM AS "WINDOW" MATERIALS

	Aluminum	Titanium
Yield Strength (room temp.)	30,000-40,000 psi	80,000-100,000 psi
Specific Gravity	2.8	4.5
Strength/Weight Ratio	14,000 to 1	20,000 to 1
Thermal Conductivity at 200°C	0.55	0.04
Operating Temperature (maximum)	400°C	600°C
Minimum available thickness for reliable vacuum tightness over an area of 2" diam.	2 mils	1 mil
Corrosion	Small	Nil

ELECTRON BEAM FURNACE FOR SINTERING TANTALUM CAPACITOR PELLETS

By
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INTRODUCTION

Electron bombardment furnaces of the type described in this paper are now in use in Japan as research or small scale production units for sintering pellets made from tantalum powder. The sintered pellets are used, after further processing, as elements of tantalum capacitors, which in turn are used as basic components of miniaturized electronic circuits.

FURNACE AND PUMPING SYSTEM

A general view of the furnace with its power supply, control panel, and vacuum pumping system is shown in Figure 1. The pumping system is composed of a 20 cfm rotary pump, a 2-in. booster pump, a 10-in. diffusion pump, and a gettering pump. The pumping speed of the 10-in. diffusion pump, measured at its inlet, is 3000 liters/second at 10^{-4} -mm. Hg. The speed of the gettering pump for active gases is over 20,000 liters/second at 10^{-6}-mm. Hg. Details of the gettering assembly are shown in Figure 2. Titanium wire, 0.5-mm. in diameter, is pulled from the spool by a driver roller, fed through a molybdenum resistance heater to be degassed, and then on to a heated post where it is evaporated. Electron bombardment (1000 V, 0.4 amp.) from a tungsten filament is used to heat the post.

The interior of the furnace tank is illustrated schematically in Figure 3. The horizontal furnace tank is divided into two approximately equal size parts, the gettering chamber and the sintering chamber, by a baffle assembly which keeps the sintering chamber free of titanium vapor.

The electron bombardment sintering assembly is a simple diode type. The cathode is composed of eleven 1-mm. diameter tungsten or tantalum wires arranged in parallel to cover the anode uniformly. The anode, a 5 x 10 cm. tantalum plate, is supported on a water-cooled post which comes through an electrically insulated flange at the bottom of the furnace. The pressed pellets are placed on the tantalum anode plate in a single layer; four-hundred 1.5-mm. long or two-hundred 3.5-mm. long, 1.5-mm diameter cylindrical pellets can be accommodated

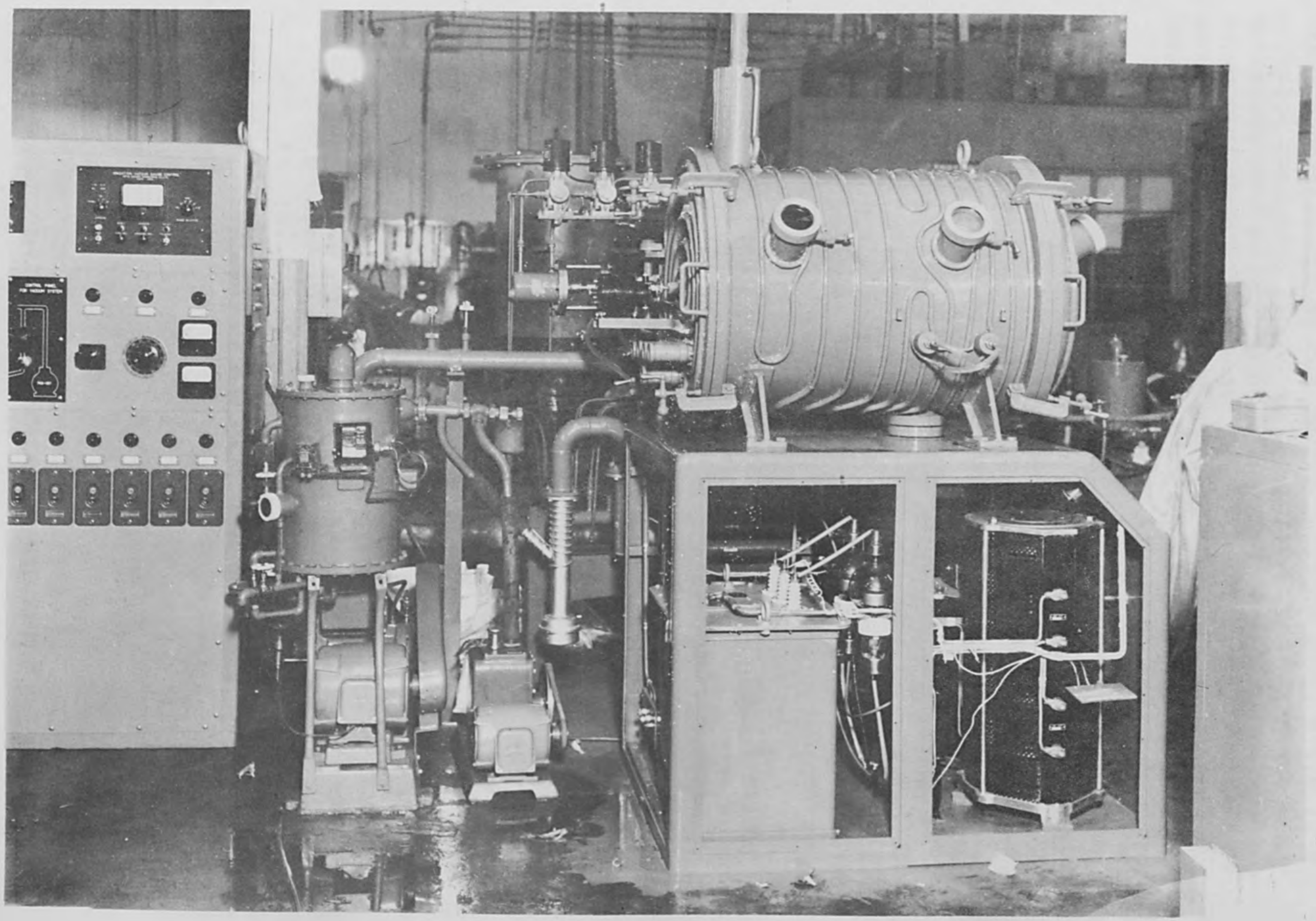

Fig. 1. General View of Electron Bombardment Sintering Furnace.

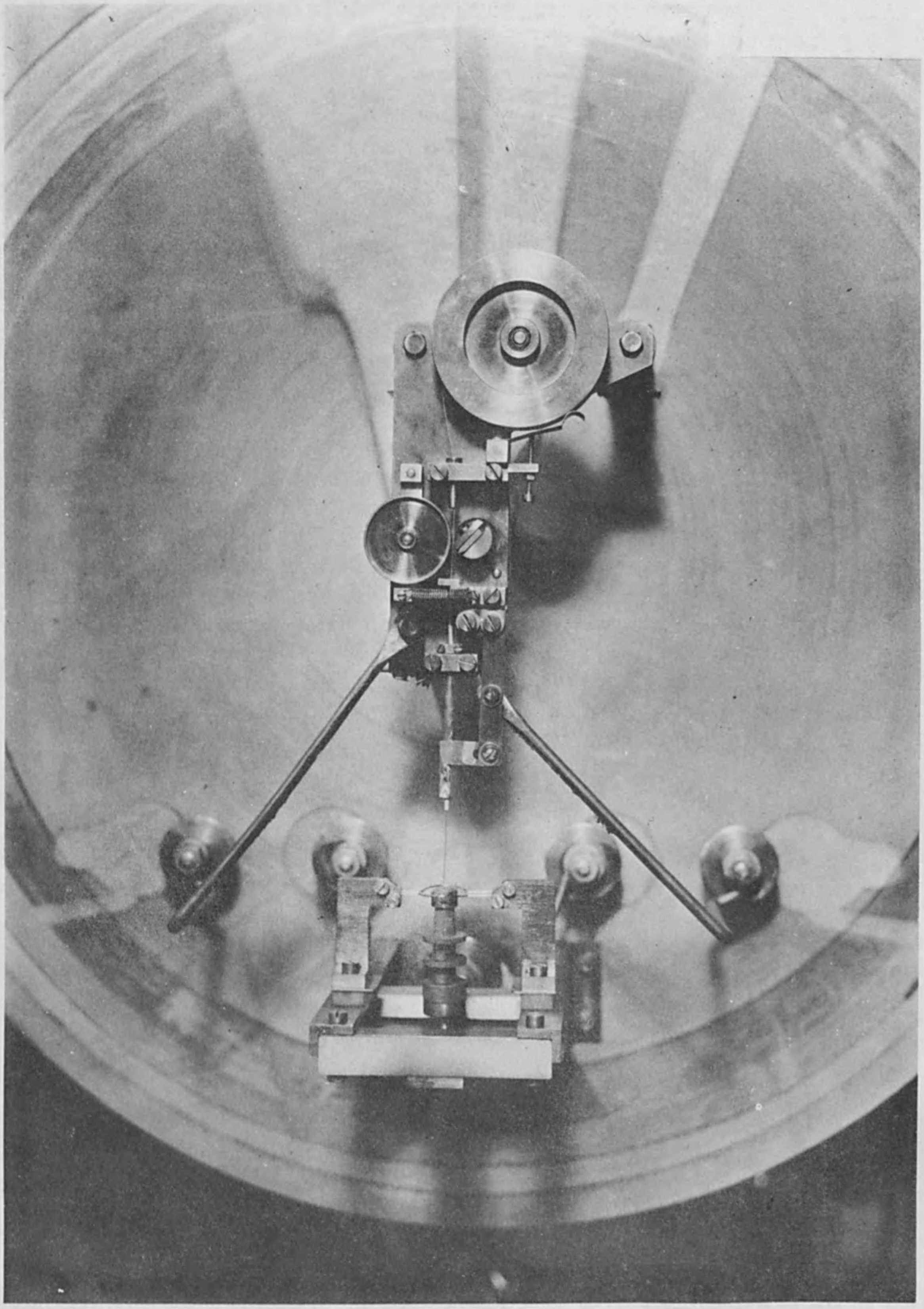

Fig. 2. Details of Gettering Pump Assembly.

on the plate. Figure 4 is a more detailed drawing of the sintering assembly. To prevent excessive heat loss, the anode and the cathode are surrounded by a set of radiation shields. Temperatures of 2000 to 2200°C, read on an optical pyrometer through the sight glass, could be obtained with a cathode emission of 3 to 5 amp. and voltage ranging from 1000 to 2000 V.

OPERATION DATA

Operational data from the users of this type of furnace are scattered, apparently depending on the starting material, size and pre-treatment of the charged pellets. Long exposure of the furnace interior to atmospheric wet air results in a long evacuation time to get the necessary high vacuum. Figure 5 shows a result of a careful test operation at the furnace manufacturer's factory, and Figure 6 shows typical operational data at a user's factory. The characteristics of the tantalum capacitors formed at the user's factory are claimed to be as shown in Table I. Stable bombardment is obtained at a pressure of 5×10^{-5} mm. Hg. or less. We have never experienced any local hot spots or bursting of the pellets during the sintering at the high vacuum. During our brief test the temperature at the centre was 50°C lower than that at the end of the anode plate when the temperature at the end was 2200°C read on a "PYRO" optical pyrometer without correction. It is believed that the users could rearrange the cathode-anode configuration in order to minimize the temperature inhomogeneity at the anode surface.

SOME CRITICISM

Limited production capacity and apparent variation of the hours required for one cycle, though the latter largely depends on the operator's skill, have been the major criticisms from the users. A solution for this would be semicontinuous operation without breaking vacuum. A merit of the electron bombardment furnace would be that each pellet receives nearly the same heat cycle.

ACKNOWLEDGEMENT

The authors are much indebted to The Alloyd Corporation for the presentation of this paper. They also wish to express thanks to Dr. Masaki and Mr. Chiba for their guidance. Thanks are also due to Mr. Kitaura with Matsushita Electric Industrial Company, Mr. Matsuo with Matsuo Electric Company, Mr. Murakoshi with Oki Electric Works Company, and to those companies, Nihon Tsushinkogyo Company, Tokyo Denki Company, and Tokyo Shibaura Electric Company for giving us necessary information.

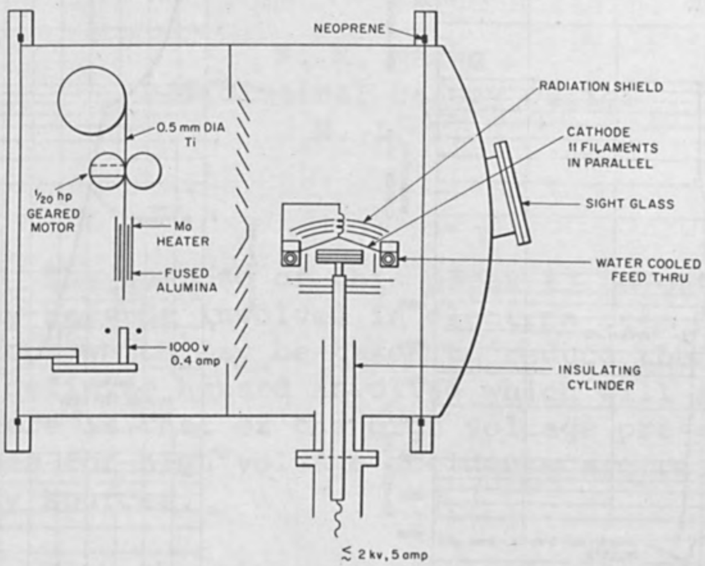

Fig. 3. Schematic Drawing of Furnace Interior.

Fig.4. Details of Sintering Assembly.

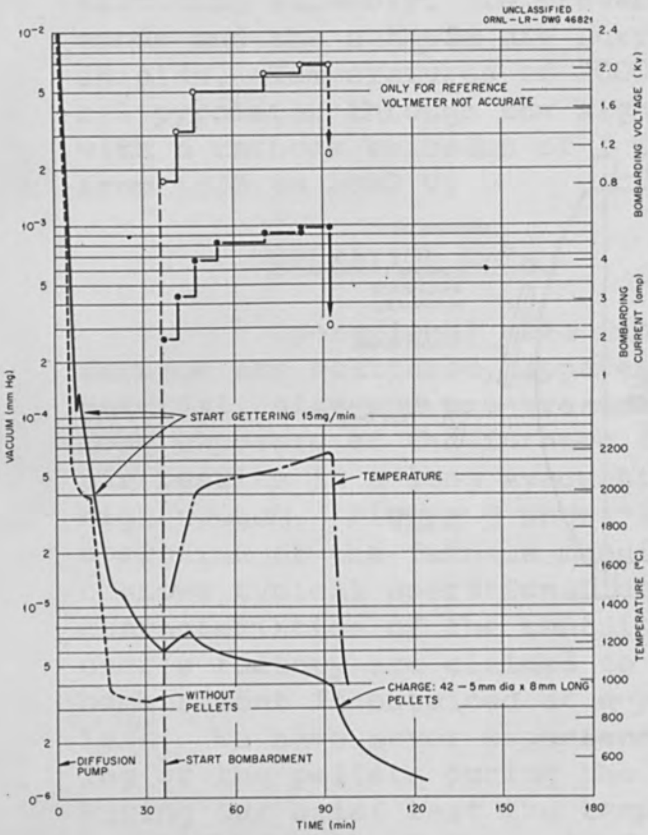

Fig. 5. Data From Test Operation at Japan Vacuum Engineering Co.

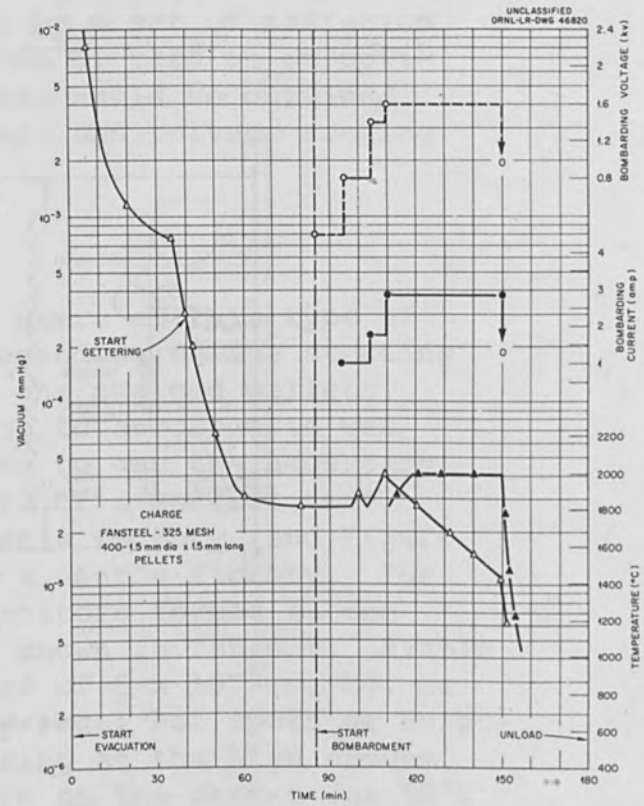

Fig. 6. Data from Operation at Furnace Users Factory.

TABLE 1. CHARACTERISTICS OF TANTALUM CAPACITORS MADE FROM ELECTRON BOMBARDMENT SINTERED PELLETS

ELECTROLYTIC CAPACITOR: 6 v, 2 μf
SINTERED PELLET: 1.5 mm dia × 1.5 mm IONS

	MEAN VALUE ($\bar{x}$)	STANDARD DEVIATION (σ)
C, CAPACITY (μf)	2.20	0.22
CR, LOSS (μf Ω)	39.0	8.6
LEAKAGE CURRENT (μa)	<0.1*	–

*USUALLY 0.005; 0.1 IS USED FOR INSPECTION.

X-RAY HAZARDS IN ELECTRON BEAM PROCESSES

by

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M. I. T.

The purpose of this paper is to outline briefly the x-ray hazards involved in electron beam processes and precautions which may be taken to reduce these hazards. Another definite hazard involved which will not be discussed here is that of the high voltage present. Treatment techniques for high voltage accidents are readily available from many sources.

With the increasing use of radiation in industry, medicine and research, advisory groups have been formed to study the effects of radiation in man and to recommend limits governing the occupational radiation exposure of workers involved in this field. These limits are set at levels agreed upon by experts as involving risks to those exposed which are considered slight when compared with normal risks of everyday life. The permissible exposure limit of concern in this type of work is that which applies to penetrating x-radiation, presently set at an average of five roentgens per year past the age of 18. It is important to remember that this figure represents a maximum permissible exposure, the generally accepted policy being to limit all exposures to a practical minimum. The present recommendation represents about 40 to 50 times the natural radiation background in the Boston area.

The main radiation hazard in this type of work is the x-rays produced with varying efficiency by the interaction of the electron beam and the target material involved with the work. The efficiency of this x-ray production varies approximately as the square of the atomic number of the target material for electrons of energies less than 1 MEV. The power supplies involved may also be a source of x-radiation.

The early research in the electron beam field was accomplished using for the most part machines with accelerating potentials of less than 20 KV in order to avoid the x-ray hazard as much as possible. At this potential, steel 1/16" or more in thickness provides adequate shielding with the only problem remaining being the glass windows of these steel machines or, more commonly, the bell-jar apparatus used in an experimental lab. At 15 KV, one-tenth inch of plate glass as shielding would allow the order of 1000 milliamp-hours per week at a distance of thirty centimeters from a copper target without exceeding one-fiftieth of the annual limit in whole body exposure. Additional distance or a lower atomic number target material would increase this figure. Increasing the potential to 20 KV under the same conditions decreases this figure to 20 milliamp-hours per week. At these potentials, less than 10% of the rays escaping penetrate beyond 4 mm in the body, most being stopped by surface layers of skin.

For machines which operate at higher voltages and/or currents and hence present a more serious hazard, the use of lead shielding may be necessary. Attenuation in lead of x-rays produced by various potentials is shown in figure 1. Intensities shown are in the 90° direction for a copper target. A level of 10^{-4}r/min or less should be achieved to operate for 20 hrs/week or more. Note for future reference that for 100 KV 3/4 mm of lead is necessary to achieve a 0.01 r level.

Figure 2 shows the effect of steel as shielding on x-rays of the same orders of magnitude under the same conditions. The shielding value of the various stainless steels is quite similar to that of steel. Note again the 100 KV line. Here 2 1/2 mm is necessary to achieve the above mentioned 0.01 r level.

At 50 or 60 KV potentials it is easily possible to provide adequate shielding in the basic steel structure, but here again the main problem is presented by the shielding of the viewing windows. As Figure 3 shows, 3 1/2 cm of glass would be necessary to obtain comparable shielding at the 100 KV level to 2 1/2 mm of steel or 3/4 mm of lead. Shielding to 10^{-4}r/min with glass would not be practical at these energies. This problem may be solved by adding an outer layer of lead glass to the ordinary glass. The shielding value of lead glass is comparable to that of steel, and this material is readily available in 1/16" sheet or may be obtained in thicker sections as necessary. A layer of plate glass is necessary as an inside wall to the vacuum chamber since the vapors released from the lead glass under vacuum would hamper the work.

Machines having potentials of 1 MEV or more have special problems of their own and should be surveyed by a specialist in the radiation protection field. Here x-ray problems become complex and at the higher energies neutron production becomes a serious problem.

The effect in man of the radiations involved here fall into two main categories; direct effects as the result of a large exposure occuring in a short period of time, and indirect effects resulting from low level chronic exposures.

The principal direct effects of concern here are as follows:

Exposure	X-ray Energy	Area Exposed	Effect
50 r	0.2 MEV or greater	Whole body	Slight transient reduction in white cell count. (No noticeable permanent effect)
200 r	10-30 KV (unfiltered)	Skin (penetration is low)	Slight reddening or tanning
400 r	0.2 MEV or greater	Whole body	Fatal to 50% of population
600 r	0.2 MEV or greater	" "	Fatal to 100% of population
600 r	0.1 to 0.2 MEV	Eyes	Cataract production
5000 r	10-30 KV (unfiltered)	Skin	Permanent skin burn

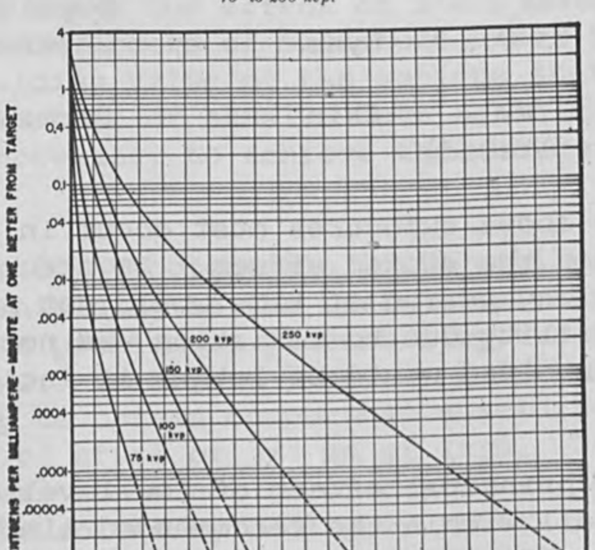
The above exposures must occur in short periods of time to produce the stated effect. An accumulation of smaller doses over a long period of time would not give comparable results. Sterility due to radiation was not mentioned here as the dose involved would be lethal if incident on the whole body.

The principal effect of low-level chronic exposures (those that fall within the recommended limits) is the possible genetic effect, which is a consideration for distant future generations of man and is of concern to the population as a whole rather than any one individual. Medical radiation exposures are most significant toward genetic effects as a much larger percentage of the population receives this type of exposure.

Little can be done to counteract effects of radiation exposures except in cases where lethal doses are suspected to have occured. Attempts are being made to replace the entire blood volume and sometimes the bone marrow in cases such as this, but a great deal of research has yet to be done in this area. These doses would be difficult to achieve in electron beam work.

It is important to formulate an adequate radiation protection program where this equipment is used. Personnel involved in extensive work with these machines should be monitored by a suitable film badge service and instructed briefly in the x-ray hazards of the equipment. A portable radiation detector should be available for checking the radiation level around the machines, and the equipment should be fitted with warning lights indicating when the high voltage is energized. A periodic survey should be made by someone in the radiation protection field, in much the same way as x-ray machines are now surveyed.

Attenuation in lead of X-rays produced by potentials of 75- to 250-kvp.



The curves were obtained with a half-wave generator and with a 90-degree angle between the electron beam and the axis of the X-ray beam. The filter was 3 mm of aluminum for the 150-, 200-, and 250-kvp curves and 0.5 mm of aluminum for the 75- and 100-kvp curves. Direct-current potentials require 10-percent-thicker barriers than for the pulsating potentials given above Data from NBS Handbook 50

Figure 1

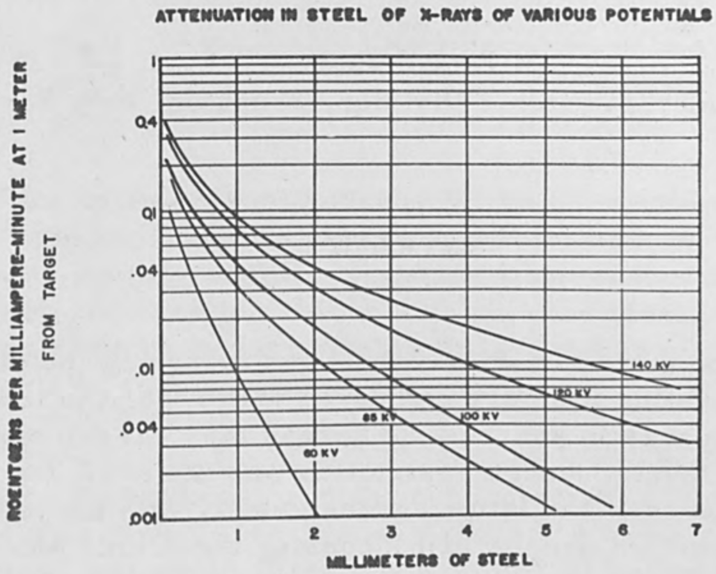


Figure 2

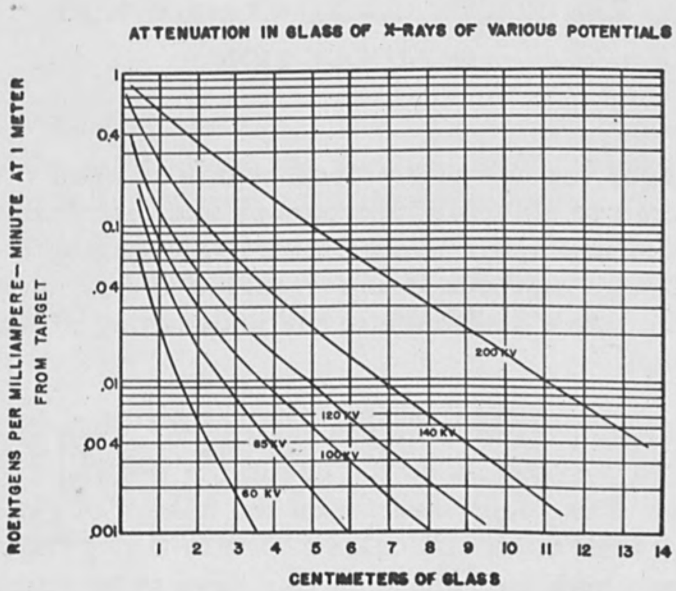


Figure 3

ON SOME ASPECTS OF ELECTRON BEAM EVAPORATIONS

by
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ABSTRACT

A two-grid electron gun and a Pierce type gun focussing the electron beam by a spherical accelerating field are compared with regard to their performance as electron beam evaporation sources. Whereas the grid gun operated satisfactorily only at low power levels, such a restriction was not found for the Pierce gun. The practical performance of the latter agrees closely with the theoretical data on power, current, current density and focussing conditions which are presented in a number of graphs. As an example for the possibilities of electron beam evaporation, a method is described for the rapid determination of multi-component phase diagrams. In this method, the system components are vacuum-deposited as stacked wedge-shaped films and subsequently brought to diffusion. The resulting sample contains all possible concentrations of the components and the corresponding compounds in a predictable geometry. By means of an electron diffraction scan across the sample surface, the phase diagram is obtained directly.

INTRODUCTION

Only a few years ago, the use of electron beams in open vacuum systems was essentially restricted to electron microscopy and diffraction, x-ray generation and high voltage oscillography. This picture is changing considerably with the rapid spread of vacuum methods in laboratories and production plants. Electron beams are now used more and more in the processing of materials as well as in their investigation.

These new applications extend from the melting of large chunks of metal over the vaporization of solid evaporants to the precision milling and welding of extremely small work pieces. The requirements on the design of guns and electron optics vary accordingly. It is most difficult to specify these requirements in an intermediate range where high current densities have to be combined with good focussing conditions at relatively high power levels.

Some design considerations can be derived from the theorem of Helmholtz-Lagrange which yields the limiting current density independently of the electron-optical system employed.[1,2]

With certain simplifying assumptions[3-5], it reads:

$$j_{max}/j_o = \frac{eV}{kT}\sin^2\gamma = \frac{11600\ V}{T}\sin^2\gamma \left[\frac{volt}{^oK}\right] \qquad (1)$$

where j_{max} is the maximum current density, j_o the current density at the cathode, V the acceleration voltage, T the cathode temperature and γ the aperture (half-angle of the cone enclosing the beam). Equation 1 shows that a large aperture angle and a high voltage are required to achieve high current densities. The use of high voltages is also advantageous in suppressing the spreading of the beam at non-conducting targets due to surface charge effects.

Unfortunately, the current density is also limited by a number of other factors such as space charge, lens aberrations, and the characteristics of the cathode emission. At the power levels considered here, these factors are usually not amenable to an accurate theoretical analysis. Simple beam producing systems are therefore attractive not only due to their low cost, but also because of the possibility of optimizing the critical parameters experimentally.

The performance of two such simple gun designs as evaporation sources and their application to a new method of determining the phase diagrams of alloys will be described in this paper.

GUN WITH TWO GRID CYLINDERS

The main advantages of heating the evaporant by electron bombardment are the potential cleanness of the method and the possibility of evaporating high melting materials. Both can be fully utilized only when the beam impact is restricted to a small area of the evaporant material. In this respect, early electron bombardment devices were less than ideal[6-8]. An electron gun was used first by Brochard and co-workers[9], but the voltage range of this gun was restricted to 5000 V_{max}.

Shortly after Brochard's publication, the author constructed and tested in cooperation with A. Boettcher and F. Leonhard a two-grid gun with a separate anode for acceleration voltages up to 40KV[10]. This gun is shown in Fig. 1 attached to a coating chamber with special features which will be discussed later on.

The biases of the two grid cylinders could be adjusted independently. With a common negative bias at both grids, a lens configuration and gun performance somewhat similar to the design of Steigerwald could be achieved[11]. This system is characterized by a great focal length and a comparatively large effective aperture. The gun performed well in this operational state, but the maximum power output was restricted to about 40 watts due to the space charge limitation of the emission current. This power was not sufficient to evaporate high melting metals at reasonable rates.

A considerable increase of the beam current could be obtained by operating the outer grid at a positive bias. In this mode of operation, difficulties arose from small pressure increases initiated by the outgassing of the evaporant or the chamber walls. During such pressure bursts, the grid current frequently exceeded the permissable value, evidently due to the generation of a strong ion current.

It is observed that the effectiveness of the bombardment increased greatly at pressures between 5×10^{-4} and 10^{-3} mm Hg. Presumably, a higher current density as well as a larger total current resulted from the neutralization of the negative space charge by positive ions[12]. The beam pencil itself was luminescent, but no glow discharge in the usual sense developed. This mode of operation was stable and well controllable, but the high residual pressure is detrimental to the goal of producing high purity films.

In summary, it can be said that the two-grid gun operated satisfactorily as an evaporation source only at moderate power levels. Similar properties were found by Braucks[13] on a two-grid gun of different purpose and design. This gun also yielded a high current density but only modest beam currents.

A PIERCE-TYPE GUN AS EVAPORATION SOURCE

More recently, Thun and Ramsey have explored the performance of Pierce-type guns as evaporation sources[14]. This type of gun focusses the electrons by accelerating them in a spherical field generated between two concentric spherical cups. The outer cup consists of a cathode and cathode shield; the inner cup of the anode (Fig. 2). The main advantages of this configuration are its mechanical and electronic simplicity, its high power output combined with good focussing conditions, and its insensitivity with regard to the stabilization of the acceleration voltage.

The concentric electrode configuration is amenable to an analytical treatment of the power and current limitation due to space charges[15]. The result reads:

$$P_{max} = 29.33 \times 10^{-6}\, V^{5/2} \sin^2(\gamma/2)/\rho \quad \text{(watts)} \qquad (2)$$

$$i_{max} = 29.33 \times 10^{-6} V^{3/2} \sin^2(\gamma/2)/\rho \qquad \text{(amp)} \tag{3}$$

ρ is a function of the ratio of cathode radius to anode radius (Rc/Ra). Pierce[5] has extended this analysis to calculate the smallest possible focal spot size considering the lens effect of the anode hole as well as the influence of the space charge. Only the result as a function of Rc/Ra will be given here, since its derivation from the paraxial ray equation and the well known formula for single aperture lenses is somewhat lengthy.* The ratio of the minimum beam diameter to the diameter of the (circular) cathode is:

$$\frac{d_{min}}{d_c} = \frac{1}{R_c/R_a} \quad \exp\left[\frac{-9\rho}{2}\left(1 - \frac{R_c/R_a}{6\rho} \cdot \frac{d\rho}{d(R_c/R_a)}\right)^2\right] \tag{4}$$

The distance of the focal spot from the anode hole is determined by:

$$F_e = R_a \;/\left(1 - \frac{R_c/R_a}{6\rho} \cdot \frac{d\rho}{d(R_c/R_a)}\right) \tag{5}$$

The value of ρ (R_c/R_a) increases with increasing R_c/R_a:

$$\rho(2) = 0.75\;;\quad \rho(2.5) = 1.531\;;\quad \rho(3) = 2.512$$

The corresponding derivatives $d\rho\;/d(R_c/R_a)$ are 1.33, 1.77, and 2.14, resp. The current density obtained without consideration of the thermal velocity distribution follows from eq. (4):

$$j = j_o\;(d_c/d_{min})^2 \tag{6}$$

According to eq. 2, a small value of R_c/R_a has to be chosen to obtain a high power output at a given acceleration voltage. A large value of R_c/R_a is required, on the other hand, to achieve high current densities. However, since the current density is limited also by eq. 1 due to the thermal velocity spread of the electrons, it is sufficient to choose R_c/R_a large enough that it does not become the decisive factor in the limitation of the current density. An R_c/R_a value of about 3 appears to be a reasonable compromise.

In Fig. 3, the power and current curves calculated according to equations 2 and 3 are given as a function of the acceleration voltage for $R_c/R_a = 3$. Fig. 4 presents

*In ref. 5, p. 185, eq. (10.16) should read:

$$I_o = \frac{4\pi\varepsilon}{9}\sqrt{2\eta}\,\frac{V^{3/2}}{(-\alpha)^2}\left(\frac{r}{r}\right)^2$$

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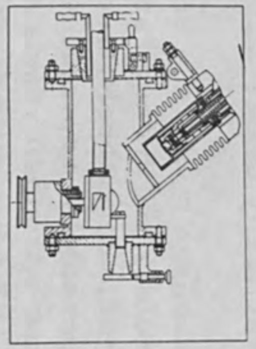

Fig. 1 Vacuum Chamber for the Deposition of Double or Triple Wedge Films with a Two-Grid Electron Gun as Evaporation Source

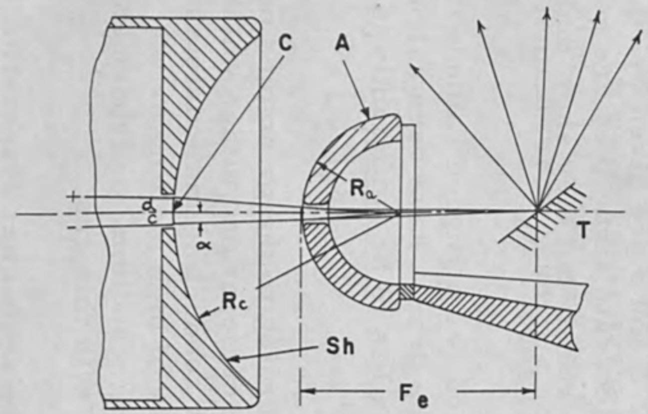

Fig. 2 Pierce Type Gun as Evaporation Source. (C cathode; Sh cathode shield; A anode; Rc cathode radius; Ra anode radius; α beam aperture; T target; Fe distance between anode aperture and effective focus (point of smallest beam diameter)

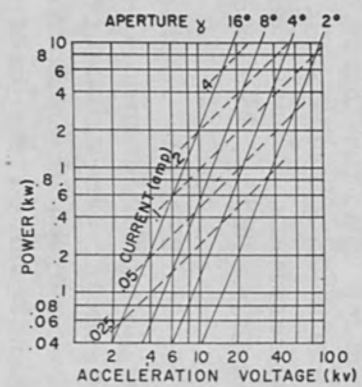

Fig. 3 Maximum Power (and Current) Versus Acceleration Voltage for Pierce Type Guns

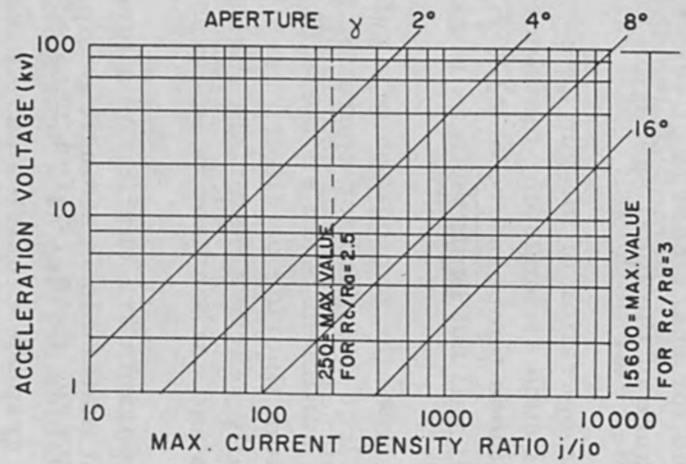

Fig. 4 Acceleration Voltage Versus the Highest Achievable Current Density Ratio j / j_o at the Focal Spot of Pierce Type Guns. (Cathode Temperature $T_c = 2320°K$)

the maximum current densities for the corresponding voltage and aperture range. The characteristics are calculated from eq. 1. Two vertical lines mark the maximum current densities for the R_c/R_a values of 2.5 and 3., resp., which can not be exceeded at any voltage or aperture due to the limitation imposed by equations 4 and 6. Fig. 5 finally shows the minimum focal spot sizes to be expected according to eq. 6. The values of F_e/R_a for R_c/R_a ratios of 2, 2.5 and 3 are given by eq. 5 as 2.45, 1.93 and 1.74. These values are not very accurate since they are not corrected for space charge effects behind the anode aperture, but they show that the distance of the focal spot from the anode aperture is about 2 R_a.

Since the operation of the gun as evaporation source requires a rugged cathode material such as tungsten, tantalum or molybdenum, the graphs have been calculated for a cathode temperature of 2320°K. The cathode area has to be sufficiently large so that it will not limit the maximum beam current.

Fig. 6 shows the photograph of a gun actually built according to the principles outlined above. It is designed for operation at about 40 kv, an acceleration voltage which yields a sufficient beam stiffness to evaporate such low conducting materials as magnesium fluoride or silicon carbide. A large number of high melting or chemically reactive materials such as silicon, platinum, rhodium, molybdenum, tungsten and carbon have been evaporated successfully with this gun.

The evaporants are carried on a turn table to permit the sequential evaporation of different materials in a single pump-down. The table top is exchangable. Plain copper tables serving as a heat sink and stainless steel tables with inserted shallow graphite crucibles have been used.

The power output of the gun is adjusted by controlling the electron emission through the filament current. The performance of the gun matches closely the theoretically predicted values up to two thirds of the saturation current. At higher beam currents, the beam spreads rapidly, the evaporation rate decreases, and the target is heated excessively. Consequently, only about 60 to 70% of the maximum power and current given in Fig. 3 should be considered as practically usable with Pierce type guns.

A possible explanation of this current limitation may be derived from an argument given by Pierce[16]. For a perfectly focussing system following Abbe's sine law, Pierce has shown that the maximum current density can only be approached by wasting an increasing fraction of the total beam current. At small ratios of focal spot to cathode diameter (d_{min}/d_c), the condition of a perfectly focussing system is closely approached.

Let the fraction of the cathode current reaching the focal spot be

$$\Sigma_c = (d_{min}/d_c)^2 \quad j_f/j_o.$$

The current density at the focal spot derived by Abbe's sine law is:

$$j_f = \frac{j_o}{(d_{min}/d_c)^2}\left[1 - (1-\beta^2)e^{-\beta^2\phi/(1-\beta^2)}\right] \qquad (7)$$

with $\beta = (d_{min}/d_c)\sin\gamma$ and $\phi = eV/kT = 11,600\ V/T$. For small β and large ϕ, the expression for the "current efficiency" E_c approaches the equation:

$$E_c = 1 - e^{-\beta^2\phi} \qquad (8)$$

On the other hand, an intensity efficiency E_i can be defined as the ratio of the actual current density j_f to the theoretical bounding current density j_{max} at the focus:

$$E_i = \frac{j_f}{j_{max}} = \frac{E_c}{\beta^2\phi} \qquad (9)$$

By using eq. 8, this can be transformed into:

$$E_i = \frac{E_c}{-\log_e\ (1 - E_c)} \qquad (10)$$

By plotting E_i as a function of E_c, it may be seen that a high intensity efficiency can be gained only at the cost of the current efficiency.

Many figures of merit proposed for electron guns have no bearing on the use of a gun as an evaporation source. In this application, a high total electron current has to be achieved simultaneously with a high current density. Therefore it seems reasonable to propose the product E_cE_i as a new figure of merit for electron bombardment guns.

$$E_cE_i = \frac{E_c^{\,2}}{-\log_e\ (1 - E_c)} \qquad (11)$$

The first derivative of eq. 11 set equal to zero yields the condition for the highest obtainable value of E_cE_i:

$$-\log_e\ (1 - E_c) = E_c/2\,(1-E_c) \qquad (12)$$

This maximum of $E_c E_i$ is given at 71.54% of the maximum beam current which is, of course, the beam current calculated according to eq. 3. This result is in good agreement with the experimental observation that the gun efficiency decreases rapidly above two thirds of the bounding current.

An advantage of electron guns in comparison with resistance and induction sources is their better controllability. This feature may gain particular importance in the vacuum deposition of electronic devices and circuits where the deposition rate and the film thickness must meet close tolerances. A sufficiently accurate monitoring of these parameters is possible by such new devices as the quartz crystal oscillator and the ion gauge rate meter. The crystal oscillator measures the deposited mass as a function of the induced frequency shift and the rate by means of a differentiating circuit[17, 18]. The ion gauge rate monitor[19, 20] indicates directly the rate. Its principle is shown in Fig. 7. A vapor ray is ionized by electron bombardment. The ions are accelerated in a DC field and intercepted by a collector plate. The resulting ion current is nearly proportional to the rate.

The high demands on the accuracy and reproducibility in the vacuum deposition of circuitry often require automatic control of the evaporation sources by rate monitoring devices even on a laboratory scale. For conventional evaporation sources, the control system becomes rather involved because of the high currents which have to be regulated (Fig. 8)*. Here the electron gun offers an inherent advantage since only a grid voltage or, in the case of a Pierce type gun, the filament current has to be controlled. The power gain of the control circuitry can be reduced by a factor of 100 or more.

A NEW METHOD FOR THE DETERMINATION OF PHASE DIAGRAMS

To illustrate a particularly elegant application of the electron gun as evaporation source, a new method for the determination of phase diagrams will be described in this last section.

The crystallographic determination of a phase diagram by x-ray diffraction requires the preparation of a large number of samples of different composition. A number of x-ray exposures has to be made of each sample at different temperature levels, and all the resulting diffractographs must be evaluated individually. This is already a formidable task for a binary system, and the labor becomes more and more staggering for ternary, quaternary and higher systems.

For survey-type studies, this procedure can be simplified considerably by preparing a binary or ternary system in a single sample with a continuous concentration change

*Courtesy of Mr. G. Giedd

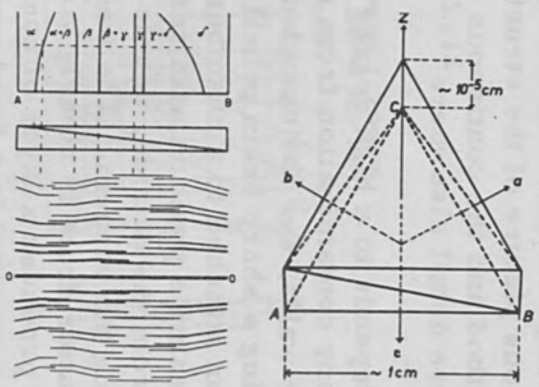

Fig. 9
Principle of Taking Electron Diffraction Scans of Wedge Samples

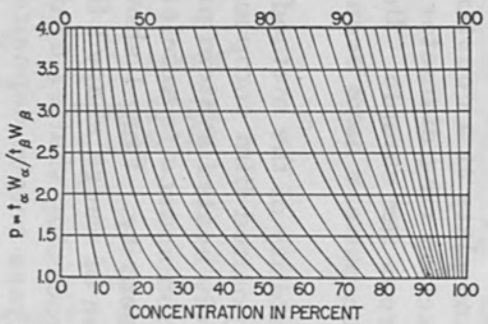

Fig. 10 Graph for the calibration of kinematic diffractograms with respect to the concentrations of the sample components. The concentration C_α is given as the function of $p = t_\alpha W_\alpha / t_\beta W_\beta$. W_α and W_β are the specific weights, and t_α and t_β the maximum wedge thicknesses of the components α and β.

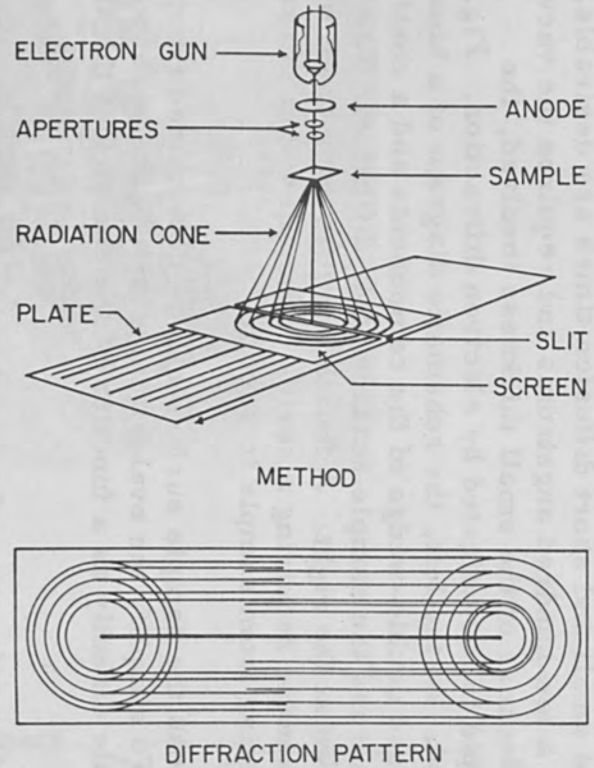

FIG. 11 PRINCIPLE OF CONTINUOUS RECORDING OF ELECTRON DIFFRACTION PATTERNS

evaporation source and substrate[21]. As an alternative choice, the use of a flat shutter disk is possible. In this case, the deposition of linear wedges requires a special aperture form bounded by an archimedian spiral[21, 22]. A single aperture yields a more accurate deposition than multi-aperture drums or disks.

Amorphous carbon or SiO films are suitable temperature-resistant substrates. They are conveniently deposited on rock salt wafers and floated off either before or after the deposition and annealing of the specimen films.

Generally, the structures and their temperature and concentration boundaries found in film specimen agree well with those observed in bulk samples. Occasional deviations can be spotted by photographing a few x-ray diffraction patterns on bulk samples of appropriate concentrations.

Fig. 12 illustrates the advantage of a continuous scan over a series of still diffractographs taken at equal concentration spacings. The scan shows very clearly the phase boundaries in the system silver-tin with an accuracy of about 2 concentration percent. The fact that the intermediary structure showing the typical line spacings of a hexagonal close packed lattice really consists of two phases with their boundary at about 25 weight-% tin can be affirmed only by a detailed analysis since the tin-rich γ - (ε' -) phase is distinguished from the β - (ε -) lattice solely by a slight orthorhombic distortion.

As an example of a more complicated binary diagram, a scan of the system gold-tin is shown in Fig. 13. The fuzziness of the $AuSn_2$ diffraction lines is caused by the large grain size of this phase which can be seen directly in electron microscope photographs.

Fig. 14 shows a series of diffraction scans through the triple wedge sample of the ternary system Ag-Pb-Sn. The phase boundaries found by an evaluation of these diffractographs are given in Fig. 15. They agree well with the results of investigations made on bulk samples. However, some samples annealed for long periods at low temperatures (40-70h at 120°C) developed in the silver corner a super structure which has not been seen in conventional specimens[10].

Diffraction scans of wedge samples have been made also at elevated temperatures. SiO and carbon substrate films are usable up to about 700 to 800°C. Local breakage may occur, however, at considerably lower temperatures when large volume changes are encountered in the sample film.

In conclusion, it may be mentioned that the performance of Pierce type guns is being explored with regard to other applications such as vacuum milling, welding and brazing. However, final data are not yet available.

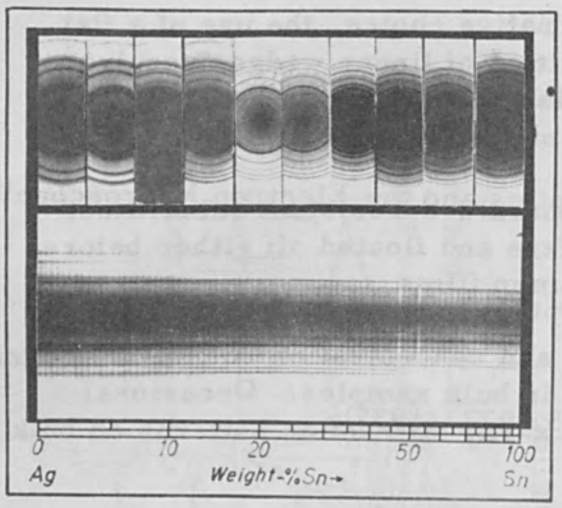

Fig. 12 Electron Diffraction Scan of the System Ag - Sn at Room Temperature

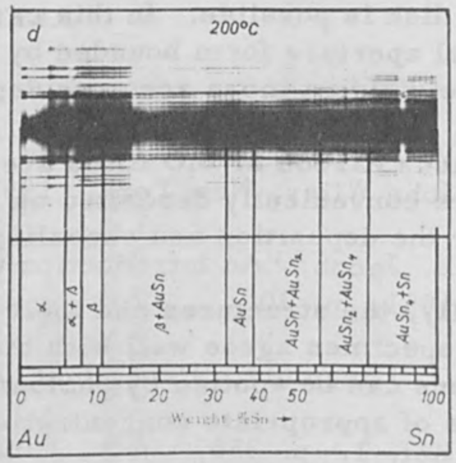

Fig. 13 Electron Diffraction Scan of the System Au - Sn at room Temperature. The Film was annealed at 200°C.

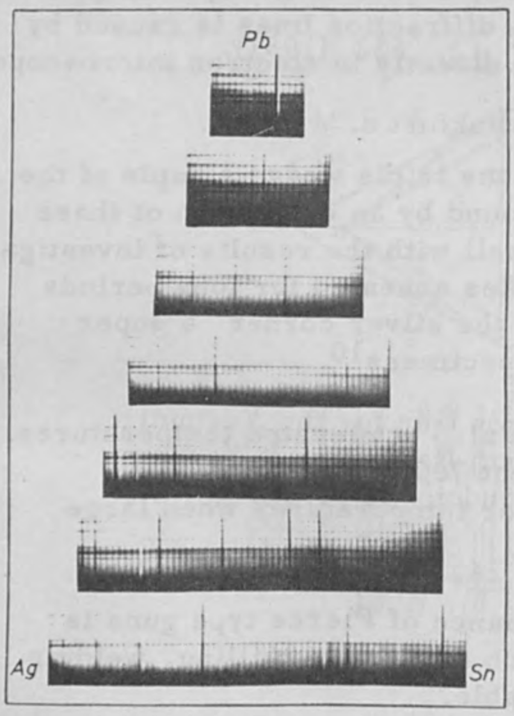

Fig. 14 Electron Diffraction Scan of a Ternary Sample Ag - Pb - Sn at Room Temperature

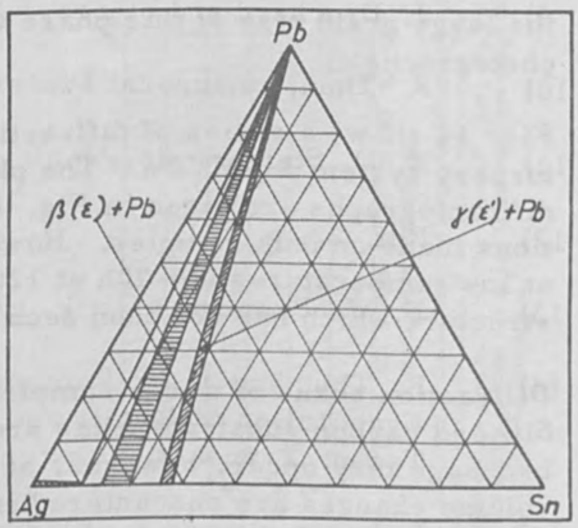

Fig. 15
Phase Diagram Ag - Pb - Sn at Room Temperature

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CAPTIONS

Fig. 1 Vacuum Chamber for the Deposition of Double or Triple Wedge Films with a two-grid Electron Gun as Evaporation Source.

Fig. 2 Pierce Type Gun as Evaporation Source.

C cathode, Sh cathode shield, A anode, R_c cathode radius, R_a anode radius, γ beam aperture, T target, F_e distance between anode aperture and effective focus (point of smallest beam diameter).

Fig. 3 Max. Power (and Current) versus Acceleration Voltage for Pierce Type Guns.

Fig. 4 Acceleration Voltage versus the Highest Achievable Current Density Ratio j/j_o at the Focal Spot of Pierce Type Guns (Cathode Temperature $T_c = 2320^oK$).

Fig. 5 The Ratio of Minimum Beam Diameter to Cathode Diameter versus Acceleration Voltage for Pierce Type Guns.

Fig. 6 Photograph of Gun.

Fig. 7 Ion Gauge Rate Monitor

Fig. 8 Automatic Deposition Rate Control

Fig. 9 Principle of Investigating Multi-Component Phase Systems

Fig. 10 Graph for the Calibration of Kinematic Diffractograms with Respect to the Concentrations of the Sample Components. The concentration C_α is given as the function of $p = t_\alpha W_\alpha / t_\beta W_\beta$. W_α and W_β are the specific weights, and t_α and t_β the maximum wedge thicknesses of the components α and β.

Fig. 11 Principle of Continuous Recording of Electron Diffraction Patterns.

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Fig. 13 Electron Diffraction Scan of the System Au-Sn at Room Temperature. The film was annealed at 200°C.

Fig. 14 Electron Diffraction Scan of a Ternary Sample Ag-Pb-Sn at Room Temperature.

Fig. 15 Phase Diagram Ag-Pb-Sn at Room Temperature.

THE FUTURE OF ELECTRON BEAM TECHNIQUES IN MICROELECTRONIC CIRCUITRY

by

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Sylvania Electronics Systems

INTRODUCTION

I have been informed that some of the people attending this portion of the Symposium represent companies and organizations who are active in the business of designing and manufacturing electron beam equipment. I would like to bring to you the perspective of the user, concerned with the application of electron beam equipment to the formation and fabrication of microelectronic circuits.

Before I discuss electron beam applications, it might be wise to spend a moment describing my point of view of the microelectronic circuit field.

THE FIELD OF MICROELECTRONICS

The field of microelectronics has as its primary endeavor the compression of size and volume of low power semiconductor electronic circuits. The objective is that our electronic equipment will function as though it contained from one million to fifty million equivalent electrical parts per cubic foot.

To achieve these size reductions we must use basic thin film electrical and molecular characteristics of materials rather than their conventionally assigned bulk properties.

As if the reduction in size and volume were not enough of an objective, we also aim to effect significant improvements in the reliability of our electronic circuits, and significant circuit cost reductions as well. The deeper one probes into the subject of microelectronics, the more one finds that all three objectives (size reduction, reliability improvements and cost reduction) appear to be so closely inter-related that technical success in achieving one of the objectives will probably yield improvements in all three.

We cannot neglect the consideration of rate of progress, and dollar investment in research and development leading to production. Because we are interested in bringing advanced state-of-the-art electronic hardware to practical reality at the earliest possible date, it is evident that a step-wise progression of improvement in our microelectronic circuitry is the logical course of action.

We anticipate three distinct steps of progress in microelectronics in working towards our ultimate size and density objectives. Each step makes use of current technology and development successes and leads us into new areas of research and development. Therefore, our progress is a continuing action with microminiature hardware available almost immediately, and ultimate molecular circuitry available in the more distant future. But each step in our progress will bring a continuing size and cost reduction and reliability improvement.

STEPS IN CIRCUIT FABRICATION

The steps that we plan in our progress can be briefly summarized as follows:

1. At present we are forming electronic circuit stages on a surface less than four tenths of an inch square in which each circuit stage contains from four to ten identifiable electronic devices. These circuits are a combination of vacuum deposited films to form resistors and capacitors and some conductive paths, combined with some micro-sized conventional attached parts such as inductors and large value capacitors. We also employ uncased transistors and diodes. For optimum protection and reliability each of these circuit wafer stages is to be hermetically sealed.

2. The next step in progress will be the employment of all vacuum-deposited films to form passive electronic devices combined with conventional uncased semiconductors. This will be followed shortly by integrated vacuum deposited films such as RC networks and LC networks. We anticipate that the passive film circuits will still be used in conjunction with conventional uncased semiconductors fabricated by conventional techniques.

3. Our final step in progress will be the achievement of entire integrated circuits formed by deposited and reworked films including the active semiconductor material. These circuits are perhaps best identified as

an integral "blob" which performs a defined circuit function such as amplification or pulse modification or pulse identirication.

As of today, we have accomplished step one and are already into step two. But before we can proceed much further, we need new fabrication tools and techniques that will permit us to use basic materials characteristics without the necessity of bulk processing.

Now, having presented a brief picture of our goals in the microelectronics circuit field, let us spend a moment discussing what we might do if we had a suitable electron beam machine.

POTENTIAL APPLICATIONS FOR ELECTRON BEAM MACHINES

Electron beam machines can be divided into two broad categories. The first category includes equipment which delivers a coarse large diameter high powered beam. The second category covers lower energy but very small diameter electron beam equipment.

COARSE BEAM JOBS

We would like to use the coarse electron beam, with beam diameters in the order of 30 to 100 thousandths of an inch, as an evaporation heat source. This would permit us to vaporize and therefore vacuum deposit films of conventional materials as well as refractory materials which are presently impossible to evaporate using conventional tungsten filament or hot crucible techniques. Lest we think only of metallic materials, I include in this category for vacuum evaporation materials that have excellent dielectric properties as thin films.

Additional uses of the coarse high powered electron beam include that of surface preparation. What I have in mind is the fusion of the substrate or film-receiving surface in order to achieve the ultimate in molecular cleanliness and suface activation as well as the creation of the ideal ultra-smooth fused surface. This would be particularly applicable to the highly desirable category of ceramic substrates.

FINE BEAM OPERATIONS

In the second category of very fine beam spot diameters, I refer to electron beam spots at the substrate whose diameter is controllable but which ranges in the order of 1 to 3 thousandths of an inch down to perhaps one ten thousandth of an inch. With beams of this type the possibilities begin to expand and the room for conjecture becomes even greater.

The first and most obvious application for an ultra-fine diameter electron beam is that of "machining" vacuum-deposited films in order to precisely define the shape or pattern of residual film material that we desire. This again is essentially the use of the electron beam as a source of heat, but this time the beam is applied to the circuit working surface to cause reevaporation from that working surface. If by this means we are able to eliminate the use of vacuum evaporation masks, or pattern etching by chemical or electrochemical techniques, then the benefits in precision, labor reduction, and approach to automation become very significant and very worthwile. In addition, we anticipate finer line definition with the electron beam than we have been able to reproducibly achieve by conventional vacuum evaporation techniques. Since we anticipate performing more and more of our circuit materials fabrication in the vacuum system, we also anticipate that we will be depositing more than one material on the substrate. The electron beam will be of value in joining or alloying together materials of different compositions while still in the vacuum chamber. The joints achieved in this manner should certainly be superb in terms of contamination control and precision of joint area definition.

Another application of the fine electron beam will be to heat treat vacuum deposited metal and dielectric films in order to give us the desired surface perfection and material crystal structure.

All or the foregoing is really a prelude to the real breakthrough which the electron beam techniques may help to make possible. This breakthrough is in the area of the creation of semiconductor devices by means of vacuum deposition and material transformation completely within the vacuum system without the requirement for mechanical operation to create the semiconductor device. When this is achieved we will finally have reached the long range objective of being able to form complete semiconductor electronic circuits within the vacuum chamber, in which the circuit entered the chamber as a base material with a supply of raw or source materials and was removed from the vacuum chamber as a complete hermetically sealed, functioning, adjusted, measured and tested circuit.

How might the electron beam machine be applied to the formation of complete semiconductor devices? Needless to say, considerable intensive research and development effort is underway in exactly this area at many organizations across the country today. We foresee the possibility of the proper preparation of the substrate surface so as to enhance the chance of single crystal film deposition (perhaps with seeding required.) The coarse electron beam would be used for bulk material evaporation and the fine beam for precise remelting and recrystallization. Secondary alloying and the addition of impurity materials would again take place by selective evaporation, and the fine beam would be employed to treat the films in place by thermal diffusion techniques or direct molten alloying.

The problem of forming conductive terminations to the semiconductor rectifying junctions may be solved by the deposition of an insulating film, followed by subsequent defined-deposition of conducting films to make contact to the junctions and to terminate the junctions to other portions of the electron beam evaporated and patterned circuit materials.

Let me be the first to state that the possibilities that I have tried to outline for you are those which one can see today. At the rate at which our technology is advancing, I often wonder whether tomorrow morning's Technical Journal will provide the clue or perhaps a new avenue to progress which we did not even visualize today. Certainly no one has exclusive right to predict the future and the crystal ball is available for all to use.

I have presented the foregoing material in an effort to give you a brief picture of why my organization is interested in the electron beam machining approach to the fabrication of microelectronic circuits. The possibilities exist for size and cost reduction as well as reliability improvement and ultimate automation. Realizing the full potential of the technique is going to be difficult, time consuming and expensive. But the investment must be made. The potential payoff is too great to ignore.

DESIRABLE APPROACH TO ELECTRON BEAM MACHINE DESIGN

As a using organization, my group does not desire to design or develop or fabricate electron beam machining equipment. We have enough problems doing microelectronic circuit development work. But I would like to take this opportunity to present a brief word picture of how we would like to see electron beam machine equipment developed and offered for sale.

First, I am sure that you will all agree with me that the field and the equipment are new. Electron beam equipment capabilities are continually expanding. For this reason, we cannot afford to consider procuring a piece of equipment whose capabilities are limited or fixed, and whose price is high.

I do not propose to tell you how to go about designing a high vacuum piece of machinery containing electron beam heads. But I would like to tell you our impressions and observations as they relate to the general machine characteristics that we desire.

We would like to see a piece of equipment which can be purchased at an initial reasonable price, but which has the growth potential of permitting many accessories and attachments and refinements to be added at a later date without forcing us to throw away our original investment.

We favor a metal horizontal tank-type machine rather than the conventional vertical glass bell jar approach. The horizontal tank vacuum chamber should be of alloy steel or stainless steel, with a tank diameter in the order of 24 to 30 inches and a tank depth of approximately 30 to 40 inches. The tank should also contain many flanged ports to permit the installation of power feed-throughs, movable work tables, gas ports, internal vessel wall heaters and high voltage electron beam heads without the necessity of tearing down the tank and sending it out for remachining, welding and vacuum testing at a later date.

Because we feel that we will ultimately do our vacuum work at pressures considerably lower than the present 1×10^{-6}mm, and probably ranging down to 1×10^{-10}mm, all seals or gaskets built into the original machine should probably be of the double seal or double gasket variety to permit differential pumping or any of the other advanced techniques for achieveing ultra high vacuums in single wall vessels. The added machining cost during fabrication should add very little to the inital equipment cost.

A versatile and high speed vacuum pumping system is the first and prime requisite for any film evaporation process, whether it be conventional evaporation or electron beam machining. The vacuum pumping system should be capable of expansion without obsolescence.

For initial development efforts, we would probably start by using the equipment with conventional hot filament evaporation sources. We will therefore be working a pressures in the order of 1×10^{-6}mm, and pumping speed and ultimate pumping pressure are readily achievable with conventional pumping equipment currently available. Later we would like to add additional pumping equipment to increase the pumping speed and to reduce the ultimate pressure within the tank. We desire a vacuum pumping system that is expandable. By this I mean that the vacuum system should not be designed as a tightly packed piece of equipment during its initial stages. Plenty of piping and flange space should be provided, so that we can purchase new flanged piping that would permit us to initially increase pumping speed by paralleling our pumps, and as a further step to increase ultimate vacuum with a series-parallel arrangement of still more purchased pumping equipment.

To do this, from the equipment supplier's point of view, involves a design at this date which is geared for the ultimate in a very high vacuum system and a very high pumping speed, but which has many of its components omitted and replaced with either blind flanges or straight runs of pipe or tubing.

As I mentioned previously, we will probably start using this equipment as a conventional vacuum evaporator using hot tungsten filament heat sources. We will want to add a coarse electron beam gun for vacuum evaporation heat source work in the very near future. Later we would plan to add a very high resolution electron beam gun of small spot diameter and lower total power, for film machining.

I recognize that the argument today between the two factions of electron beam developers centers about the significant point of beam voltage. Frankly, I am buying beam characteristics and results. Whether these are achieved at very high voltages in the order of 100,000 volts, or in the 20,000 to 25,000 volt range is a problem for the equipment developers. You must work this out between yourselves or show me what I must pay and what benefits I can achieve with either system in order to permit me the final choice. I would like to state that we are interested in beam power control and beam spot diameter control because we are unable to predict these variables in advance of extensive development work.

This point is pertinent as @ will show what has been achieved in about 5 years

Precision electron beam steering is a desirable machine operating characteristic, in order that the beam can be located at any precise point reproducibly within approximately a 3/4 inch diameter working circle. A moving work table within the vacuum chamber is of course the alternate method of scanning the beam over the working surface. I would like to see more equipment manufacturers offering both types of beam positioning accessories and the relative cost comparisons. Without considerable development practice I find it difficult to state a preference for one beam steering system or another.

CONCLUSION

The growth approach to electron beam machines is probably the only way that equipment manufacturers can hope to create a market of significant size. Most research and development organizations are hard put to justify a very large initial investment for equipment which is the ultimate in complexity and capability. It is usually easiest to convince management, and certainly easier on the capital equipment budget, to purchase a basic piece of equipment first. After a demonstration of the capabilities of the basic equipment and the development limits of that equipment, one can detail the required equipment accessories necessary to move into more exotic areas of research and development. In short, progress is usually a step by step forward operation, with due allowance made for the occasional flash of genius.

I believe this growth philosophy must be applied to electron beam machinery. We are only at the threshold of the development and utilization of electron beam techniques. Equipment must be built in recognition of this fact and must allow for growth and expansion without undue penalty to the customer.

Electron beam machining is here to stay. But how quickly it takes hold and how broadly it is applied must be reviewed in the light of growth potential, initial capital investment and technological potential. No man can say how far the electron beam field will progress. No equipment manufacturer should build equipment as though he could.

LABORATORY SCALE PERFORMANCE
OF A LOW VOLTAGE (25 KV) ELECTRON BEAM WELDER

By
M. H. Hablanian
NRC Equipment Corporation

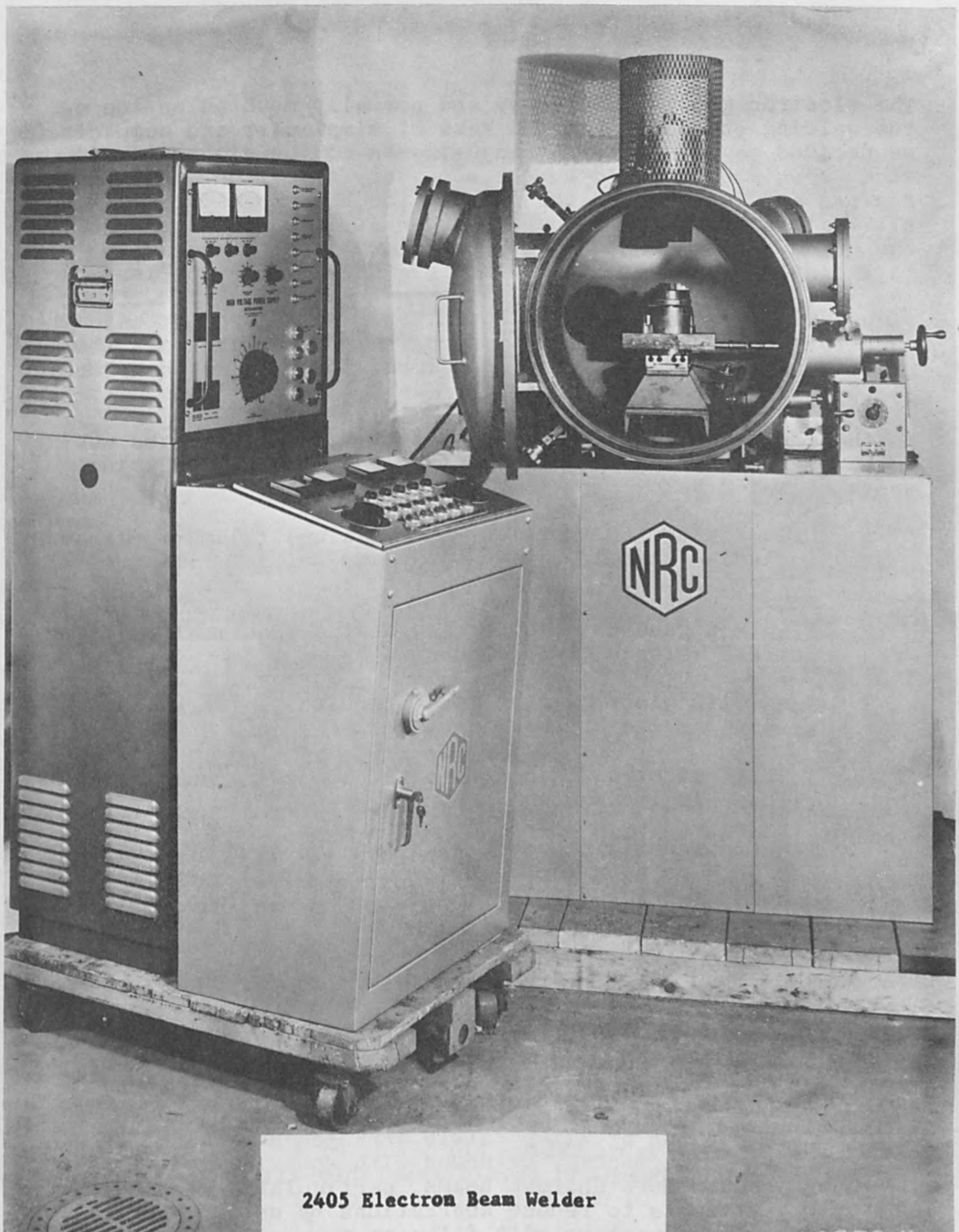
INTRODUCTION

Experience with electron beam welding in our development laboratory extends to voltages up to 30 kv and power levels up to 6 kw, which is sufficient to weld stainless steel of more than one-half inch thickness.

As the title of this paper indicates, our experience is mostly laboratory scale. However, the equipment which we use may be called "standard" in the sense that it is a commercially available unit designed for industrial use. It was installed in the laboratory approximately a year ago for evaluation and sample processing following the initial development work.

There are always problems, generally, in going from a laboratory set-up to an industrial model. The problems are not only in achieving an economically feasible design but, also, in simplifying operating techniques, obtaining minimum of adjustments, reproducibility, reliability and minimum of maintenance. Maintenance must be periodic rather than erratic so that there is no interference with satisfactory production work. The equipment we use is simple enough to operate and reliable enough so that we have on several occasions let outsiders use it for small production work after only a few hours of supervision.

The welder itself has been described elsewhere [1,2]; however, it should be briefly described here. Figure 1 shows the general appearance of the machine which consists of a welding chamber with the electron gun assembly, high voltage power supply and a control panel. The chamber is approximately two feet in diameter and two feet deep and has two perpendicular linear motion tables and a rotary table manually or motor driven through vacuum seals. With the existing work tables any point of a 4 x 6" area can be placed under the beam and the rotary table with the three-jaw chuck tilted zero to 90° from the horizontal position shown. The pumping system consists of a 6" oil diffusion pump and a 30 cfm mechanical vacuum pump. The power supply used at present is rated at 25 kv 200 ma DC, continuous duty, but can be used at voltages up to 30 kv.



2405 Electron Beam Welder

Figure 1

The electron gun is stationary and normally mounted on top of the welding chamber. For the sake of simplicity and compactness we decided to eliminate any adjustments of the electron gun electrodes and to build in the necessary precision during manufacture and assembly of the gun and the beam focusing system. All that is required to operate the unit is to put the high voltage on, start filament heating power and focus the beam by adjusting the current in an electro-magnetic focusing lens.

Figure 2 shows the welder in operation. With the left hand the operator is adjusting the beam focusing control and with the right hand the lateral table adjustment for precise workpiece positioning.

In the course of our work with electron beam welding and melting we have investigated various electron emitting and focusing systems listed below.

1. Directly heated tungsten (or tantalum) filament cathodes including hairpin, flat spiral and helical filaments (Figure 3).

2. Electron guns with indirectly heated spherical emitting surface (Pierce type) (Figure 4).

3. Guns with electrostatic focusing with the workpiece serving as the anode (Figure 3).

4. Initial electrostatic and final electro-magnetic focusing with a single magnetic lens (Figure 5).

5. Electromagnetic focusing with two lenses: the first one used to pass the beam through a small aperture, the second used for final focusing. The aperture in this case separates the welding chamber from the gun chamber and the latter may be pumped by a separate pumping system (Figure 5).

6. Electro-magnetic beam deflection.

7. Stationary and movable electron guns.

Each of these systems has certain advantages and disadvantages. Detailed discussion of all possible arrangements cannot be attempted here. In general, cathodes with spherical emitting surfaces produce more uniform beams, particularly at higher beam currents. Attempts to reduce aberrations by using spherical electrodes in conjunction with filament type emitters (Figure 6 3.) do not produce satisfactory results because various sections of the filament are not located uniformly with respect to the accelerating electric field. However, heating of pure metal

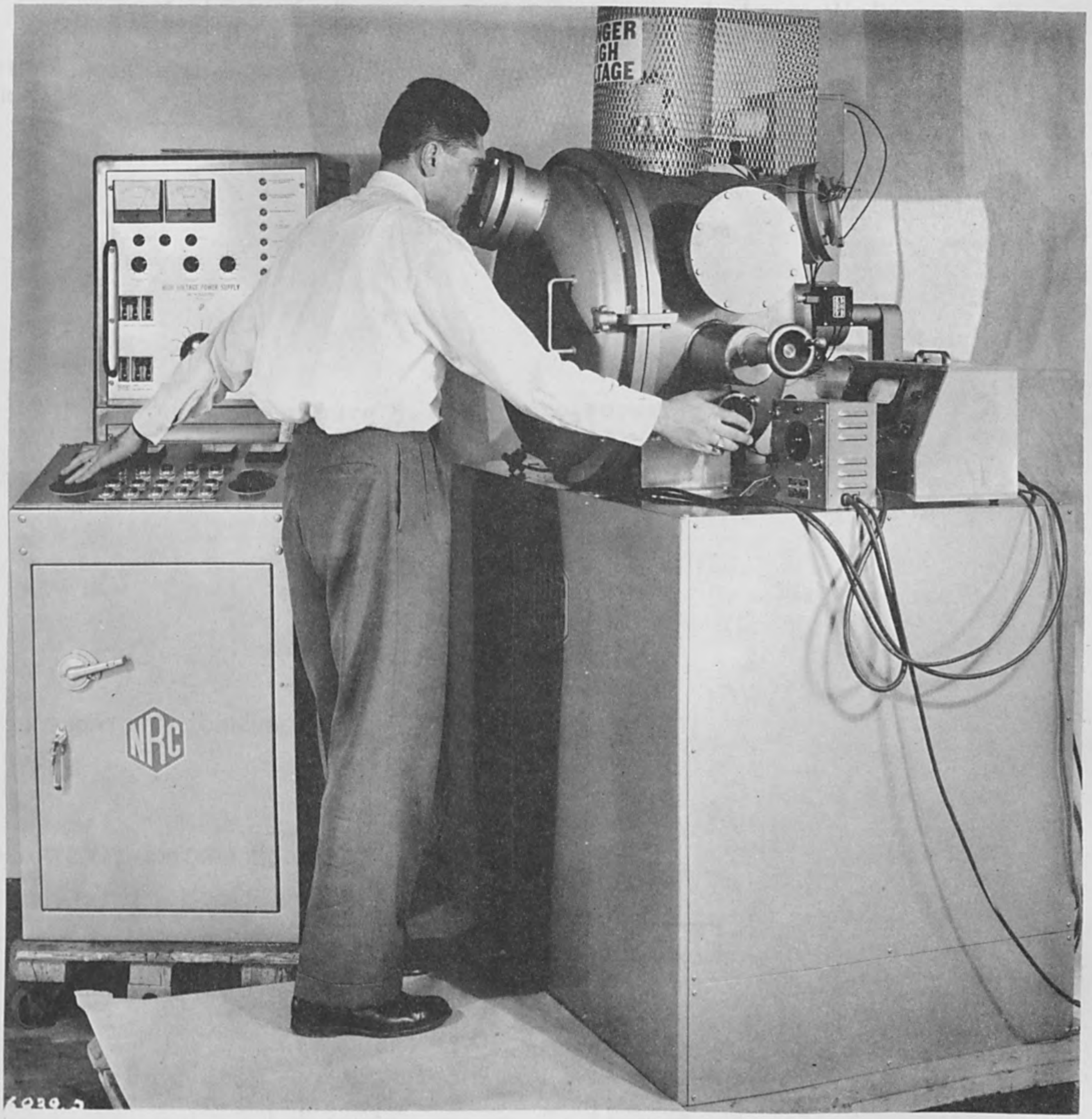


Figure 2

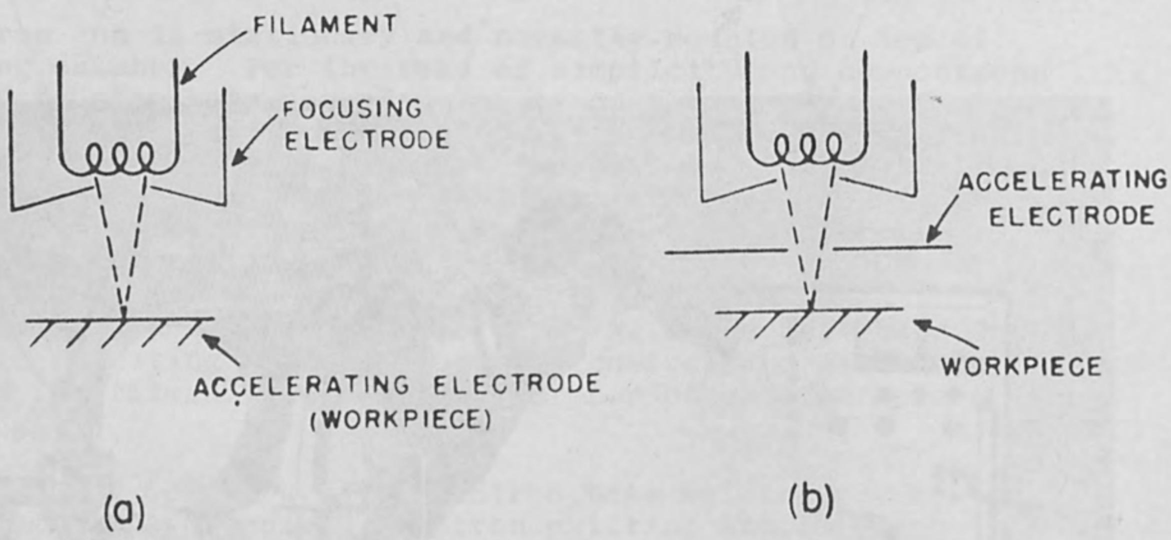


FIGURE 3

SIMPLE ELECTRON GUN CONFIGURATIONS

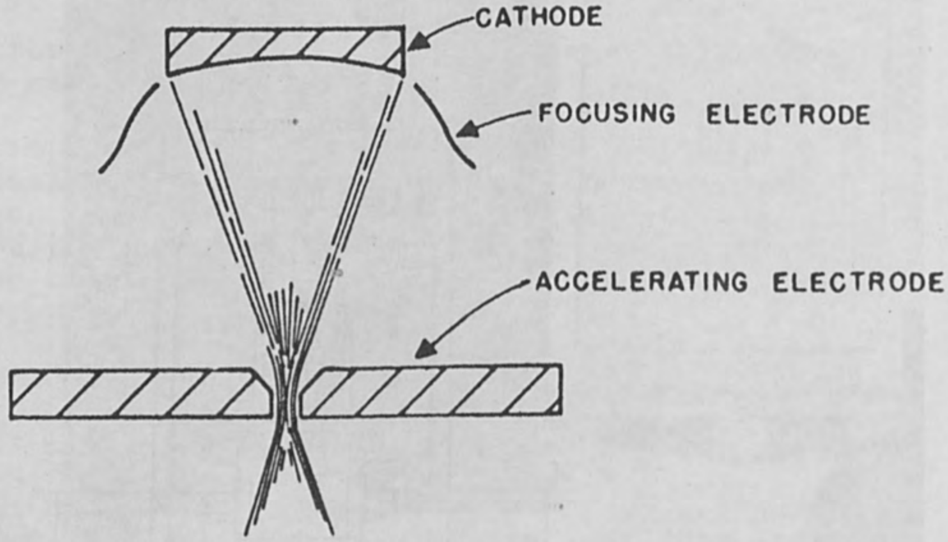


FIG. 4 GUN WITH SPHERICAL CATHODE

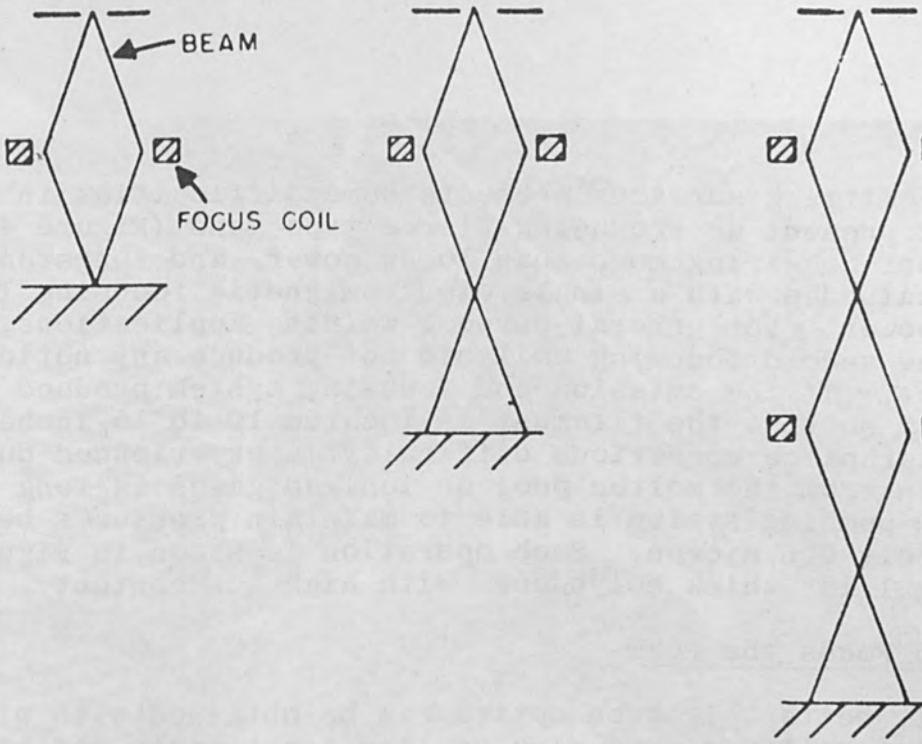


Figure 5. Magnetic Focusing Systems

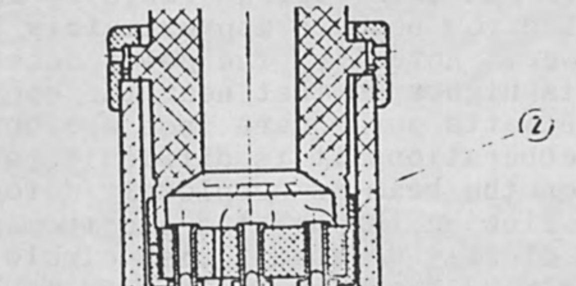


Figure 6

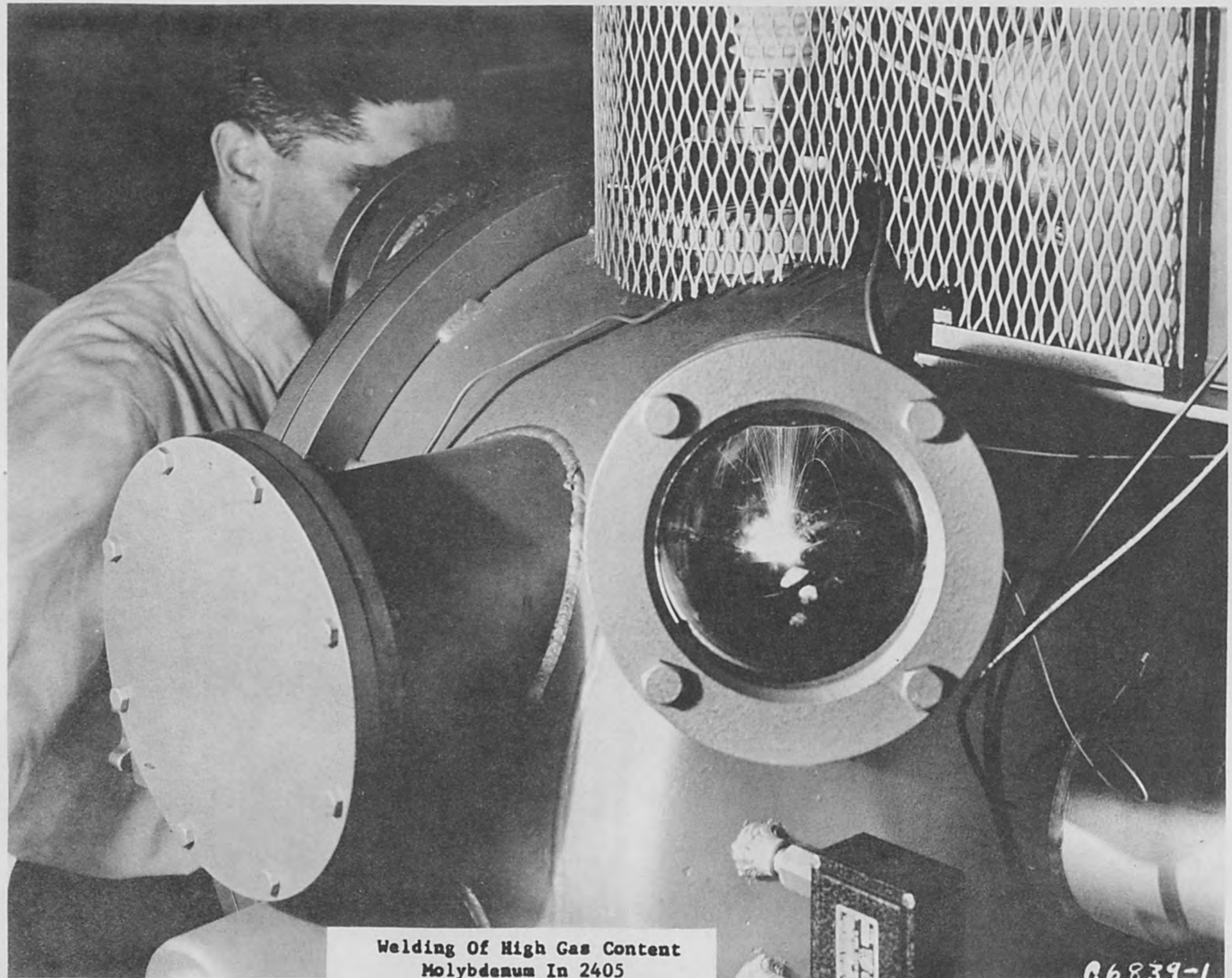
spherical emitting surfaces presents some difficulties in small sizes. At present we are using Pierce type guns (Figure 4) for applications requiring more than 10 kw power, and tungsten filament cathodes with a single electromagnetic focusing lens at lower power. For general purpose welding applications, addition of the second focusing coil did not produce any noticeable improvement. If the emission and focusing system produce a narrow beam so that the filament is located 10 to 15 inches from the workpiece no serious difficulty is experienced due to evaporation from the molten pool or ionized gases as long as the vacuum pumping system is able to maintain pressures below approximately 0.5 micron. Such operation is shown in Figure 7 in welding 1/16" thick molybdenum with high gas content.

Ability to Focus the Beam

In general, better electron optics can be obtained with higher accelerating voltages producing smaller focal spots and higher power densities. In view of this we normally weld at the highest available voltage so that our experience is in the range of 15 to 25 kv. In this voltage range it is relatively easy to focus the electron beam to approximately 1/16" diameter spot at a few kw power. Actually, the power density in the center of the beam is higher so that near the center of the spot several million watts per square inch are obtained. Due to the presence of abberations it is difficult to define the beam precisely. When the beam is completely defocused (i.e., there is no current flowing through the electromagnetic lens), it will appear as a clearly defined bluish circle on a piece of metal approximately 2" diameter at 3 to 5" working distance from the lens. As the current in the lens is slowly increased this spot decreases to about 1/8" diameter, still remaining a uniform and clearly outlined circle. Further focusing produces a very bright spot in the center (from 0.010" to 0.080" diameter, depending on power level) and a faint halo formation around the spot. This halo could be removed by beam limiting apertures but, again, for reasons of simplicity such apertures were omitted.

One simple way to estimate the percentage of beam power delivered to a desired spot size is to pass the beam through a hole in an insulated and shielded plate and measure the amount of current picked up on the plate by an ammeter placed between the plate and ground. In this way it can be said that 90% or 95% of beam energy is delivered to a certain area.

It should be noted that the molten pool formed on the surface of the workpiece can be smaller or larger than the beam diameter itself. This depends on the total power input, power density and thermal conductivity of the material. One way to judge the quality of the equipment is to compare the results with the



Welding Of High Gas Content Molybdenum In 2405
Figure 7

reports of other investigators. The equipment of French, German and domestic origin have been described in several American publications. It would be interesting to look at a few other recent references. N. F. Eaton [4] described a welder (20 kv, 100 ma) from Britain which is somewhat similar to the French equipment [5]. It is reported that a molten pool on flat plates below about 2 mm (0.080") could not be obtained. In comparison, the 5 kw gun we normally use can produce a molten pool on stainless steel plates of less than 1 mm diameter. When the cathode and anode apertures are reduced so that the maximum emission is limited to about 30 ma, the beam can produce clearly outlined lines as narrow as 0.003" with the workpiece moving at about 6 ipm.

Theoretical heat transfer calculations can also be used to evaluate the results obtained at various voltages, currents and welding speeds. Temperature distribution in a workpiece due to a small moving heat source on its surface have been calculated by Jaeger [6]. The maximum temperature at the center of a stationary circular heat source is shown to be

$$q\,r/k$$

where q is heat supplied per unit time per unit area, r is radius of the heat source and k is thermal conductivity of the work. However, the variation of conductivity with temperature and the phenomenon of deep penetration associated with some electron beam welding equipment (which cannot be due to surface heating) complicate the heat transfer problem.

It is interesting to note that Jaeger's calculation indicate that the maximum temperature and the average temperature over the area of the spot do not change significantly when the spot is assumed to be circular or square shaped, or when the energy delivered at the surface is assumed to be uniformly distributed or increasing toward the center according to a parabolic distribution.

<u>Depth of Penetration</u>

Until about a month ago all low voltage electron beam welders were reported to produce depth to width ratios in the fusion zone of approximately 1:1. (The depth of penetration should not be confused with the depth to width ratio. Any penetration can be obtained with the low voltage guns as long as the equipment is capable of producing sufficiently high power.) Data reported by Russian investigators [7] showing depth and width of welds associated with various welding parameters is shown in Figure 8 for titanium. The ordinates of all graphs are depths and widths of the weld in mm; the lower curves are for the depth in each case. The upper left plot shows variation with beam current at 15 kv and 3.3 ipm. The upper right plot shows variation with voltage at 80 ma and 3.3 ipm. The lower left plot represents dependence on welding speed in meters per hour for 17 kv and 100 ma.

The final plot shows the effect of varying the distance (mm) from the emitting filament to the focusing electrode aperture at 17 kv, 50 ma and 3.3 ipm. This effect is due to better focusing obtained so that the depth to width ratio improves from a very low value of 0.07 to about 0.35. To obtain the same emission with a larger distance from the aperture the filament temperature must be raised which will have an adverse effect on filament life.

It would be useful, also, to plot the variation of power with welding speed at constant value of penetration. This function is not linear because at high power and speed the material cannot diffuse the heat quickly, which is particularly true in the case of metals having low conductivity such as stainless steel or titanium.

Compared to data from Figure 8 and reports on other low voltage welders, we were fortunate to obtain depth to width ratios as high as 4:1 in stainless steel at voltages not higher than 25 kv and about 3.5 kw power. Examples of photomicrographs of weld cross sections obtained in our laboratory are shown in Figure 9 and Figure 10. There is reason to believe that considerably higher depth to width ratios can be obtained without going to higher voltages. It should be noted here that these results were obtained with a power supply having a 4% ripple which, at 25 kv, means a change of 1000 volts. If the accelerating potential is intentionally changed by 1000 volts after focusing the beam at a given voltage, a very noticeable change in focusing can be observed. Reducing the ripple should improve the spot size. In the last photomicrograph (250X) showing the boundary of the fusion zone, the disturbed small grain area represents the welded metal. It appears to be similar to structures often obtained in a fast chilled cast material.

Electron Gun Design

Judging from the wide variety of gun designs presently used, electron beam welding is still in its infancy despite considerable progress achieved during the last two years. Design of electron guns for metallurgical applications presents problems not normally encountered in vacuum tube work. The following example may illustrate the progress made. Figure 11 shows a gun reported in May 1959 [8]. It could produce 1 kw power (25 kv, 40 ma), is one foot in diameter and two feet high and both the cathode and the anode appear to be water cooled. The gun in

Figure 6, reported by the same authors in August 1959 [3], is only one third the size of the former but is said to be capable of twice the voltage and ten times greater current. However, the filament life is reported to be only five to six hours.

The gun used in our equipment is about 2.5" diameter mounted on a 4" OD flange and is 4" long including the high voltage insulator. There are no glass, organic or similar materials in its structure. The filament can be replaced without disassembling the enclosure in order not to disturb the basic alignment of components. The cathode focusing electrode and the anode plate are adjustable and are aligned in assembly. The filament life is at least several weeks and can be much longer if used at low power. The gun is constructed in such a way that all high voltage and high current lead wires are completely insulated at the vacuum side. This helps to eliminate high voltage discharges (arcing) which would make satisfactory operation impossible.

Our welder is equipped with a separate diffusion pump at the electron gun. This pump can be isolated from the rest of the system by a valve. Operation with and without this pump did not demonstrate any significant difference. It appears to help only at higher power operation with high gas content materials when the pressure in the main chamber rose close to 0.5 micron. If the welder has a sufficiently large pumping system, and if the shield designed to protect the gun from evaporated material has sufficiently large pump-out apertures, the separate pump near the gun may be omitted. In the future "standard" welders a recently developed 6" diffusion pump will be used which has almost twice the pumping speed of the conventional 6" pumps. The increased capacity should compensate any need for a separate pumping system. Working with normal metals in relatively small welding chambers a conventional 6" diffusion pump is sufficient for about 4 kw welding power and the increased capacity pump for about 6 kw. Above that, generally a 10" diffusion pump should be used assuming the design of the chamber, the pumping system, the seals, tables and fixtures is consistent with good high vacuum practice.

Operating Pressure

No systematic work concerning the effect of operating pressure on the welding process was performed in our laboratory. The welder has been used at pressures ranging from 2×10^{-5} to 7×10^{-4} mm Hg, and no noticeable difference has been observed except, perhaps, the fact that the beam becomes visible at higher pressures. The effect of pressure on electron beam focusing characteristics has been discussed, for example, by Wadia [9]. Graphs are given showing beam divergence at pressures from perfect vacuum to full space charge neutralization for several beam angles and perveances.

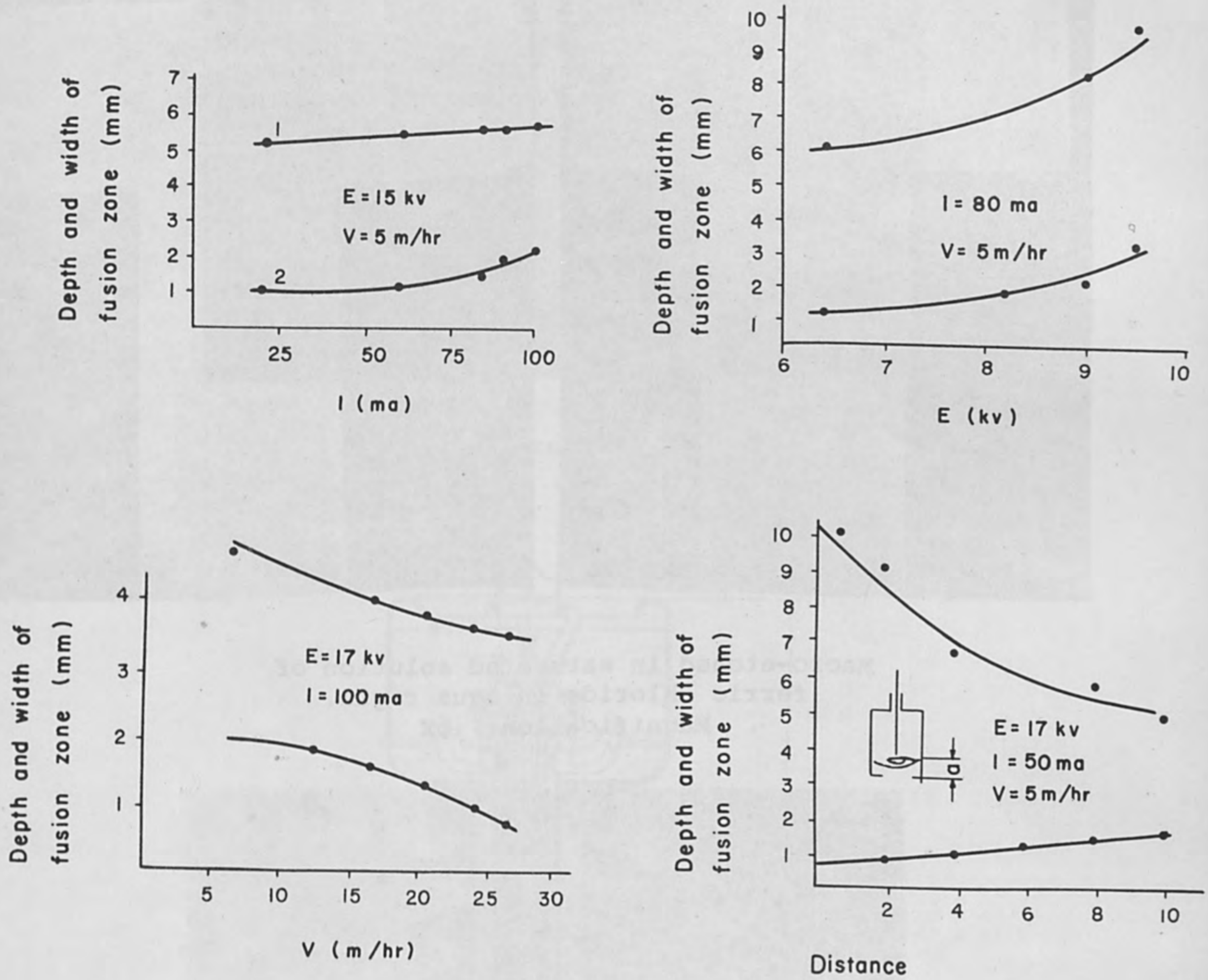
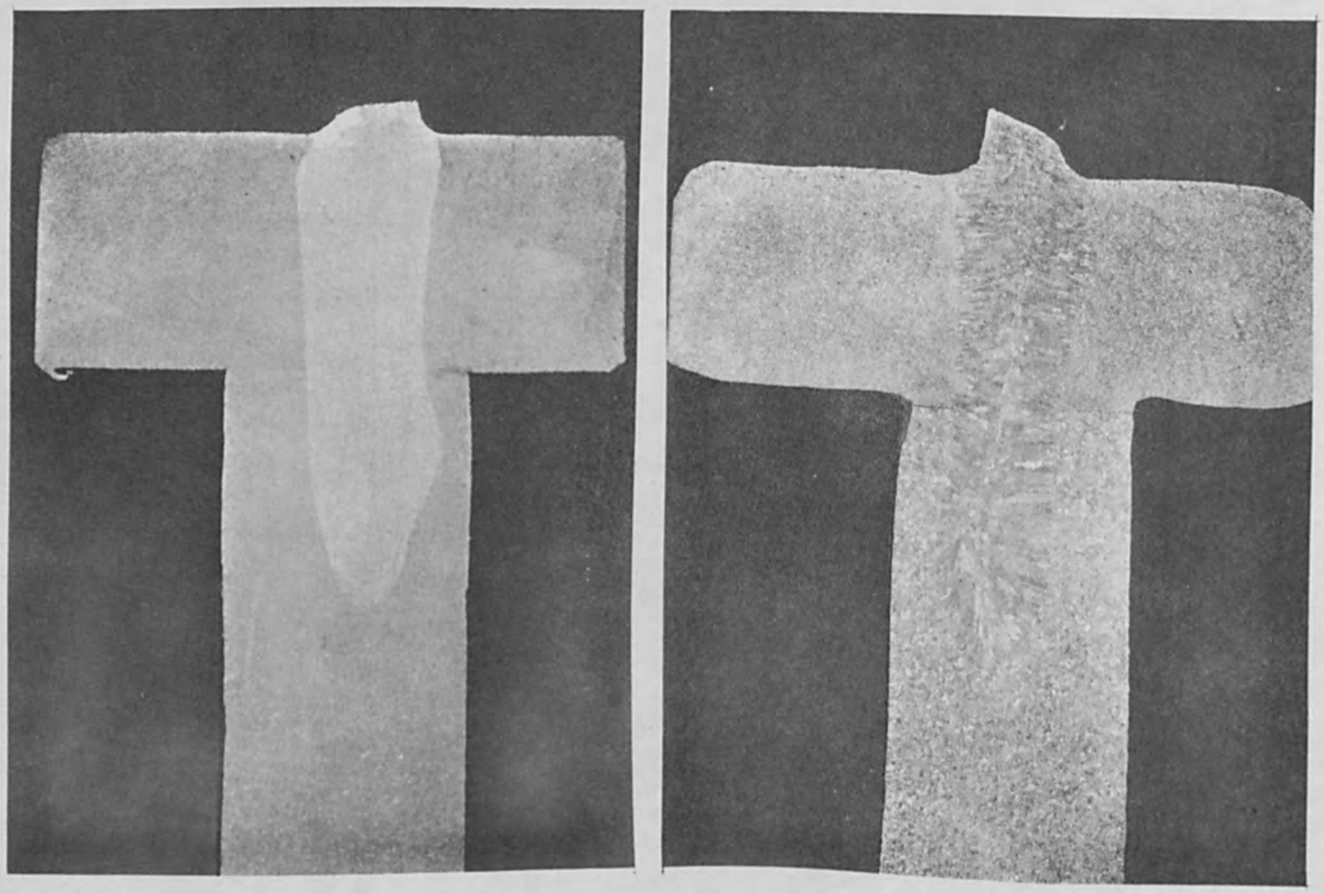


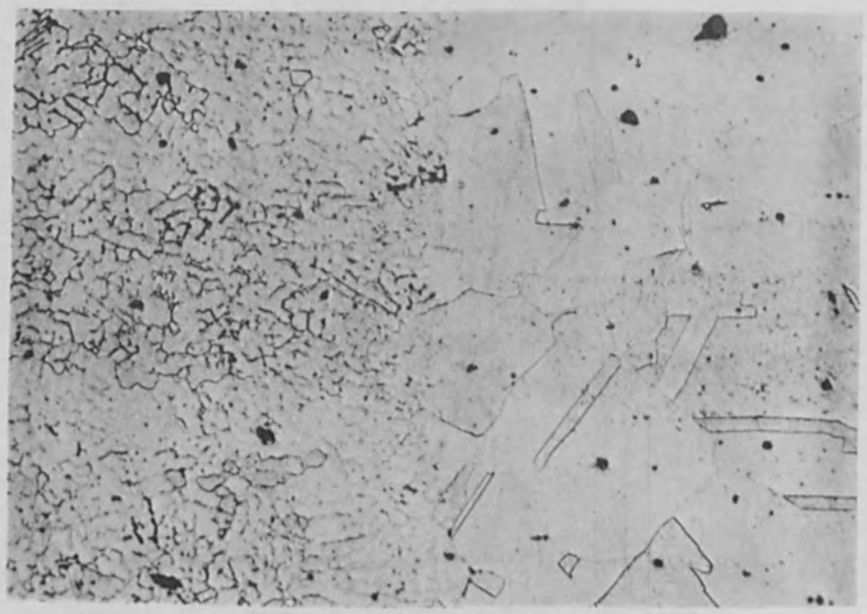
Figure 8

Penetration data dependence on current, voltage, speed of travel and gun optics. Upper line in each figure represents width, the lower line depth. (Ref. 7)

PHOTOMICROGRAPHS OF TYPE 347 STAINLESS STEEL WELDED IN ELECTRON BEAM WELDER



Macro-etched in saturated solution of
ferric chloride in aqua regia.
Magnification: 6X



Micro-etched electrotytically in 10%
oxalic acid solution.
Magnification: 250X
Fig. 9

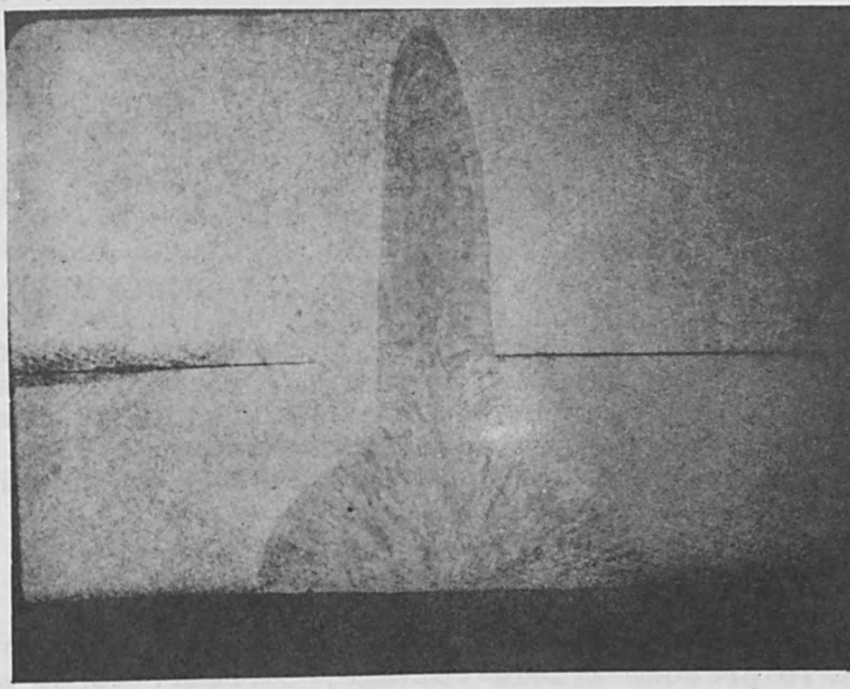


Figure 10

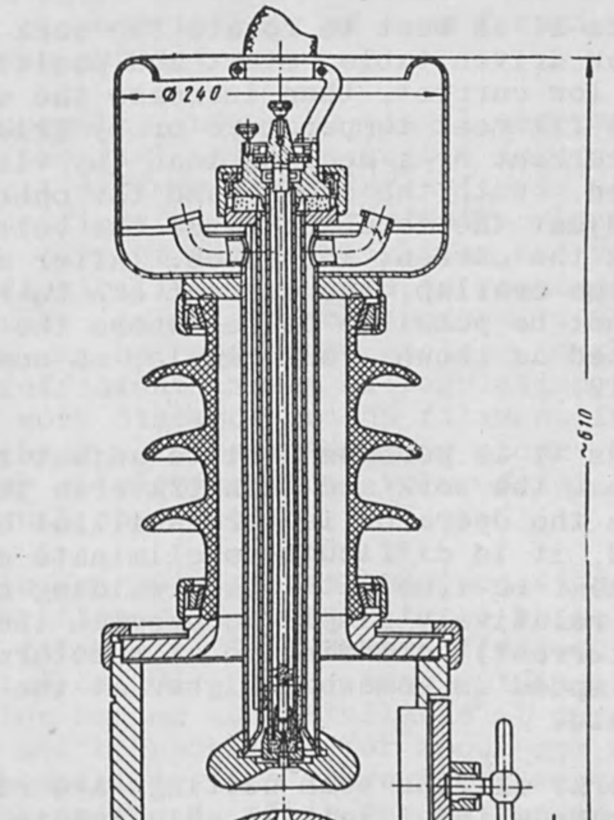


Figure 11

We normally use the welder at 0.1 or 0.2 micron simply because of impatience to wait until the pressure is reduced further. When the equipment was new the chamber could be evacuated to 0.1 micron in about 3 minutes. After six months of use (several hours almost every day), it took two or three times longer to obtain the same pressure, apparently due to evaporated metal deposited on the chamber walls which adsorbs atmospheric gases and water vapor.

Welding Technique

There are several ways to accomplish a weld with the present equipment. To produce a weld voltage, current, focus and motion of the work must be adjusted. Accelerating voltage and the focusing lens current are associated, since a stronger magnetic field is necessary to deflect faster electrons. On the other hand, the beam current and the voltage are not independent unless the power supply is load regulated.

For circular welds it is best to rotate the work at a selected speed with a motor driven table, start and position the beam at full voltage but low current, then increase the welding current by increasing the filament temperature or by grid control until a predetermined current or a desired bead (by visual observation) are obtained. With the other hand the operator can simultaneously adjust the focusing since the voltage will generally drop as the current increases. After a complete revolution and some overlap, the current can be reduced slowly so that it will not be possible to see where the weld was started or finished as shown, for example, on some of the welded parts in Figure 12.

For straight welds it is perhaps best to adjust the beam on a starting piece near the work and then traverse the part under the beam. Unless the operator is very skillful or special fixtures are used, it is difficult to eliminate end effects entirely, which must be true with other welding methods. If necessary, it is relatively simple to program the work motion (or the welding current) according to a predetermined schedule so that the work speed is somewhat higher at the beginning and the end of the weld.

For repetitive work, all the beam settings are reproducible and the weld can be made without initial adjustments by starting the voltage and the work motion simultaneously or a few seconds apart.

Difficulties

Several subjects appear to be worth mentioning here. First, it should be noted that according to our experience well designed fixtures are just as important in electron beam welding as they are in many other welding processes. It is, for example, easy to make a butt weld in 0.010" thick material with simple clamping bars, but it is not easy to butt weld foil less than 0.005" thick without a precision fixture. In general, it is profitable to spend the time and money to design appropriate holding and perhaps chilling devices when attempting difficult welds. The equipment should not be expected in every case to produce satisfactory results with a first try on a single sample.

Some materials such as aluminum and magnesium are more difficult to handle than others due to high vapor pressure, strongly adhering surface oxides or other properties. However, the difficulties mentioned above are present in other welding methods, also.

More important in the writer's opinion are properties associated specifically with electron beam welding. The two most noticeable difficulties are reproducibility of beam focusing and occasional instability of beam current.

The focusing is normally judged by visual observation, i.e., the operator adjusts the dial until he gets a desired weld bead appearance or until maximum light intensity is obtained at the weld spot. The settings in present electron beam welding equipment for voltage, current and focalization are very flexible, and due to this flexibility more care is required to obtain optimum performance. As pointed out before, for repetitive work the settings can be reproduced as long as the various power supplies have a sufficient amount of regulation. However, when the work, gun to work distance or the filament in the gun are changed, slight changes in beam focusing occur. We find a magnifying binocular or a telemicroscope very useful in establishing best focus by visual observation.

The instability in emission occurs only occasionally and only at high power operation. It appears to be associated with the condition of the filament. The current fluctuations, when they appear, are about 5 or 10%. Once, when welding heavy zircalloy pieces the emission became uncontrollable at current above 50 ma. The filament had not been changed for about six weeks and when examined showed a small section where the diameter was approximately half of the original. This may be due to a fault in the tungsten wire, but more likely it is caused by positive ion bombardment. When the filament was replaced the emission instability disappeared, so it seems to be a good practice to change the filament at regular intervals.

None of the mentioned difficulties appear to be insurmountable. No doubt, as the equipment is further developed and improved, all these conditions can be minimized or eliminated.

Materials and Samples

Many different metals and alloys have been welded in our machine. The metallurgical and mechanical properties of the welds were not investigated systematically. In general, good sound joints were obtained with tantalum, tantalum-tungsten alloys (90-10), columbium, titanium, stainless steel, nickel, copper, beryllium copper and many steel alloys. Welding of tungsten, molybdenum and aluminum may be considered only partially successful due, in all cases, to the nature of the material rather than the process. Results with magnesium (only once tried) were poor.

Most of these welds were simple butt welds made as samples to demonstrate the capability of the machine. Some of the more unusual applications are described briefly in the following section.

Figure 13a shows specimens of nickel and stainless steel (in center) treated under the electron beam to purify the surface. This method produces a vacuum melted top layer eliminating the necessity to vacuum melt the whole material. The purpose was to produce a highly lapped surface without any pits resulting from possible voids in untreated material.

Figure 13b shows another nickel specimen with aluminum oxide deposited on its surface. The aluminum oxide layer was glazed by traversing under the beam at low power without melting the nickel substrate despite its considerably lower melting point.

Figure 13c shows plates of columbium welded together around all four edges. Usually, when this is attempted by arc welding the final edge is difficult to seal because of the pressure of heated air trapped between the plates.

Two different configurations of copper cylinders with titanium end plugs are shown in Figure 14 (top). Judging from the appearance of the cross section, the joint looks more like a braze than a weld. At the bottom of the same figure is a rolled up 0.010" thick tungsten tube welded along the seam. When such tubes are twisted they often fracture along 45° lines; however, the fracture appears to be initiated from the welded areas. If the weld does not have 100% penetration the fracture occurs along the seam.

The example shown in Figure 15 approaches production type work. It was done for our own manufacturing department after some difficulty was experienced with arc welding the thin nickel iron flanges of the high temperature, high vacuum feed throughs to

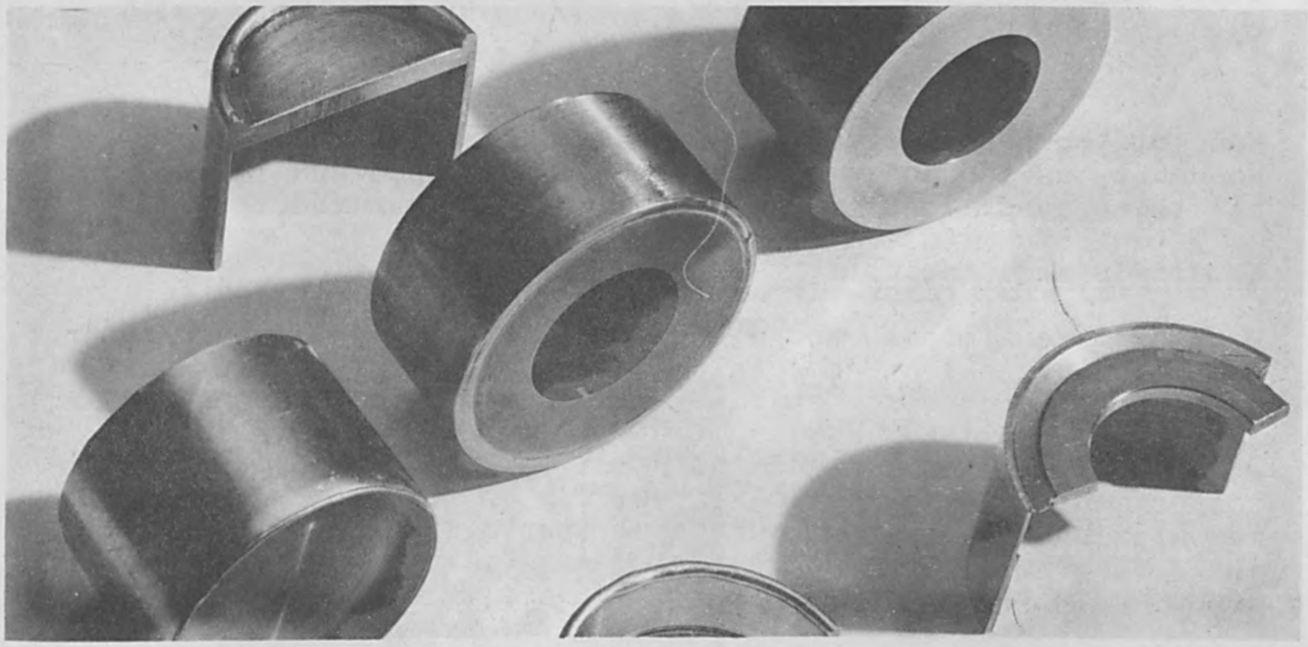


Figure 12

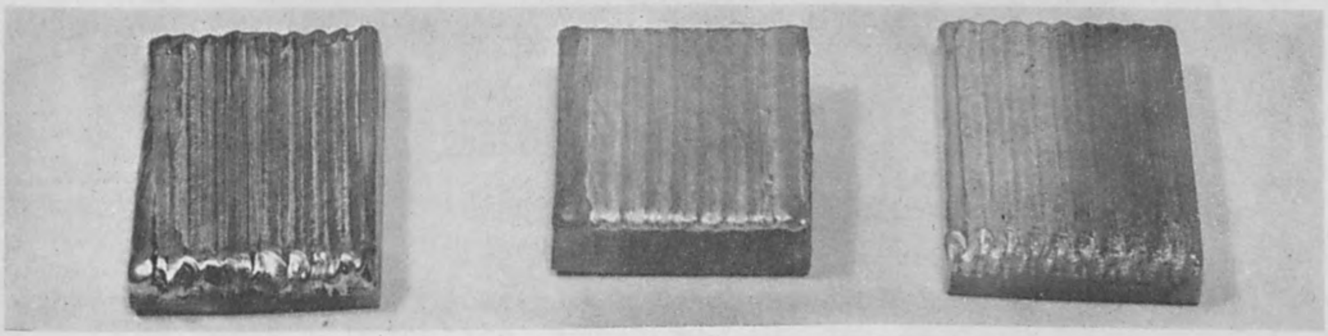


Figure 13A

Figure 13B

Figure 13C

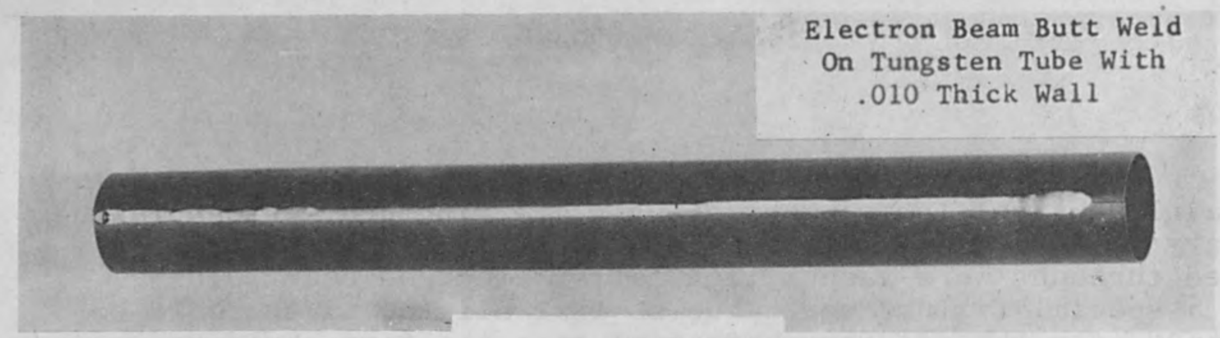


Figure 14A

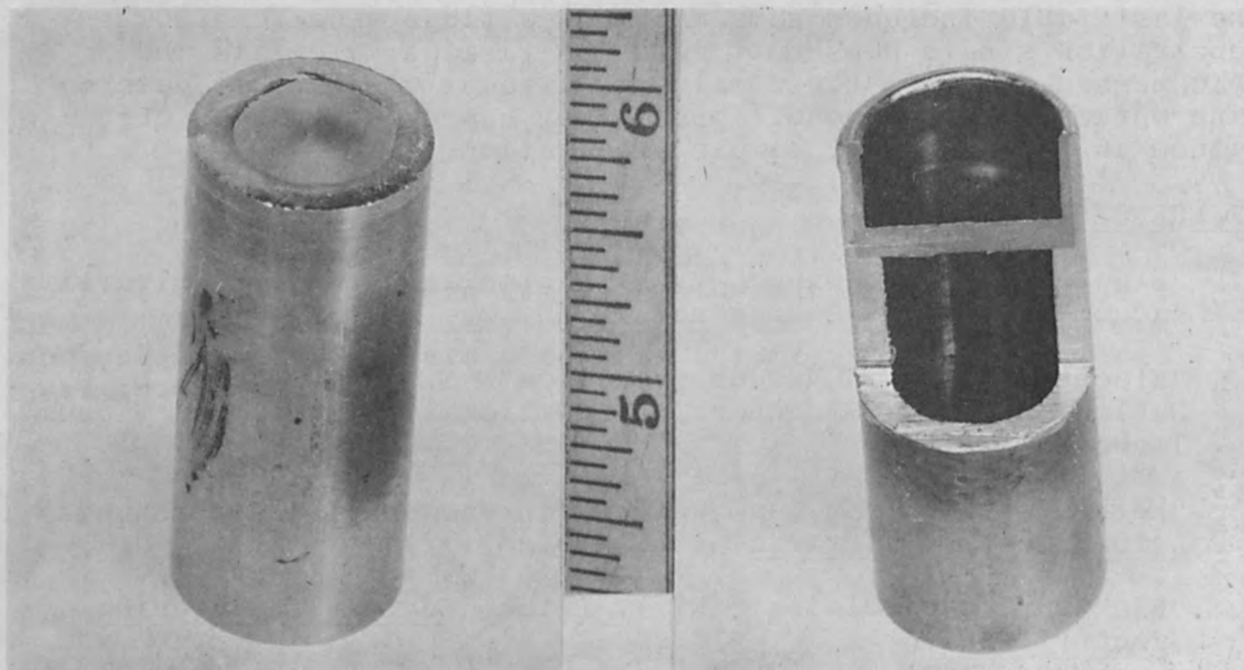


Figure 14B

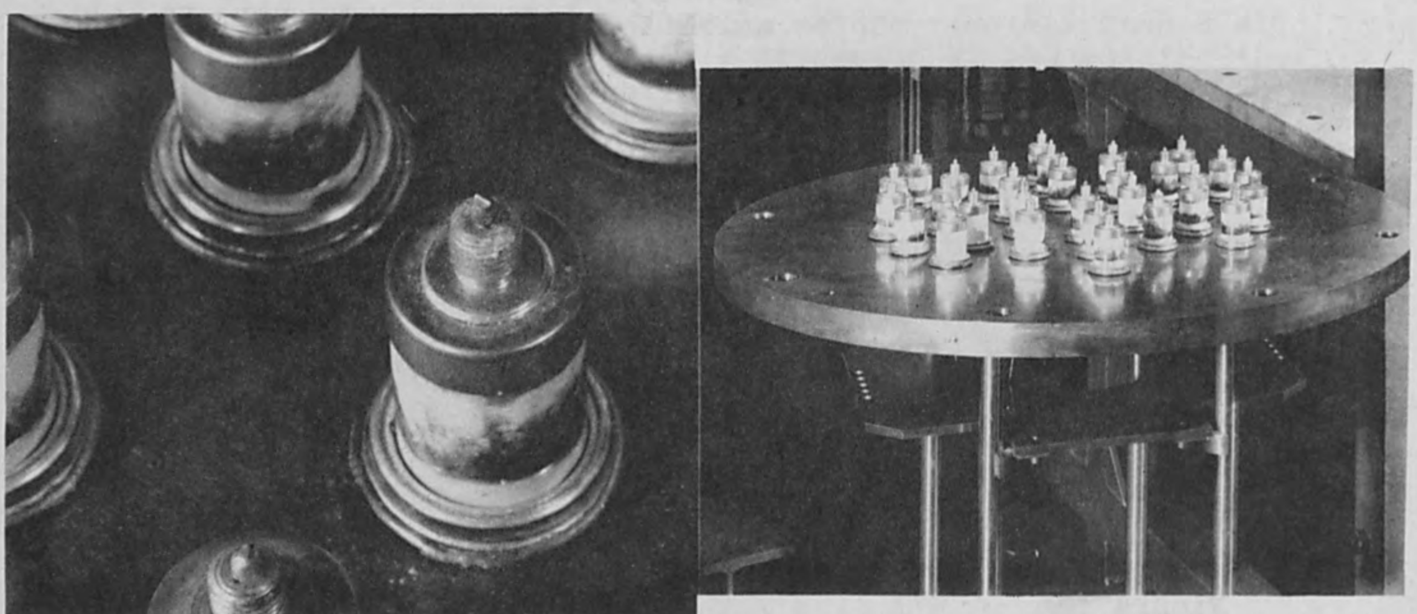


Figure 15

stainless steel tubes. These tubes are, in turn, welded to the heavy flange. The work was done in about 8 hours and all 30 feed throughs were vacuum tight after electron beam welding. If a special fixture were made so that all the parts could be placed into the welding chamber at once the time could be shortened to one or one and one-half hours.

The last table includes some machine settings used for 100% penetration single pass butt welds on various materials and thicknesses. In all these welds no attempt was made to determine optimum welding conditions. They represent results obtained in the course of sample preparation.

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TABLE I. Some machine settings used for 100% penetration single pass butt welds with various materials and thicknesses.

Material	Thickness in.	Voltage kv	Current ma	Speed ipm	Depth/ Width Ratio
Tungsten	0.020	20	50	13	
		20	60	6.25	
	0.040	20	100	9	1:3
	0.060	20	170	9	1:2
	0.060	20	140	11.5	1:2
Tantalum-tungsten 90-10	1/16	20	90	11.5	1:2
Tantalum	0.040	14.5	40	6	
Molybdenum	1/16	15	70	6	1:1
	1/16	20	70	8	1:1
	0.042	20	50		1:2
Zirconium	1/8	20	30	6	1:1
Stainless steel	1/16	20	50	13	
	1/16	20	30	7	
	1/8	20	60	5	
H-11 Steel	3/32	20	45	6	1:1
17-7 PH	0.102	20	45	6	1:2
VCA-120	3/32	22	40		1:1
	3/32	24	35		1:1
Rene #40	0.045	15	25	12	
Beta Titanium	0.069	15	40	11.5	

NOTE: Some of the above welds had more than 100% penetration. Where depth to width ratios are omitted they were not recorded.

Panel Discussion on Electron Beam Welding

Panel Chairman

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Panel Members

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Hartbower

I would like to preface the panel discussion with a few remarks about the need for electron-beam welding.

Last year, several Materials Advisory Board Committees, engaged in a continuing review of Department of Defense Materials Research and Development Programs, met at Dartmouth. It was pointed out that the improvement of present weapons systems and the development of new weapons systems is predicated largely upon advancements in the materials field - and that the ability to produce new materials in commercial quantities and to fabricate them economically into useful end-item hardware is equally important. Economics dictates weld fabrication rather than contour machining, flow turning, etc.

In the last few years, it has been generally recognized that new and improved metals-joining processes are needed. For example, the Materials Advisory Board Committee for Development of Manufacturing Processes for Aircraft Materials reported that there is an important need for fundamental welding research on new welding processes. Electron-beam welding was one of the new processes specifically mentioned.

Earlier, the Materials Advisory Board Panel on the Joining of Metals critically reviewed the Department of Defense Materials Research and Development programs on welding and brazing; one conclusion was that the welding industry cannot hope to meet the future needs outlined by the military services unless new fundamental knowledge in the sciences relating to welding becomes available. And one of the most serious criticisms of the research programs relating to welding concerned the almost complete lack of activity to develop basically new methods for welding metals. These observations were made in 1957. Electron-beam welding is one of the new processes now available to industry.

Other relatively new processes now available for industrial application include ultrasonic welding, diffusion bonding, explosive welding, and electroslag welding.

The great potential in electron-beam welding lies in the fact that in certain important respects the process is uniquely suited to the joining of some of the difficult-to-weld metals such as molybdenum, certain titanium-base alloys and cold-worked stainless steel.

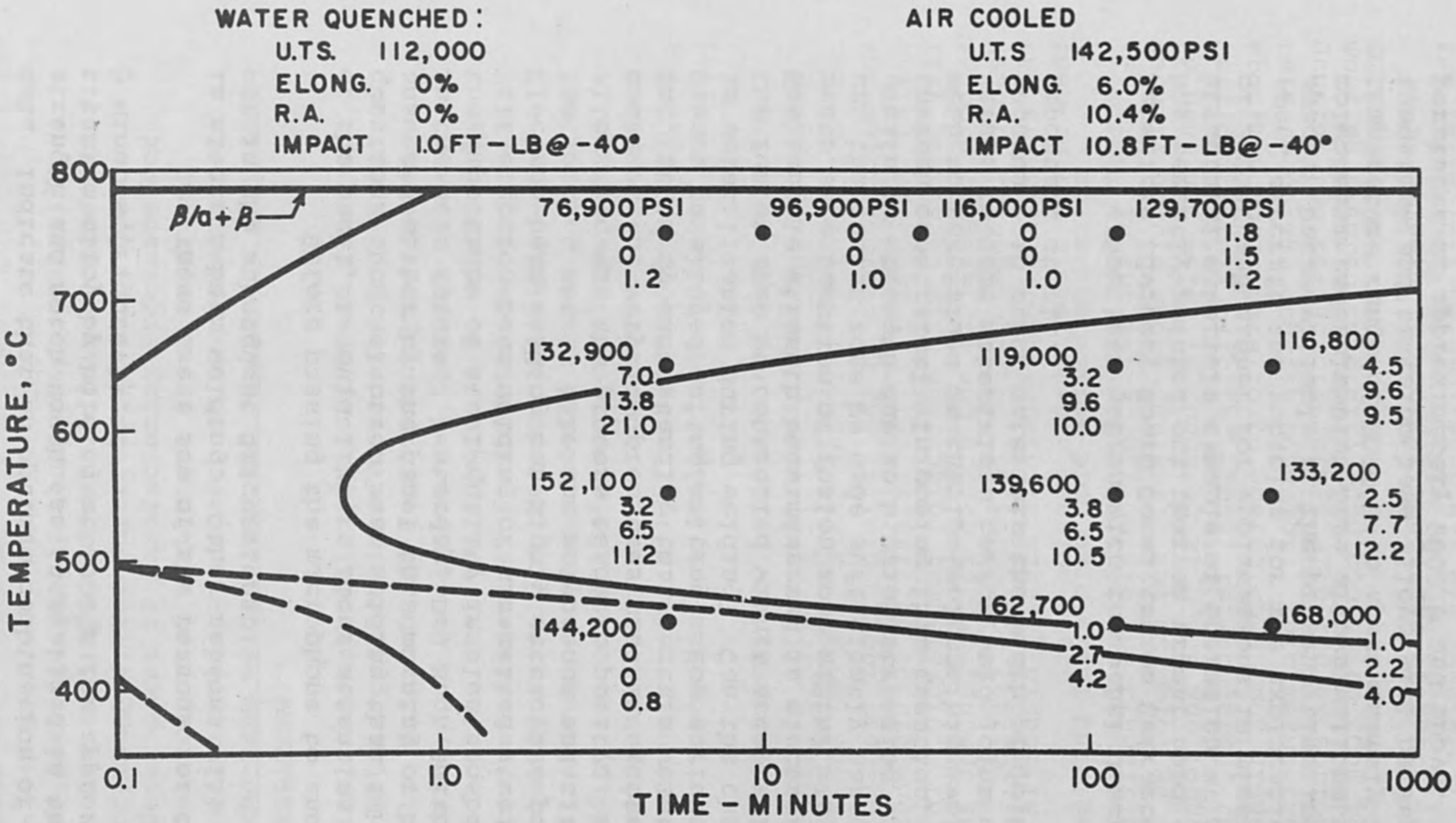
For welding fully-hard cold-worked stainless steel, its success will depend upon achieving a very narrow fusion zone and a very narrow heat-affected zone. If the fusion zone is sufficiently narrow, so that when transversely loaded, the weld will be subjected to a biaxial stress field, it should be possible to approach 100% joint efficiency.

In the case of certain difficult-to-weld titanium alloys (e.g., titanium alloyed with 7% manganese) welding with preheat and postheat would be highly beneficial but highly impractical when welding in open air. The use of preheat and postheat while electron-beam welding in an evacuated chamber should be quite practical. Isothermal transformation data indicate that an optimum combination of tensile strength and notch toughness is realized in the 5% Mn titanium alloy by holding at 1000°F for approximately 5 minutes,(Figure 1).

These are a few of the reasons for our interest in electron-beam welding. Other reasons will be brought out in the subsequent discussions.

Before passing the microphone to another member of the panel, I would like to focus attention on a few questions about electron-beam welding that I hope will be answered either by the panel this morning or by research in the near future. Yesterday, Dr. Hugh Smith emphasized the importance of steel quality in electron-beam melting. Will electron-beam welding of air-melted steel be a problem? Electron-beam welding has highly attractive possibilities for joining metals like the molybdenum and titanium-base alloys because the process tends to purity. However, because of the very low pressures used in electron-beam melting, it is my understanding that certain volatile elements cannot be alloyed during melting. How serious a problem is volatilization during welding? Can the chemistry of the fusion zone be controlled within acceptable limits? Has tensile strength been measured in electron-beam weldments as a function of fusion zone width? In other words, can the fusion zone be made sufficiently narrow to realize a gain in strength due to biaxial stressing introduced through constraint? In posing this question, I do not mean to take sides in the low-voltage high-voltage controversy; in some materials a narrow weld joint may be advantageous - in other materials the width of joint may not be important at all.

Now lets get on with the panel discussion. The Materials Advisory Board Committee on Refractory Metals has recently pointed out that an urgent need exists for structural materials capable of operation at temperatures of 2000°F and higher for applications in missiles, high-speed aircraft and vehicles for the exploration of outer space. Data available at the present time indicates that molybdenum-and columbium-base alloys will be useful in the temperature range of 2000°F to approximately 2800°F, while tungsten- and tantalum-base alloys will be superior at temperatures of approximately 2600°F and above. The principal difficulties in joining the refractory metals are related



TTT-DIAGRAM, AND V-NOTCH CHARPY IMPACT FOR A Ti-7% Mn ALLOY
(7.10 Mn .07 C .073 O .0064 H .030 N)

(GOLDENSTEIN AND ROSTOKER)

FIGURE 1

to their inherent ductile-to-brittle transition at relatively high temperatures and their high chemical reactivity with gaseous non-metallics, and the marked effect of these impurities on mechanical properties.

The possibility of electron-beam welding is clearly indicated. The Materials Advisory Board Panel recommended that research be done leading to the development of better joining processes; electron-beam welding was specifically mentioned.

Bill (Platte), you have been fusion welding molybdenum base alloys in the Westinghouse Research Laboratories for several years, - and I understand more recently you have done some electron-beam-welding. Would you care to comment on the use of the electron-beam-welding process for joining refractory metals?

Platte

Before discussing the electron beam welding of refractory metals, it will be wise to have some background information on the properties of these materials. The refractory metals W, Ta, Cb, Mo and Cr have several properties in common; they are all body-centered cubic and with the exception of Ta have a high ductile-to-brittle transition temperature. The ductile-to-brittle transition phenomena has been observed for many years in steel and was one of the major factors in the failure of our transport ships during World War II. The transition occurs when the ductility decreases with decreasing temperature. This property is both temperature and strain rate dependent and, as a result, is dependent on the method of testing. For example, the transition temperature is usually higher in impact than in the slower strain tension tests.

In the refractory metals the transition temperature usually occurs above ambient. For example, we attempted to bend arc welds in tungsten at 600°F and found that they were completely brittle. Thus, for tungsten, the test specimen would have to be heated to a much higher temperature to obtain ductile behavior. This means that in general the refractory metals with the exception of Ta must be treated carefully when cooled to room temperature.

There is another important property common to the refractory metals; they all are moderately good getters.

That is, they have an affinity for oxygen and nitrogen which is sufficiently great to cause difficulty during welding. This means that they must be protected either by an inert gas or, as in the case of electron beam welding, by a vacuum. In addition, the oxides of these metals are highly volatile. Molybdenum oxide is perhaps the worst offender. The porosity shown in a previous paper was probably due to oxide boiling in the weld metal. The influence of oxygen on molybdenum weld metal is shown in Figure 1. While alternate causes of porosity are possible, weldments can be very porous if the oxygen content is high.

All the refractory metals have high melting points and high vapor pressures at temperatures considerably below their melting point. This combination of properties could cause difficulties when welding under vacuum with an electron beam. Heavy metal vapor deposits will occur and cathode damage may also result if the metal vapor or evolved gas molecules are positively ionized by the electron beam.

The thermal expansion and conductivity properties of the refractory metals must also be considered. These values are shown in Table I.

Table I

Metal	Thermal Expansion Coefficient	Thermal Conductivity Coefficient
Mo	4.9×10^{-6} in/in/°C	.35 cal/cm^2/cm/°C
W	4.3×10^{-6}	.48
Cb	7.1×10^{-6}	.13
Ta	6.5×10^{-6}	.13
Cr	6.2×10^{-6}	.16

Molybdenum, for example, has a moderately high thermal expansion and thermal conductivity. The combination of these two properties with the ductile-to-brittle transition characteristics of this material can cause cracking when welds are cooled to room temperature. These cracks occur because of the very high residual stress

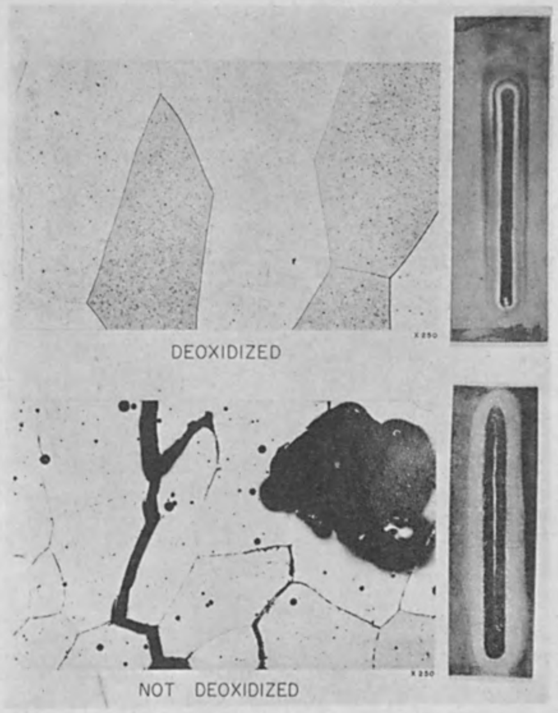


Figure 1

Molybdenum welds (electro-polished, Ferricyanide etch)

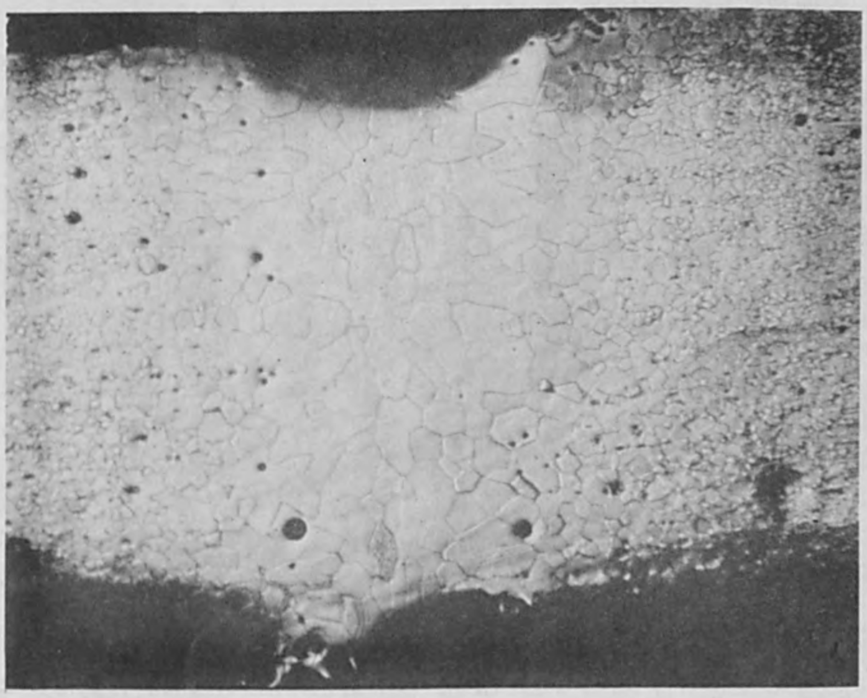


Figure 2

Electron beam weld in molybdenum with .06% Carbon (50X) pattern which has been established in and around the weld bead. Stresses as high as 100,000 psi have been observed. The residual stress and transition temperature problem in columbium is not as serious because Cb does not have as high a value for thermal conductivity as Mo.

The properties of the refractory metals discussed above are important when they are considered in relation to the characteristics of the electron beam welding process. It should be stressed that the metallurgy of the refractory metals will not be changed by using the electron beam welding process.

Let us look briefly at the characteristics of the electron beam welding process and try to relate them to the properties of the refractory metals. Since electron beams require a vacuum for their operation, the weld metal is subjected to a purifying action with respect to high vapor pressure impurities. Hence, the use of the electron beam welding process may increase the chance for porosity with a given high gas content in the metal. We have made sound TIG welds in a given heat of molybdenum, but electron beam welds in the same heat were found to be porous. See Figure 2.

The penetration characteristics of the low voltage (up to 25 KV) and high voltage (100 KV) welding equipment may determine the residual stresses found in and around the welds. The stress patterns which occur around the low voltage electron beam welds should be very similar to those found in TIG welds. The deep penetration welds made with the high voltage equipment may have residual stresses associated with them in spite of their outward appearance. Welds in a heat of molybdenum which was not especially prone to cracking when welded by the TIG process cracked when welded using the high voltage electron beam welding process. It is suspected that cracking was related to the thermal conductivity and expansion of the metal combined with the ductile-to-brittle transition temperature and the narrow molten zone due to deep penetration. Thus the deep penetration weldment, in itself, may not guarantee sound welds, and we should be cautious since the electron beam welding process is not a panacea for refractory metal welding problems.

Hartbower: Thank you, Bill. Now I would like to call on Lou Stark to tell us something about the possibilities of porosity in electron beam welding.

Stark

A chance remark, made to Carl during a tour of Mallory-Sharon Metals' electron beam melting facility, lead to the preparation of this morning's comments and results of several experimental tests. The remark was to the effect that electron beam welding might not be satisfactory for other than electron beam melted metals with respect to weld metal porosity.

Not having an electron beam welding machine, we used our electron beam melting furnace to produce simulated electron beam welds in sheets of several titanium alloys in the thickness range of 0.09 to 0.25 inch. The alloys were MST 6Al-4V, double vacuum melted; MST 8Mn first stage vacuum melted and second stage argon pressure melted; MST 4Al-3Mo-1V, double vacuum melted; MST 4Al-3Mo-1V, first stage vacuum melted and second stage argon pressure melted; and unalloyed MST 70, double vacuum melted.

On each sheet containing an electron beam weld we made a TIG weld bead. Radiographs of the welded sheets showed that all the TIG welds were sound and all the electron beam welds in double vacuum melted material were sound. The electron beam weld in pressure melted 8%Mn was very porous and the electron beam weld in pressure melted 4Al-3Mo-1V contained slight porosity.

We calculated the vapor pressures of the 8%Mn and the 4Al-3MO-1V alloys at their melting temperatures using information from "A Vapor Pressure Chart for Metals", by R. L. Loftness, NAA-SR-132, July 10, 1952 and Henry's Law $p = X\,p_o$, where p is the partial pressure of a component in solution, X is the mol fraction and p_o is the vapor pressure of the pure component. The calculated vapor pressure of the 8%Mn alloy at 1627°C was about 2290 microns of which 2250 microns were due to the partial pressure of manganese. The porosity in the 8%Mn electron beam weld could be attributed to active boiling of the molten weld metal due to the high partial pressure of manganese when exposed to the electron beam chamber atmosphere of about 0.01 microns.

The calculated vapor pressure of the 4Al-3Mo-1V alloy at 1627°C was about 430 microns of which 390 microns were due to the partial pressure of aluminum and 40 microns were due to the partial pressure of titanium. The partial pressures of Mo and V were negligible. The porosity in the pressure melted 4Al-3Mo-1V electron beam weld could not be attributed to boiling as a result of the vapor pressure of the pure alloy since the vacuum melted alloy, having the same calculated vapor pressures, gave a sound weld and the vacuum melted 6Al-4V alloy, having a calculated vapor pressure of about 625 microns, also gave a sound weld. The porosity in the pressure melted alloy must then be attributed to the presence of greater amounts of residual impurities, such as hydrogen, which contributed additional partial pressure to the vapor pressure of the alloy in sufficient amount to cause active boiling.

The significant effect of residual impurities can be realized from the fact that as little as 3 ppm hydrogen disolved in iron can exert a partial pressure of about 7600 microns in molten iron.

The level of vapor pressure which can cause bubble nucleation and retained porosity in an electron beam weld, assuming that no impurities are introduced from the chamber environment, may depend on many factors, such as the rate of heating and cooling and time in the molten condition, the rate of evaporation and pressure distribution above the surface, surface tension and other physical properties of the liquid, material thickness, and size and configuration of the molten puddle. For example, a liquid head of about 0.06 inches of titanium or 0.035 inches of iron is equivalent to about 500 microns Hg pressure.

We know that under the conditions of simulated electron beam welding applied in our tests, titanium alloys with vapor pressures in the order of 400 to 600 microns could produce sound welds. We do not know with certainty that a vapor pressure of about 2300 microns exceeded that necessary for bubble nucleation in the 8% Mn alloy since residual impurities could have caused significantly higher vapor pressures for this alloy.

We believe that our test with titanium alloys and our interpretation of vapor-pressure relationships to porosity formation indicate the need for careful selection of materials for electron beam welding.

Hartbower

Thank you, Lou. Herb, would you please give us your comments on the relative merits of high versus low voltage electron beam welding.

Kalish

First hand experience at Olin Mathieson Chemical Corporation has been with the high voltage Zeiss unit. This machine is rated at 2 KW and will operate as high as 150,000 volts. We have had samples welded with various low voltage machines, however, and this has been beneficial in comparing the two types of operation. In addition, our investigations have covered many metals having a variety of properties, including both low and high melting points. For example, we have welded copper, aluminum, stainless steel, zirconium, Zircaloy-2, titanium, molybdenum, niobium, tungsten and various alloys made up from these base metals.

In welding these various metals, a prime observation is the unique high depth-to-width fusion zone resulting from the high voltage units. There are various theories which try to explain this deep weld penetration depth compared with the width. Some of them stem from the idea that the thermal conductivity is the main factor. Others comment that it is related to the electrical conductivity. Since electrical and thermal conductivity are so closely related, it is difficult to isolate the true casual factor. I prefer the popular theory based on thermal conductivity. This concept states that in high voltage electron beam welding the unit acts like a drilling operation and a hole is drilled at the weld seam with a molten pool around it. As welding progresses, the molten pool fills in the hole. This concept is fairly logical and there is some experimental proof. Specifically, with too much energy on the beam, an overwelded condition occurs which amounts to a series of holes in the weld bead. The explanation is that the holes were too large for the molten pool to fill in and seal up. The width of the weld, based on this concept, is certainly related to the thermal conductivity of the metal. Experiments indicate that this is correct in that the lower conductivity metals exhibit narrower weld zones at constant depth than high conductivity metals.

Let us now go a little further into the comparison between the two types of machines. The high voltage machine obviously needs better electrical insulation than the lower voltage device. This, however, is a relatively simple problem and is resolved by the machine manufacturer utilizing more or less standard high voltage components.

Another item for comparison is the generation of X-rays. The high voltage machines definitely generate X-rays, but proper lead shielding will prevent any harmful effects. For example, particular care must be taken to insure that lead glass ports are replaced only with proper lead glass. Carelessness in such an instance involving the utilization of ordinary glass ports can result in a situation which presents a hazard to the operator. This X-ray hazard, although virtually non-existent with proper shielding, is one of the disadvantages of the high voltage equipment.

The high voltage equipment is usually significantly more expensive than the low voltage equipment. Lead shielding is but one extra item of expense. In selecting a high voltage unit, then, one must evaluate whether the advantages gained warrant the extra expense.

In my opinion the main advantage of high voltage electron beam welding is the particularly large depth-to-width ratio of the weld. This, however, can also be a disadvantage, since it makes a good fit-up mandatory between the two pieces of metal to be welded. Despite this difficulty, the ability to produce very narrow welds can be a very significant advantage in that such welds result in far less shrinkage than is normally encountered in welding practice. For example, a comparison was made between ordinary TIG butt welds of Zircaloy-2 and high voltage electron beam welds. Careful measurements on a series of both types of samples revealed that the TIG weld shrinkage was ten times greater than the electron beam weld. This is the main advantage of the high voltage unit.

If the prime concern is the vacuum welding of materials which tend to pick up gasses readily, the low voltage unit is certainly adequate.

Because of the relatively fine focus spot in the high voltage unit, an electronic deflection which moves back and forth across the weld seam in essentially instantaneous operation can be used to cover a wider gap. Otherwise, the actual weld zone may often be too narrow.

One other thing that should be mentioned is the question of changes in weldment chemistry. We have examined primarily gaseous content and established that at the low pressures of the process one prevents gas pick-up in sensitive metals such as titanium and zirconium. Actually the purity of the weld will most likely be improved because welding in vacuum should remove some gas and volatile elements. On the other hand, this could lead to difficulties if porosity is created in the fused zone. The phenomena occurring in stainless steel in which top and bottom convex weld beads are obtained signifying more metal after welding than before is perhaps due to some micro porosity or to voids left because of gaseous evolution on welding. This particular question, as well as many others related to electron beam welding, warrants further investigation.

Hartbower

Thank you Herb. Bob,(Niedzielski) would you tell us of your low voltage electron beam welding experience at Airco.

Niedzielski

Operation of low-voltage electron beam welders is quite simple. The low-voltage unit by Air Reduction Company allows a welding operator to pre-set the welding conditions for any welding application and then to initiate the weld by operating a switch on the control panel. Laboratory experience indicates that welding technicians can operate the beam welder after only a short indoctrination.

The overall operation is comparable to conventional arc welding practice. The work is mounted on a carriage which moves so that the weld joint travels under the beam. After the chamber is evacuated, the filament and plate voltages are applied while the voltage on the control grid is adjusted to prevent the formation of a beam. The focus-coil current is adjusted to a predetermined value for the application and the table is set in motion. A beam of the desired current level is formed by reducing the grid voltage to a pre-set level with a switch in the grid circuit. No adjustments are required while welding.

A high-voltage welder can produce a smaller beam spot than a low-voltage welder. Also, the high-voltage welder can be used to produce a weld that has a higher depth to-width ratio than a weld produced with a low-voltage welder. For many applications, however, this characteristic of the high-voltage welder may not be required, as welds

QUESTION: What can you say on electron beam welding of copper to tungsten, and copper to stainless.

ANSWER: If you will consult the phase diagrams for these materials, you will find that brittle intermetallics are present. This means that although a weld can probably be made (almost anything can be welded to anything), it is apt to be brittle. In general, a weld may be predicted to be ductile or brittle as shown by the phase diagram of the alloy system involved, regardless of whether welding is done in air by conventional techniques or in vacuum by electron beam techniques.

I have now two questions on 4340 welds.

QUESTION: Have there been noted changes in chemical composition of the fusion zone? If so, what elements? What correlation with vapor pressure of these elements has been made.

ANSWER: I haven't done this type of welding, but I can give a general answer. If particular alloy elements have high vapor pressures at the temperatures in question, these constituents will be lost as has been pointed out before by one of these other gentlemen. If an element does not have a high vapor pressure, it will be retained.

QUESTION: Many low alloy steels such as 4340 had a tendency to crack on cooling from welding temperatures because of phase transformation to martensite. This is overcome in more conventional welding by pre-heating and post-heating. Would electron beam welding also require pre-heating, and if so, how can it be controlled?

ANSWER: You would definitely need pre-heat as in any other metallurgical joining of these materials. One convenient method to pre-heat, if the weld is not too large, is to de-focus the beam and run it back and forth over the weld area before actually stepping up the power and making the weld. This won't be too controllable unless some sort of thermocouple arrangement were added before the weld was made.

Hartbower

Thank you, Ed. Herb, do you have some questions you would like to discuss?

Kalish

QUESTION: What is the size of the beam spot in a high voltage unit?

ANSWER: I have heard this mentioned in thousandths of inches (0.001") focused spot for the high voltage system, but I do not believe it is that small in the welding units, although it is certainly that small in the drilling units. I don't know the exact size of the spot, but I would guess it is more on the order of 0.005".

QUESTION: What is the largest spot attainable.

ANSWER: I would say that to get the larger spot involves going out of focus. Although the spot could be enlarged significantly, it is difficult to make adjustments when dependent on adjustments in and out of focus range. So the way to obtain larger weld zone, with these units, is by the deflection mechanism, rather than increasing the size of the focus spot.

I do not agree with the concept that one can obtain a narrow weld zone in a low voltage unit simply by getting a finer focus. The Zeiss unit can go down to 50,000 volts and the welds are characteristic of lower voltage machines, i.e., the weld zone is much wider than at 150,000 volts.

QUESTION: What's the power at that level.

ANSWER: If the power level is kept constant by milliamperage adjustment, the weld begins to get wider as voltage is decreased. Now, the fact is that the electrons are getting a lot faster when you go from 20,000 volts to 150,000 volts potential, where (at 150,000 volts) in fact their speed begins to approach the speed of light.

This is the important fact rather than the size of the focus, because even when we have a deflection of 0.050" on the beam (maximum deflection is about 2mm on this unit), and make a weld, relatively deep penetration is still obtained. In other words, there is not much spreading of this weld beyond the actual weld area. There is little heat-affected zone, whereas with a low voltage unit the main energy seems to be imparted to the surface of the metal. Heat energy is imparted from the top, more or less as is done in arc welding.

Let's see if there is any other question here that should be commented upon.

QUESTION: Do fit requirements become very exacting with high voltage electron beam welding?

ANSWER: As far as joint configuration and degree of mis-match, a lot of work has been done with ordinary butt welds and I would say you need a better fit-up in a high voltage unit than you would in a low voltage unit. In general, I would say degree of joint mis-match possible depends pretty much on the type of welder you would be using, i.e., high or low voltage.

Hartbower

Thank you, Herb. Bob, do you have some questions to cover for us?

Niedzielski

QUESTION: Are you using filler wire in electron beam welding?

ANSWER: We have a filler wire program but are not ready to report. Filler metal has been used when welding stainless steel as thick as 1/4 inch. We support a vertical shim section between the pieces to be fused with the excess material extending above the joint. This works very well and the reinforced nugget has approximately the same width as that produced without filler.

QUESTION: Is it possible to make a multi-pass weld with an electron beam welder.

ANSWER: We have made single and multi-pass welds in lap joints of 1/4 inch thick stainless steel. In the multi-pass weld, the edge of the top piece is used as filler metal.

QUESTION: Please elaborate on the advantages and disadvantages of work-accelerated as opposed to self-accelerated or annular-accelerated guns.

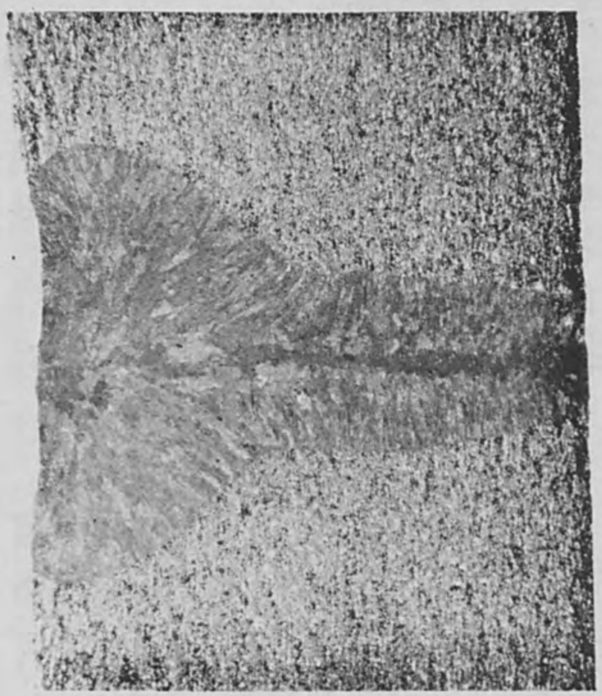
Two-pass weld in lap joint of 1/4 inch
thick Type 304 stainless steel

ANSWER: A self-accelerated gun can operate with stability even though the vaporization and outgassing rates for the material being fused may be very high. These gases and the ions produced by electron bombardment of them are prevented from reaching the high voltage fields of the gun by a small aperture which is in the base of the gun housing and through which the beam enters the welding chamber. A separate vacuum system maintains a hard vacuum in the housing.

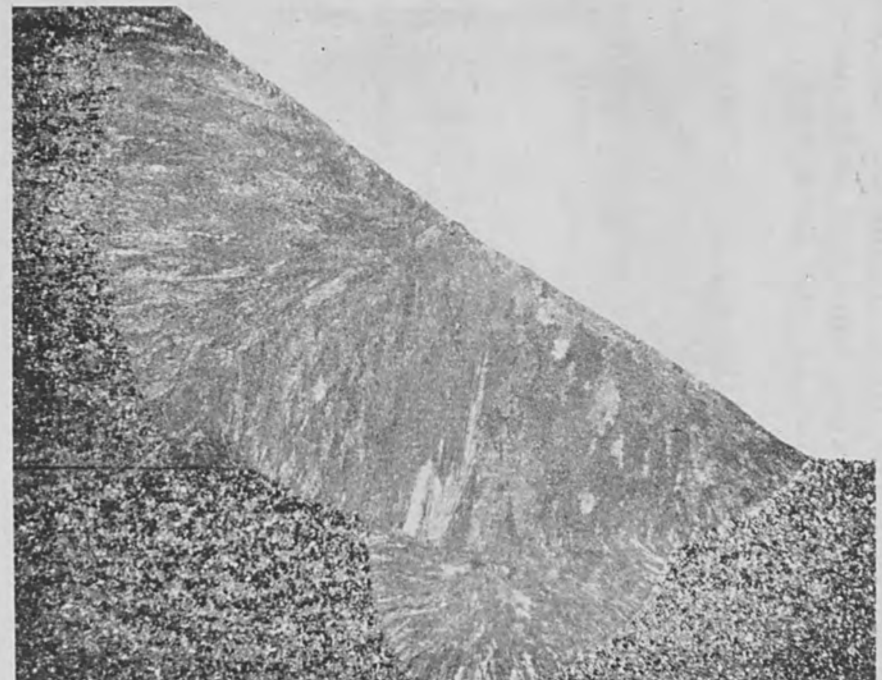
With work-accelerated designs, ions formed by electron bombardment can disturb the high voltage fields and cause fluctuations in the beam current. Flashovers within the gun may be produced when the high voltage fields accelerate ionized particles into the gun.

The focal length of the Air Reduction self-accelerated gun can be varied from 3 to 15 inches by a magnetic lens. Most work-accelerated guns require an adjustment of the distance between the gun and work in

TYPICAL WELDS MADE WITH AIRCO'S 15KV UNIT



But Joint in 0.25"-thick
Type 304 Stainless Steel



Butt Joint in 0.060"-thick
Mo - 1/2 Ti Alloy

order to place the work in the focal plane of the beam. In addition, the self-accelerated guns can weld non-conductors with far less distortion of the beam spot.

QUESTION: What is the possibility of homogeneously heat treating small parts up to 2800°F?

ANSWER: A defocussed beam can be used to heat small parts. However, uniform heating may present a problem.

QUESTION: What depth of focus, attainable by electronic control only, pertains to a welding machine when working on irregular surface contours?

ANSWER: We can vary the focal length by adjusting the current in the focus coil. The minimum focal length is 3 inches, while the maximum may exceed 12 inches.

Hartbower

Does that cover your questions? Thank you, Bob. Bill, do you have some questions you would like to bring to the attention of the group.

Platte

QUESTION: Since columbium is relatively easy to weld with tungsten arc, is electron beam welding necessary.

ANSWER: I did not mean to imply that it is easy to weld columbium, it is less difficult than welding molybdenum. Concerning the question, the use of electron beam welding depends on the application. If the weld configuration requires deep penetration, high voltage electron beam welding is needed. If deep penetration is not required, welding with a tungsten arc in a suitably controlled inert gas atmosphere (free of oxygen, nitrogen and hydrogen) will produce satisfactory results. If, for example, it is necessary to seal an evacuated part, the electron beam could be used because it is operated under a vacuum.

QUESTION: What effect would titanium have on the ductility of columbium welds.

ANSWER: This information, I hope, will be published soon. We find that titanium additions will first increase the ductile to brittle transition temperature slightly and then decrease it. Just what happens and why, we are not yet sure. These changes occurred in the welds which we made. The particular welds were made using a tungsten arc under inert gas, and presumably you would not change the metallurgy if you used an electron beam welder. However, the titanium might be volatized during welding and change the composition.

QUESTION: Have you electron beam welded forty mil tungsten sheet.

ANSWER: We made one weld recently. We did not achieve 100% penetration over the whole weld. We used 100KV, 10 ma and a travel speed of 8"/min. We used beam deflection so that we obtained a greater weld width than would be obtained with an undeflected beam. Since we did not obtain 100% penetration, perhaps some of the weld parameters should be adjusted slightly.

QUESTION: What, if any, are the advantages of electron beam welding?

ANSWER: I believe this question has been covered by one of the other panel members. In general, a balance must be obtained between the welding requirements of the material and the characteristics of the equipment which you plan to use.

QUESTION: What, in essence, is the electron beam welding gun?

ANSWER: An oversimplified explanation would be that we have a heated filament which is a source of electrons; these electrons are accelerated by a high voltage potential and focused by electron optics on the work piece.

QUESTION: Are there any chances of trapping gas bubbles in the weld with the narrow weld zone and higher speeds possible with high voltage electron beam equipment?

ANSWER: The time element is important in bubble formation. However, I assure you they can form when the sharp focus devices are used. Due to the short times involved, bubbles often cannot escape to the surface and are left in the material at the weld metal base metal interface. This condition can cause considerable difficulty. I think that any one who has done a large amount of welding has found that the deeper the weld penetration, the more likely the chance of trapping gas bubbles in the weld so that calculations on bubble nucleation time may be misleading. Furthermore, electron beam welding may provide a weld metal which has been purified, but at the interface between the weld metal and base metal there is a "no man's land" where purification is still occurring. It is in this region that porosity can occur and it will remain after the weld has been completed.

Hartbower

Thank you, Bill. There is another question over here. Lou, would you care to take it?

Stark

QUESTION: Is there any correlation between the vapor pressure of constituents and porosity formation?

ANSWER: For any particular alloy or metal at its melting temperature, you will find a vapor pressure either greater or less than the pressure of surrounding atmosphere. If this vapor pressure is greater and the evaporation rate is such that bubbles form in the molten metal, you would expect to form porosity in the weld.

For titanium alloys, we know that a vapor pressure in excess of about 625 microns was necessary to produce porosity in electron beam welds. The MST 6Al-4V alloy, having a calculated vapor pressure of 625 microns, produced sound electron beam welds. The MST 8Mn alloy, having a calculated vapor pressure of 2200 microns, produced a porous electron beam weld but a sound TIG weld. We would assume that a vapor pressure of 2200 microns exceeded the limiting pressure for bubble formation in an electron beam chamber atmosphere. Our vapor pressure calculations did not include partial pressures due to hydrogen and other residual elements, so that the actual vapor pressure of these alloys may have been considerably higher than indicated but certainly not high enough to exceed the limiting pressure for bubble formation in the open atmosphere of a TIG weld.

With careful experimental work and use of available data on vapor pressures of elements and their alloy solutions it should be possible to establish the alloy vapor pressure and weld atmosphere pressure relationship for porosity formation. With this information, one could predict the safe composition level for alloy and residual elements and the probability of porosity formation in the weld.

Hartbower

Thank you, Lou. I find on the table a few more questions that were not answered. I would like to refer them to those to whom they were addressed. Ed, could you pick up a couple of these questions please?

Franco- Ferreira

QUESTION: Compare the thickness of oxide films in electron beam welding versus those formed with TIG welding on stainless or titanium?

ANSWER: I take this to mean that these would be oxides on the materials prior to welding. As far as I am concerned, in welding with an electron beam cleanliness is most important. However, for best results this is true whether the material is going to be welded by TIG, electron beam, or anything else. For a high quality weld, the surface should be as clean as possible before welding.

QUESTION: We have seen equipment with power supplies in the range 30 KV to 150 KV. maximum output. Are these all of the power supplies available? Why is the voltage on commercial electron beam welders made in this country limited to 20 to 30 KV?

ANSWER: By contacting a suitable vendor, you can get a power supply which will produce almost any voltage you want. I think that low voltage machines are being built in this country mainly for reasons of economics.

Hartbower

Herb, I have a question for you.

QUESTION: Has work been done in developing guidance systems for electron beam welding?

ANSWER: I don't know whether I am equipped to answer this or not. It would seem to me that some of the speakers, previously, have partially covered this, especially in discussing the high voltage equipment. I suspect that the Carl Zeiss laboratory has probably been or is working on fancy control devices. If fancy holes can be drilled, fancy welds can be made by modification of the equipment. They were talking about this some two or two and a half years ago. I don't know if they have accomplished complete weld programming or not, but I presume it could be done.

Hartbower

Thank you, Herb. I am afraid that our time has run out.

If I were now to summarize the essential points of this panel discussion I believe it could be done best with the following statements:

1) There appear to be metallurgical problems associated with electron beam welding.

2) There are some limitations to the process, as there are to all processes.

3) There is considerable enthusiasm for this welding process.

4) There is a real need for this welding process.

Thank you.

A BIBLIOGRAPHY ON THE APPLICATION OF ELECTRON BEAM TECHNIQUES IN METALLURGY

by

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The application of electron beam heating techniques in various areas of metallurgical and allied fields has been vigorously pursued in the past five years. A sizable literature has evolved from this effort.

This bibliography has been complied in the hope that it will assist in some small measure the current and future investigators in this area. It is divided into five sections, as shown below, with an alphabetical listing within each section. The writer wishes to acknowledge with thanks the suggestions received from several workers in this area of vacuum metallurgy.

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Appendix to Electron Beam Bibliography

While Alloyd's proceedings on the second symposium were in print we received A. Calverley's proceedings of the British symposium on Electron Beam techniques and their applications. As they contain much valuable information a list of the subject matters discussed at that symposium and the names of the contributors are appended to Dr. Bunshah's bibliography.

Subject Matter	Author	Page
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