Electron Beam Machining (EBM)

ELECTRON BEAM MACHINING (EBM) is a method of cutting material in a vacuum using a focused beam of high-velocity electrons. On impact of electrons with the workpiece, the kinetic energy of the electrons changes into heat, which vaporizes a small amount of the workpiece. The vacuum is necessary to prevent scattering of the electrons by collision with gas molecules. By controlling beam energy at a lower level, the process is used for welding instead of machining.

In machining, electrons are accelerated in an electrostatic field to velocities of more than half the speed of light. The electron beam, and the laser beam (p 255), exceed ordinary heat or light sources in energy density, precision and mobility. By focusing the beam with optical precision on a 0.0005 to 0.001-sq-in. area of the workpiece, energy is delivered at a power density of 10 billion watts per square inch and can vaporize any material instantly.

Electron beam machining is applicable to parts 0.010 to 0.250 in. thick, and can drill holes as small as 0.0005 in. in diameter in all materials, including ceramics, at a penetration rate of 0.010 in. per second or faster. It cuts slots as narrow as 0.001 in. at a spacing as close as 0.005 in. The process is used also to scribe thin films and to remove small, broken taps from holes.

Process Principles. A typical setup for electron beam machining is illustrated in the schematic diagram of Fig. 1. A stream of electrons is emitted from the tip of a hairpin tungsten filament 0.008 in. in diameter that is heated to 2500 C in a vacuum of about 10^{-5} mm of mercury. The cloud of electrons is shaped into a cylindrical stream by the magnetic field produced by the grid cup, and is directed through the hole in the anode without colliding with the anode itself. The stream is accelerated toward the anode by a potential difference of 50 to 150 kilovolts between the filament (cathode) and the anode.

The electrons reach maximum velocity as they leave the anode and (because of the vacuum) maintain this velocity until they strike the workpiece.

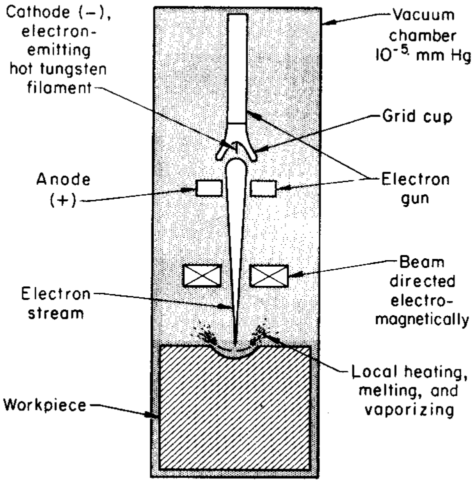

Fig. 1. Setup for electron beam machining

The beam may be redirected or focused by magnetic fields before reaching the workpiece. Beam current usually is 100 to 1000 micro amp, with continuous power of 100 to 1150 watts. Pulse duration is 4 to 64,000 microseconds at a frequency of 0.1 to 16,000 cps.

The distance from electron gun to workpiece usually is about 4 in. The chamber must be shielded to absorb the x-ray emission produced, as with commercial x-ray equipment.

Control of the accelerating potential, pulse duration, pulse frequency, and other factors involves different power settings for various cutting applications. Electromagnetic focusing makes beams of full power only 0.001 in. in diameter, and can make weaker beams as small as 0.0005 in. in diameter.

The electron beam is focused by a magnetic lens. Magnetic deflection coils beneath the focusing lens can deflect the beam anywhere in an area ¼ in. square on the workpiece. The beam can be programed in this area by saw-tooth-wave and sine-wave generators that drive the deflection coils. This system can cut in many different patterns, varying from a small round spot to a square or a rectangle.

Cutting conditions can be adjusted over a wide range. The electron beam is controlled to suit the work material, and the size and shape of the cut. High-melting alloys and thicker stock generally are machined by electron beams with greater beam current in longer pulses and at higher frequencies. Materials that have high melting and boiling temperatures, high specific heat, and high heats of fusion and va-

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porization require more heat for cutting by EBM, which is essentially controlled vaporization of material. Relative power requirements to remove equal volumes of various metals in equal time, based on aluminum as 1.0, are:

Aluminum	1.0
Titanium	1.5
Iron	1.8
Molybdenum	2.2
Tungsten	2.9

The heat-affected zone may extend to a depth of 0.010 in. Although heat damage cannot be eliminated completely, heat flow into the workpiece can be minimized by using pulses of shorter duration. Shorter pulses can minimize surface effects such as local recasting, and an electron beam of lower amperage in short pulses is essential to prevent ceramic workpieces from cracking during machining.

Applications

Ten applications of EBM are summarized in Table 1. Holes and slots that are only a few thousandths of an inch wide are cut with a focused beam. Larger holes are made by trepanning, using magnetic deflection coils, with rotation of the workpiece.

An optical tracing device, a "flying spot scanner", can be used with EBM to copy patterns from negatives made by photographing the pattern. The magnetic deflection coils deflect the electron beam to the correct position on the workpiece to cut a pattern that reproduces the negative, with a linear reduction of 10 to 1. This method is used in drilling accurate grids, in etching copper gravure plates, and in making accurate film resistors.

Drilling Holes. In drilling holes, the beam usually focuses on one spot and evaporates material until it has completely penetrated the workpiece, or until it is switched off after a specified hole depth has been reached. Hole diameter depends on beam diameter and energy density, and can be changed by varying the amplitude of the voltage generator connected to the electromagnetic deflection system. If holes larger than the beam diameter are required, the beam is deflected electromagnetically in a circular path. For extremely large holes, the workpiece can be moved off-center and rotated.

Holes 10 to 20 diameters deep are produced readily by EBM (see examples in Table 1); maximum depth-to-diameter ratio is about 200 to 1. Figure 2 shows a portion of the length of 0.0008-in.-diam holes through an investment casting (Ni-15Co-10Cr-5.5Al-4.7Ti-3Mo-1V-0.06Zr-0.014B). These holes, 100 diameters in length, could not be produced practically in any other way.

The contour of the holes shown in Fig. 2 illustrates the effects of separate pulses of the electron beam. The hairline cracks visible did not constitute a problem in this application, but exposure to service stress sometimes requires the removal of a heat-damaged layer up to 0.010 in. thick in EBM products. Depth of heat damage is much less in welding with an electron beam.

Typical tolerances are ±0.001 in. on ⅛-in.-diam holes, and ±0.00005 in. on 0.0005-in.-diam holes.

Cutting Slots. Cutting speed, in general, depends on the amount of material to be removed — that is, on the cross section of the slot to be cut.

All slots cut by EBM exhibit a small amount of material spatter on the side where the beam enters, which can usually be removed by light abrasive cleaning. Electron beam machined slots in material less than 0.005 in. thick have parallel sides with essentially no wall taper. In thicker material, slots show some taper because of beam divergence and nonuniformity of heat flow. The walls of electron beam machined slots in material 0.005 to 0.125 in. thick exhibit a taper of 1° to 2°. The edges of the walls can be maintained parallel to a tolerance of 0.002 in. The narrowest slots cut to date by EBM have been in material approximately 0.001 in. thick and have had a width slightly less than 0.001 in. When cutting slots of these dimensions, it is often necessary to make more than one pass in order to obtain a sharp, smooth edge.

Less than a third of the 100-diameters length of the holes is shown. Holes are bell-mouthed and irregular at entrance end (top of picture) and are irregular in cross section. (Compare with holes produced by laser beam machining, shown on page 256.) Cracks extend to a depth about equal to the hole diameter.

Fig. 2. Holes about 0.0008 in. in diameter made by electron beam machining a nickel-base alloy investment casting

Table 1. Typical Applications of Electron Beam Machining

Work material and thickness (footnotes describe shapes machined)	Machining time or speed	Accelerating voltage, kv	Average beam current, microamp	Pulse duration, microsec	Pulse frequency, cps
Low-carbon steel, 0.040 in.(a)	30 in./min	150	9000	2100	300
Hardened steel, 0.125 in.(b)	10 min	140	150	80	50
304 stainless, 0.250 in.(c)	10-20 in./min	130	5000	5300	35
410 stainless, 0.250 in.(d)	......	150	7000	1000	3.3
Hastelloy, 0.[illegible]50 in.(e)	1 min, 10 sec	130	5000	5300	100
Molybdenum, 0.010 in.(f)	Less than 1 sec	140	20	20	50
Tungsten, 0.010 in.(g)	Less than 1 sec	140	50	20	50
90 Ta – 10 W, 0.010 in.(h)	10 sec	140	100	80	50
Alumina, 0.030 in.(j)	30 sec	125	60	80	50
Quartz crystal, 0.125 in.(k)	Less than 1 sec	140	10	12	50

(a) Cut. (b) Rectangular hole, 0.018 by 0.072 in. (c) Cut to reopen welded container. (d) Slot, 0.030 in. wide at entrance, 0.010 in. wide at exit. (e) Hole, 0.100-in. diam. (f) Holes less than 0.002 in. in diameter, 0.003 in. between centers. (g) Hole, 0.001-in. diam. (h) Hole, 0.005-in. diam. (j) Hole, 0.012-in. diam. (k) Hole, 0.001-in. diam.

Advantages of EBM include:

1. Capability of making very small holes and slots with high precision, in a short time, in any material (holes, slots and orifices not producible by any other method)
2. Absence of mechanical contact between workpiece and tool
3. Suitability for automatic machining.

Disadvantages of EBM include:

1. High cost of equipment
2. Limited applicability (Depth of cut is ¼ in.; vacuum chamber limits the size of workpiece; only small amounts of metal can be removed.)
3. Slow production rate, because of slow removal rate and time required to evacuate the chamber
4. Nonuniformity of holes and slots (Holes are tapered, and entrance to a hole usually is cratered.)
5. Need for skilled operators.

Commercial Equipment

One general-purpose commercial machine for EBM uses accelerating voltages as high as 150,000 v to produce a power output of 100 watts and a maximum power density of about six billion watts per square inch. The beam can be pulsed at frequencies as high as 10,000 cps. For continuous-beam operation, the maximum beam current is 800 microamp, but a much higher current can be used for pulsed-beam operation.

The machine is equipped with a beam-deflection system that allows beam movement of about 0.040 in. Mechanical worktable movement is used for machining larger areas. The workpiece is viewed from above through a microscope.

Accuracy of ±0.0002 in. can be obtained with this machine in cuts 0.020 to 0.040 in. deep, as follows:

Round holes: 0.002 to 0.008 in.
Slots: 0.002 to 0.004 by 0.040 to 0.080 in.

Manipulation is slower and more difficult for smaller shapes; larger ones can be made, but with less accuracy.

The high temperatures necessary for practical removal rates require the use of high beam currents. Beam current density at the cathode tip is limited to about 14 amp per sq in. at the operating temperature of 4580 F for the tungsten cathode. Cathode life drops off sharply at higher temperatures.

A major factor in the efficiency of the process, particularly in machining metals that have high thermal conductivity, is the conduction of heat away from the electron-impact zone. A pulsed electron beam is used to improve efficiency, because heating of the machining zone is much more rapid than heat loss by conduction.