

INTRODUCTION

Micro-joining techniques employing electron beam energy sources may be one of the most under utilized joining process in industry today. The unapprised engineer may never fully exploit its full potential because of the introduction of alternate beam energies. The electron beam process for welding and joining purposes has been in existence for more than forty years. There have been numerous micro-joining miracles performed by private industry, jobshops and government labs throughout North America. In fact, weapons and space exploration programs relied on electron beam welding (EBW) processes when there were no alternative solutions. The highlight of this technical discussion is to revisit the opportunities and limitations the electron beam welding process offers manufacturing and R&D. We will expose some of the unique applications utilized in industry and ongoing development.

BACKGROUND

The advent of electron beam welding (EBW) as a commercial process for joining materials occurred in the mid fifties when Stohr published articles on his applied use of the EB process (in France.) Stohr, reported his development for welding fuel elements for the nuclear industry. Prior to this time, Steigerwald (in Germany) had been experimenting with electron beam for machining (e.g., drilling and cutting) purposes. Carl Zeiss, another German scientist also contributed to the promotion of electron welding and was the first to obtain a patent for EBW for deep penetration welding. Later, Zeiss participated with United Aircraft (UA), now United Technologies Corp. in providing patents for the first commercially available electron beam systems in the United States. (UA) acquired Zeiss's patents and became the first American company to commercially manufacture electron beam equipment in the USA. UA's interest concentrated on aerospace manufacturing needs. The electron beam process in the

early sixties, was considered a high technology process that could provide joining opportunities for American nuclear and space programs, vital to America's competition with the Soviet Union. It wasn't until the late sixties that the first electron beam jobshops emerged as free enterprise to challenge the metals joining applications from new emerging technologies. In the early seventies, the British entered into the EB market with a basic, low cost, low voltage, electron beam system for singular small component welding.

Today only a select few participants share the EBW equipment market which is segmented into particular niche areas: e.g.) High Voltage, Low Voltage, Large Chamber, Low Cost and Non-Vac. It is estimated that approximately 1400 electron beam welding systems are currently in use in the USA today, with a significant greater number than that in use throughout the rest of the industrialized world. The most common industries employing electron beam welding are: aerospace, automotive, nuclear, and electronics, consumer products, medical devices and jobshops.

BACKGROUND ON FUSION WELDING

In fusion welding, coalescence of the faying surfaces of the joint is achieved by providing the heat needed to initially melt these interface surfaces. One distinguishing feature of all fusion welding processes is the intensity of the heat source used to produce the melting. Virtually every concentrated heat source has been applied from time to time; however, many of the characteristics of each heat source are determined by the intensity of the source. For example, if one considers a planar heat source diffusing into a very thick slab of steel the surface temperature will be a function of both the surface power density and the time. At 400 watts per square centimeter it takes two minutes to melt the surface. If the 400 watts/cm² heat source were a point on the flat surface, the heat flow would be divergent and it might not even be possible to melt steel; the solid metal might be

able to conduct the heat away as fast as it is being introduced. Generally, it is found that heat source power densities of approximately 1000 watts/cm² are necessary to melt most metals.

At the other end of the power density spectrum, it is found that intensities of 10⁶ or 10⁷ watts/cm² will cause vaporization of most metals within microseconds. Above these power densities, all of the solid interacting with the heat source is vaporized and no fusion welding can occur. Thus it is seen that the heat sources for all fusion welding processes lie between 10³ and 10⁶ watts/sq. cm on the power density spectrum. The electron beam spot size determines the heat intensity. Smaller spot size has more heat intensity, that is why beam energy positioning is extremely critical. The positioning accuracy must be on the order of the heat source diameter.

POWER DENSITY REQUIREMENTS FOR EB TYPE PROCESSING

THE ELECTRON BEAM PROCESS DEVELOPS

The electron beam process was initially a solution for the high energy requirements for joining thick metal cross-sections of refractory, and reactive materials: e.g., Tantalum, Columbium, Hafnium, Tungsten, Titanium, Beryllium, Molybdenum etc.

Micro-joining using electron beam energy was reported as early as 1962, at the Forth Symposium on Electron Beam Technology in Boston MA. The proceedings covered micro joining for the electronics packaging industry and were presented by Alloyed Electronics Corp. The micro-joining applications developed by Hamilton Standard, Division of United Aircraft Corp. The equipment used was a Hamilton-Zeiss model EBM2, approximately 4 kW and utilized an X, Y, table and a 40X microscope. The operator was able to manually

position the beam to within 0.0005" of true position. Another important feature of this early conceptual machine was the ability to deflect the beam and rapidly pulse simultaneously. This equipment was specially designed and capable of energy densities reaching (10^9) required micro machining (drilling, and cutting). The electron beam joining program proved successful and Hamilton Standard went on to market and produce its own line of electron beam processing equipment for commercial use. Hamilton Standard became renowned leaders in electron beam welding up until the mid seventies when the business was sold to Leybold Heraeus(Germany). At the time of the acquisition over 600 electron beam-welding machines had been installed in a variety of industries. Today, many of the early Hamilton Standard brand electron beam machines are still operational in jobshops and industry and are often refurbished to incorporate new electronic controls and motion systems.

MICRO-ELECTRON BEAM WELDING

High power electron beam welding equipment is capable of penetration into several inches of solid metal. The stream of focused electrons to even greater thickness can penetrate materials with low thermal conductivity. In this regard the electron beam process has no rival.

The previous statements were not intended to imply that electron beam welding is confined to high power heavy section welding. Quite the contrary, electron beam energy is readily adapted for micro joining miniature components. In fact their computer generated and documented parameters are dynamically accessed for repeated small or single piece production lots. The modern vacuum chambers equipped with state of the art seals, vacuum sensors, and high performance pumping systems enable rapid evacuation of chambers on the order of seconds. The electron beam process can be an economical micro-

joining alternative. With a microscope viewer, or magnified video monitor the electron beam becomes a super accurate energy resource, with resolution of beam energy and placement on the order of 0.0005 inches. Thin, critical welds have become common place for this process. Modern digital electronic controls, coupled with the modern computer controlled operator console, allows for continuous cycle to cycle repeatability. Many of the process advantages have yet to be matched by laser energy sources. A primary reason is that the electron beam energy formation and the control systems are relatively basic when compared to the science and physics required for the precision energy reproduction by lasers when used for welding. One of the requirements to producing an electron beam is the need for a soft vacuum in the gun column (1×10^{-3} torr). Joining in a hard vacuum (5×10^{-4} torr) can also be an advantage when joining reactive metals, or for evacuated and hermetic seals. Another significant advantage the EBW process offers, is the ability to magnetically deflect the beam energy as patterns or shapes. The digitally generated special patterns are stored and called up when needed. The beam deflection control unit is a especially useful tool for micro-joining miniature details and complex configurations. The beam energy can be precisely fitted to the shape and a secondary pattern can then be superimposed to widen the beam energy. This can be useful when hermetic sealing thin materials. The beam deflection control can be used to locate independent spot welds in a precise array of patterns. The energy levels and coordinates can be repeated without extensive calibration.

Electron beam, comparable to laser, can utilize pulsed energy cycles. The pulsing of high energy electron beam has been extensively studied for the advancement of joining materials. High repetition rates of up to 1000 Hz have been found to control the undesirable thermal shock normally found in conventional EBW processes. Pulsed electron beam energy when coupled with programmable beam deflection can offer the user versatility for micro-joining applications.

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MODEL ELECTRON BEAM MICRO-JOINING APPLICATIONS

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In 1989 a paper published by the Mitsubishi Electric Corp. highlighted the unique application for electron beam micro joining on high speed printing heads. The challenge was to produce 96 spot-welds on 48 "T" joints and 48 lap joints. The previous attempts were

made with pulsed Nd:YAG laser, resulting in shrink cracks in the micro-welds. The electron beam equipment employed a magnetically deflected beam scanning system to precisely locate each impending spot weld. The electron beam process was able to produce the individual spot-welds without cracking and minimal reduction to the temper of the material being joined. The deep penetration characteristic of the electron beam provided the ability to produce a keyhole mode for this application. The 96 spot welds were produced in approximately 2.5 seconds with favorable fatigue test results. In conclusion, the Japanese reported that the electron beam process was suitable for the precision fabrication of electronic and miniature mechanical assemblies.

MICRO-JOINING SENSOR AND MINIATURE INSTRUMENTS

Sensors and measuring instruments are devices, which monitor changes or variations in an object or process relative to a reference or standard. Depending on their intended function, sensors recognize variations in weight, vibration, motion, pressure, color, heat, light, magnetism, chemistry. Sensing devices may be part of a system controlling a manufacturing process, activating a warning system, controlling the smoothness of vehicle motion, sensing the changes in blood flow, heart rhythm, or electrical pulses. The sensor may supply a signal by changing pressure to an electrical voltage or digital output.

Differential thermal expansion of a bimetallic strip provides mechanical motion to operate a switch or move a needle on a calibrated gauge. Volume changes resulting from thermal expansion (or contraction) of liquid in a sensor well create bellows or diaphragm movement useful for operating a switch or providing control of process gradients. Forces are measured by detecting mechanical displacement, balance changes, elastic material movement, variations in electrical resistance, etc.

With modern, rapidly developing technology, new sensors and instruments are continuously being developed to detect extremely small changes, whether it be heat, pressure, chemistry, etc. Their components are miniaturized, sensitive, and precisely arranged in a very small and compact assembly. Most often they utilize micro-electronics, to protect them from the elements of the user environment, sensor devices are packaged to protect from contamination, moisture, impact, abrasion, heat, magnetism, etc. Thus, the sensor is assured consistent and reliable performance throughout the life of the product. Product reliability is especially a concern with medical implants.

As mechanical assembly (screws, gaskets, clamps, etc.) causes time related failures, welding is often the preferred joining process for both intermediate and final assemblies. When hermetic sealing is required, welding is mandatory. Another important area is process fluid isolation. Many processes today use corrosive gases or demand ultra-clean (less than 0.1 micron particle count) fluids, requiring a 316L stainless steel, or Hastelloy C isolation diaphragm material to be in contact with the process fluid. Permissible leak rates are often specified at less than 1×10^{-9} cc/He per sec.

APPLICATION CRITERIA

Sensor welding presents unique problems related to thermal effects. The metals used for housing and other components have melting temperatures in excess of 2500; F. Local surface temperatures at the weld may exceed 3000; F. Care must be taken in the location of other components to avoid damage by heat from the molten weld zone. Weld and base metal cracking can develop into leak paths. Deposition of metallic vapors on electrical surfaces can destroy the sensors ability to function. Weld bead shapes should have smooth transitions with the base metal to avoid the development of stress concentration areas leading to early fatigue failures. Undercutting, concavity, and other visual defects are also detrimental. Weld penetration verification to the

drawing or specification requirement is performed by macro or micro-sectioning assemblies or costly non-destructive test methods. The strict verification is essential to assure pressure integrity of the assembly at the required proof and burst pressures.

Sensors frequently include diaphragms as thin as .001 inches to provide the system response. Their thinness affords little resistance to bending or buckling and distortion is unacceptable. Obviously they are easily distorted from the heat of welding unless special precautions are taken. In some pressure monitoring assemblies, the diaphragm is sandwiched to form a cavity or chamber on both sides of the diaphragm. An actuator rod can be coupled to the diaphragm, enabling the flexing motion to be transferred to perhaps a motion amplifying device, switch or a graduated control. Fittings can be joined to the diaphragm by micro-welding. The thin diaphragm, because of its minimal heat sink capability, is particularly sensitive to variations in the micro-welding process. The small diameter, circumferential weld creates expansion and contraction constraints which if not considered, could cause buckling deformation and tensile stresses jeopardizing the necessary intimate contact for joining. When the intimate contact is compromised, separation occurs and causes instantaneous melt-back. For this weld, the energy focus must be precise and part location repeatable. The targeting characteristics of either the electron beam or laser welding processes are ideally suited. Their high energy density enables minimal heat to be used for welding this critical, heat sensitive weld joint. To complete the assembly, the parts are circumferentially welded at their outer periphery. In effect a butt weld is created. Weld control is critical to avoid excess heat conducted into the thin diaphragm, which could cause distortion and residual stress. Residual stress can have long term, insidious effects manifested as shortened fatigue life and calibration drifting. These concerns emphasize the importance of minimal heating and proper control of weld penetration.

Occasionally, difficult to weld materials are involved. Hastelloy,

Beryllium Copper, Inconel X, and Aluminum alloys are typical. Heat treatable alloys require special consideration during the development of weld parameters to preserve the special hardness, strength or corrosion resistance characteristics for which the material was selected.

WELD JOINT DESIGN

In some instances the weld joint is a combination of thin and thick materials producing a heat unbalance during welding. It is evident that with GTAW techniques, the thinner detail would reach its melting temperature and melt back in advance of the thicker member. Solutions to this problem include the use of fixtures designed to chill or cool the thin component thereby decreasing the heat unbalance. Other options are the use of either electron beam or laser for welding. Their precisely focused and targeted beams enable heating to be focused on the thicker detail, thus compensating for the heating unbalance. Heating unbalances can also occur when materials having dissimilar conductivity are welded. An example would be joining copper to stainless steels. There are other examples of this material unbalance. Not only may they differ in thermal conductivity but also in their melting temperatures. These conditions are typical welding problems. Designing for electron beam welding is relatively straight forward and practical. The basic rule is intimate contact of surfaces to be joined. When gaps appear in mating parts the beam energy will enter the void and disrupt the energy distribution. Most stringent aerospace process specification are often a good resource for joint design criteria.

PROCESS SELECTION

Each metal joining process has its unique characteristics. When selecting a process for a specific joining operation, the particular requirements and conditions involved must be examined. Questions concerning depth of penetration, joint preparation, cleaning, inert gas or vacuum environment, weld joint accessibility, proximity to heat

sensitive materials, productivity and cost must all be addressed.

Product designers and manufacturing engineers should have basic understanding of at least, the commonly used welding processes. Too often the welding requirements are ignored, making the final assembly operation the most difficult, troublesome and costly phase of the manufacturing process.

Electron beam, laser beam, plasma arc and gas tungsten arc are the dominant choices for micro-welding processes. Technically, electron beam and laser are the ideal candidates of choice. The precise narrow welds and low total energy input prevent distortion and minimize heat affected zones. Both processes produce welds of high metallurgical quality.

In view of these significant advantages one would question why any welding process other than electron beam or laser would be considered. Perhaps the most comprehensive answer is cost. The capital investment starts at \$ 250,000. Depending on energy output levels, automation, number and range of axis of motion control and other levels of sophistication, the cost can quite easily exceed several hundred thousands of dollars.

ELECTRON BEAM BRAZING

Brazing with EB energy can offer solutions to joining dissimilar material combinations. A unique feature of electron beam energy is that dependent on the atomic number and density of the material it is possible to form new types of brazed joints. This is accomplished by preferentially heating a bonding material between two lower atomic number materials. It is possible to form metal bonds for new metal matrix composites.

RECENT BRAZE APPLICATION SUCCESS

NASA developers have recently reported to ASM (American Society for Materials) an electron beam braze on a Sapphire fiber to Platinum. The application addressed the difficult task of joining the Sapphire to Platinum with a ceramic epoxy which with the current method ultimately would fail after thermal cycling. Electron beam brazing was chosen over conventional vacuum brazing methods by reason of the ability to focus the highly concentrated energy onto the braze filler. The fiber optic probe were miniature components made up of a .015 "dia. Sapphire fiber joined to a .059" Platinum coupling .250" in length. The braze material was Gold reactive filler formed into a wire ring, the total braze cycle time was 5 seconds. More information can be acquired at www.lerc.nasa.gov/www/ant/01projects.htm

CLASSIC ELECTRON BEAM APPLICATION

Sensors and miniature instruments as metal assemblies are potential prospect for EBW. There is one classic application worthy of mention to give perspective to on this discussion. A device called an aneroid capsule, which can be found in the heart of an altimeter is an excellent example of how many of the electron beam welding attributes make the manufacture of this product possible. Fabrication entails material; two mil thin BeCu, is formed into a capsule half. Two separate capsules halves are positioned with a high degree of accuracy with respect to the beam energy. The sections are held open during the vacuum evacuation cycle. When the precise vacuum level is achieved the machine computer advances the capsule halves and proceeds to the weld execution cycle. With ultra-precise energy control the BeCu halves are joined at the mating knife edge. The welding or clamping fixture is assembled in a drive and tailstock arrangement, which provides accurate and precisely controlled rotation. The workpiece clamping details of the fixture consist of two circular die shaped tools between which the diaphragms are clamped. Clamping pressure is

pneumatically controlled. The outer diameters of the dies are machined to create a knife edge to assure clamping pressure is effectively confined to the immediate area of the weld joint where the intimate contact for edge welding is needed. The dies correctly align the details but they also act as heatsinks forming a barrier against the flow or conductance of welding heat into the thin diaphragms, thus preventing their distortion. The clamp material is also considered so it can resist becoming joined to the component. The fixture brings the assembly details together at the knife edge location so that any independent melting of each detail is forced together and coalesce at the fixture line. Without this action, voids can form due to the lack of coalescence and resultant leakage would occur. This coalescing action is also time dependent, weld travel speed must be compensated to allow melting and combined coalescence. To facilitate loading the small and delicate workpiece details into the fixture, a vacuum force is utilized. The operator can quickly position the first detail in the fixture die, where it is held by the vacuum force. The second detail is placed against the tailstock in correct alignment where it is also held by the vacuum. Pneumatic pressure is then applied and the second tailstock fixture disk moves forward to complete the clamping and heatsink action at the circumferential edge weld joint. The use of the vacuum assist dramatically demonstrates the timesaving of correct fixture design.

All welding parameters are controlled and documented to assure consistently good weld quality by different machine operators. After welding, the assemblies are visually and dimensionally inspected for flaws. Leak testing is the final quality control operation.

SUMMARY

The electron beam welding process is a viable option for micro-joining applications today. The lost popularity and lack of technical press has pushed the once well recognized energy source to the rear of the process selection list. Joining Technologies, along with a few

dedicated jobshops, continue to promote the benefits of this extraordinary and well developed process for micro-joining. There can be many specific variables and subtleties that can limit EBW, there are, however, some generalities to help define a given process for micro-welding.

For penetration beyond 0.050" without preparation of the weld joint for filler metal, electron beam is the indisputable candidate. For critical, heat sensitive weld joints and widely dissimilar materials laser and electron beam would be favored. When distortion to any degree is unacceptable laser, electron beam, and plasma arc are suitable choices. For assemblies requiring hermetic seal with vacuum tight environment electron beam is prime. For high volume, long production run welding of electronic or precision assemblies, electron beam and laser offer the best approach. For maximum flexibility, accuracy, visual monitoring, minimal development, less critical joint tolerances, reactive, or refractory materials are concerned, the EB process is prime

For more information about Joining Technologies, please reference our highly informative website@ www.joiningtech.com or e-mail mikef@joiningtech.com

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