NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-396

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Abstract

A survey was made of electron beam and laser techniques as applicable to spacecraft electronic joining. A brief description is presented, of conventional and advanced joining techniques requiring contact between the parts to be joined and the joining equipment, for comparison to focused energy devices which do not require contact. Advantages and disadvantages of the laser and electron-beam devices are discussed, as is device operation.

Results of evaluation tests as well as typical applications for both laser and electron beam welders are presented. Certain data and applications were not available due to their proprietary nature. The information was obtained through literature reviews and discussions with manufacturers and users of these devices. New developments and required improvements are also briefly discussed.

Application of Electron and Laser Beams to Spacecraft Electronic Joining

I. Background

Much effort has been expended in recent years toward development of joining techniques for spacecraft electronic hardware. A great portion of this joining development has resulted in new packaging design concepts and the continued reduction in size of electronic circuitry. Numerous joining techniques are available to the electronics industry. The more conventional techniques include soldering, resistance welding (cross-wire and parallel gap) and thermocompression bonding. Other, more advanced, techniques include electron beam welding, laser welding and ultrasonic bonding. A characteristic common to the conventional techniques, as well as to ultrasonic bonding, is that contact is required between joining equipment and the components to be joined. It is recognized that soldering can be accomplished by dipping processes; however, for joining discrete components, contact is usually necessary. The opposite is true of laser and electron beam welding. Here, contact is not necessary to achieve a joint. Because of this basic difference, it was decided to survey the characteristics of the non-contact joining processes to determine their applicability toward use in future spacecraft electronics.

A. Basic Joining Process Criteria

Four basic characteristics must be exhibited by a microelectronics joining process to afford use: (1) producibility, (2) inspectability, (3) repairability, and (4) reliability; they are defined, Ref. 1, as follows:

(1) Producibility: Joints must be made rapidly and economically with optimum uniform material combinations and configurations. Human variables should be eliminated wherever possible.

(2) Inspectability: The process must provide joints that are inspectable by visual means or by a reliable process-monitoring system.

(3) Repairability: Any assembly whose value is greater than the established maximum throw-away value must be easily repairable without the use of unusual equipment or procedures. Also, damage to materials or components must be avoided.

(4) Reliability: An established minimum failure rate must be met.

In addition to the above, consideration must also be given to current-carrying capacity, voltage drop, contact resistance, connection noise level, size, thermal sensitivity of joined members, mechanical strength and metallurgical integrity, Ref. 1.

B. Joining Processes Requiring Contact

Prior to covering the laser and electron-beam welding processes in detail, a short summary of the contact joining processes is required for comparison.

1. Soldering. The definition of soldering is given as a group of joining processes where coalescence is produced by heating to a suitable temperature below 800 F, and by using a non-ferrous filler metal having a melting point below that of the base metals, Ref. 2.

With the development of more complex electronic assemblies, soldering has undergone extensive development, not only with regard to processing and control, but with regard to automation. The soldering process can be divided into four basic techniques: (1) hand-bit, (2) dip, (3) flow, and (4) resistance. In all cases a filler material, usually lead-tin solder, is used to produce the metallurgical connection between circuitry and components, Ref. 1.

Soldering requires contact between the parts to be joined and the soldering iron tip. For a high-reliability assembly, solder joints must be evaluated with regard to the environments in which they must operate. This may include humidity, temperature, vibration, etc. Normally, the strength of solder joints is usually low, since they depend primarily on the filler metal to obtain their strength. In addition, the introduction of the filler metal has an effect on joint resistance because the current then has an extra medium through which it must travel. Solder joints may also be considered visually inspectable to some degree; however, for reliability, sectioning of preproduction joints is required to establish exactly the nature of the subsurface of the solder joint. This usually requires fairly extensive effort early in the program. Needless to say, cleanliness is of utmost importance to provide for the wetting of the mating surfaces required for a proper solder joint. Subsequent to soldering, cleaning is required to rid the assemblies of excess solder and any flux residue. Thus, an additional processing step is necessary to implement this joining technique.

2. Resistance welding. Resistance welds are usually produced by discharging a stored capacitor bank through the materials to be joined, Ref. 1. There are two basically different types of resistance welding techniques: the first, cross-wire; the second, parallel-gap welding. In the cross-wire technique, pincer-type electrodes are used. The two leads to be joined are gripped between the electrodes and the current is passed through. In the parallel-gap technique, current is applied through the leads in series with a split electrode. The resistance welding process requires that a weld schedule be developed to produce adequate welds for production. The energy and the electrode force are varied in the development of the weld schedule, and extensive testing is done to determine the optimum combination of energy and force to be used during the production cycle. Since resistance welding is dependent on the resistivity, the heat capacity, the thermal conductivity, and the melting point of the materials involved, a separate weld schedule must be produced for each combination of material, lead size and lead geometry.

Due to the variation in weld schedule between the different leads used, the human factor can be very important in performing resistance welding. As a result, semi-automatic weld parameter selection has been developed to allow operator selection of the desired schedule by merely pushing color-coded switches, Ref. 1. Due to the nature of the resistance welding process and its dependence on the above listed properties, different types of welds are formed. These include fusion welds where a nugget is definitely obtained between the faying surfaces, and the forge weld where solid-state diffusion takes place between the faying surfaces. Therefore, inspection by visual means is not totally adequate in this welding process. Certainly, such things as set-down and expulsion can be determined; however, the extent and nature of the weld zone cannot be determined unless metallurgical sectioning is used. This welding process, being very susceptible to many variables, is usually subject to interim checks on the established weld schedule for a given process. Compared to the solder process, resistance welding does eliminate the third medium, the filler metal, Ref. 3. In most cases it provides for better joint strength, is not as susceptible to vibration, allows for higher operating temperatures, minimizes possible damage to heat sensitive components during assembly, and is more reliable, Ref. 3.

3. Thermocompression bonding. In thermocompression bonding, the materials to be joined are brought into intimate contact by a shaped bonding tool at a temperature below that required for interface melting. Usually at least one of the materials is ductile, and joining is accomplished by diffusion between the two members being joined. Ductility is required in one of the members to eliminate spring back, which could degrade a joint when the bonding tool is removed, Ref. 1.

Certain considerations must be taken into account when thermocompression bonding is used, one of them being the fact that soft, ductile materials are required. Schedules are also required to establish bonding force, time, and temperature. The radius of the bonding tool is important to prevent stress risers, and as in the case of soldering and resistance welding, cleanliness is the utmost importance, Ref. 1.

Two basic thermocompression bonding processes are available, namely, wedge bonding and nail head bonding. They merely differ in the technique in which the bond is formed and configuration of the bond region, however, the bonding mechanism is the same for both, Ref. 1.

4. Ultrasonic bonding. The three procedures for joining microelectronic components discussed above are the conventionally used techniques, whereas ultrasonic bonding is a more recent development. Ultrasonic bonding is accomplished by a tool which provides force and ultrasonic energy to the members being joined. This combination welds by plastically deforming the faying surface in such a manner that oxide films or minute foreign particles are dispersed, and the irregular surfaces made to conform to each other, ultimately producing a metallurgical bond, Ref. 1. Normally considered a cold-joining process, substantial temperature rise is accomplished at the bond surface. It has been noted that these temperatures, although very localized, sometimes reach 30 to 50% of the melting point of the materials being joined, Ref. 1.

Some distinct advantages are available through use of ultrasonic bonding. These include low joining temperature and the capabilities of obtaining sound welds in dissimilar metals. In addition, no electrical discharge is required, and there is thus no accidental damage to electronic parts. Fine wires can be joined to thin foils or thick sections. Also, hermetic seam welds can be produced, Ref. 1. Limitations include the fact that one of the members must have a certain degree of ductility. There also appears to be an upper limit to the thickness of materials which can be bonded and butt-welding techniques have not been developed satisfactorily, Ref. 1.

II. Focused Energy Joining Device Operation

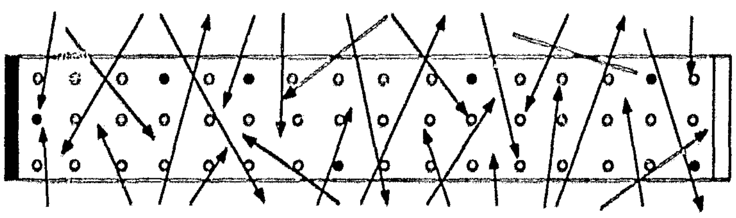
It should be noted that all of the previously discussed techniques require contact between one of the tools used for the joining process and the members being joined. This is the distinct difference between the above techniques and the focused energy techniques used in electron beam and laser welding, discussed in the following.

A. Lasers

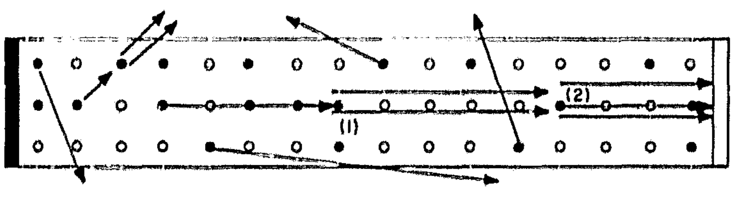
In 1958, Schawlow and Townes first proposed a laser; however, not until 1960 was such a device first operated at the Hughes Aircraft Company Research Laboratory. Since that time, this unique device has undergone continual rapid development and has found numerous applications in the scientific community. Various types of lasers are available, although their basic modes of operation are alike.

The word *laser* is an acronym for *light amplification* by *stimulated emission* of *radiation*. To summarize the operation of a laser, it must be pointed out that electromagnetic radiation [wavelengths between 300 and 0.01 μm (micron)] can interact with matter in three ways: absorption, spontaneous emission, and stimulated emission, Ref. 4. By absorption of energy from an outside source, atoms which have been at equilibrium (occupying the lowest energy level) can be excited to a higher unstable level, Refs. 5 and 6. At this point, decay to a metastable state takes place after about 0.05 μs, Ref. 6. After an additional 1 ms, spontaneous emission occurs, the atom returning to the equilibrium state, Ref. 6. It is during spontaneous emission that fluorescence occurs, Ref. 5. This emission is generally isotropic in nature, energy being given off in all directions, Ref. 4. To achieve stimulated emission, energy is imparted to the excited atoms at which time they return to the equilibrium state, giving off energy to augment the impinging energy. The energy emitted is in the same direction, the same phase, and has the same wavelength as the inducing energy, and thus amplifies it. This resultant amplification is the laser phenomenon, Ref. 5. It can be seen that the process of stimulated emission is the inverse of the process of absorption, Ref. 4. Thus, a laser requires a material in which more atoms can be excited to a higher energy level than in a lower energy state; i.e., a population inversion, Refs. 4 and 6.

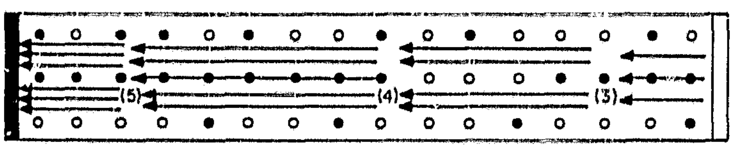
To develop the laser phenomenon, various types of materials can be used. This has resulted in the development of numerous laser systems encompassing solids, liquids and gases. One material which has been utilized a great deal is the pink ruby (Al_2O_3 doped with Cr_2O_3). To illustrate the phenomenon, consider a ruby laser. A ruby rod, having optically flat and parallel ends, is the active material. To its ends are applied mirrored surfaces,



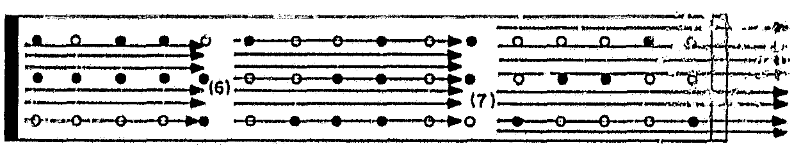
a. PUMPING OF ACTIVE ATOMS FROM GROUND STATE (DARK) TO EXCITED STATE (LIGHT)



b. SPONTANEOUS EMISSION (FLUORESCENCE). POINTS (1) AND (2) INDICATE STIMULATED EMISSION RESULTING IN AMPLIFICATION. NOTE: PHOTONS DIRECTED IMPROPERLY PASS OUT OF THE RESONANT CAVITY



c. REFLECTION OF PHOTONS BACK INTO THE ACTIVE MEDIUM AND STIMULATED EMISSION AT POINTS (3), (4), AND (5)



d. WAVE FRONT REFLECTED AGAIN, STIMULATING EMISSION AT POINTS (6) AND (7) AND FINALLY ESCAPING THROUGH PARTIALLY SILVERED END OF RESONATOR

Fig. 1. Feedback amplification principle as applied to the laser (from Ref. 5)

one being a totally reflective surface, while the other is partially reflective. In the ruby laser, the energy is supplied (or pumped) by a flash-lamp (usually xenon) which gains its energy from the discharge of a capacitor bank. The operation, shown in Fig. 1, proceeds as follows:

The flash lamp raises the energy level of the active atoms (Cr^{+++}) from the ground state. They, in turn, spontaneously return to the ground state, emitting energy while doing so. The spontaneous emission is randomly oriented, thus some energy merely passes out of the ruby rod (Fig. 1a). However, those having an orientation the same as the induced energy result in amplification of energy (Fig. 1b). This amplified energy is reflected back and forth between the two mirrors resulting in continued amplification (Fig. 1c) until saturation is achieved (Fig. 1d) at which time most of the energy is emitted through the partial mirror on the ruby rod, Ref. 5. This greatly amplified wave of light is a highly collimated and monochromatic beam which can be focused by simple optics. A simple laser schematic diagram is shown in Fig. 2.

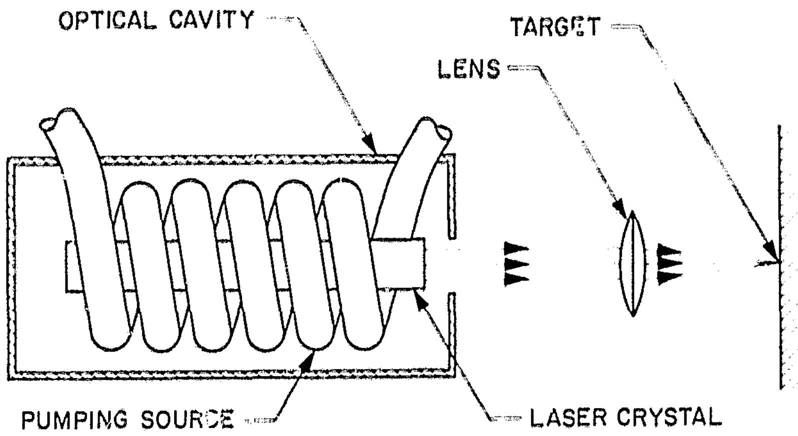


Fig. 2. Schematic diagram of laser welder (from Ref. 7)

Lasers can be divided into four classes: optically-pumped solid state lasers, gas lasers, injection or semiconductor lasers, and liquid lasers, Ref. 8. The present state of development of lasers shows that only the optically-pumped solid state device has the necessary characteristics and development to make it suitable for welding applications.

In addition to the pink ruby laser described above, a second solid state laser is the neodymium-doped glass laser. This device consists of an optical glass rod to which has been added the rare-earth element neodymium in amounts of about 4%, Ref. 4. This device emits a laser beam of 1.06-μm wavelength, Ref. 4. Monochromaticity, small beam divergence, and the ability to be operated continuously are the chief attributes of the gas laser, Ref. 8. In general, this laser is such that its power output is too low to make it suitable for welding applications; however, work is progressing in this area. Laser oscillation can result by mixing carbon dioxide, nitrogen, and helium gases under special conditions. The oscillations result in a 10.6-μm wavelength, as achieved by simply running a current through the discharge, Ref. 8. This is basically the carbon dioxide laser. Most of its work has been limited to cutting and slitting, while very little welding development has been done. A second gas laser is the helium-neon gas laser. It operates in very much the same manner as the carbon dioxide laser. However, continuous oscillations can be obtained at any one of various wavelengths, Ref. 4. The most useful ones are 0.63 and 1.15 μm. Of the remaining two types of lasers, the injection laser is a very efficient device that can be continuously operated. Its power output is much too low for welding applications. In addition, a relatively high beam divergence is a characteristic of this type of laser. Liquid lasers have a like characteristic, that of beam divergence. Also, they have not been developed sufficiently for use in welding, Ref. 8. The specific lasers discussed above under the different classes of lasers, are the more common types. Table 1 presents the spectrum of laser systems and shows not only the type of laser, but the mode of operation that can be expected, the wavelength achieved,

Table 1. Spectrum of laser systems (from Ref. 9)

Type of active medium	Mode of operation P = pulsed CW = continuous wave	Primary output wavelength Å = Angstroms μm = microns	Typical or potential applications	Other considerations
Solid state crystal Ruby	(From several P/s to 1/min)	6943Å (Red)	Variety of uses which require high laser output energies [1 to 100 J (joules) typically], including: Welding, drilling of metals and other materials (see text), medical research, ranging, space communications, and ionospheric studies	Ruby is structurally quite rugged and chemically stable. Available output power from pulsed solid state lasers ranges up to many gigawatts
YAG (Yttrium aluminum garnet doped with neodymium)	P + CW (for very short durations—few seconds)	1.06 μm (Infrared)		
Calcium tungstate, calcium fluoride, and others	P + CW	1.06 μm 2.04 μm 2.59 μm and others	CW operation of this group offers potential as general research tool	This group of crystals may be somewhat fragile and sensitive to many environments (water soluble)
Glass Various glasses (borate, silicate, soda-lime-silicate) doped primarily with neodymium	P	1.06 μm	Used where the very highest energies are required, including: Metalworking, weapons research, and medical research	The family of glass laser materials are not single crystals and consequently allow for the fabrication of laser rods of several feet in length by inches in diameter
Gas Helium and neon (alone and in various combinations)	Usually CW (can be pulsed)	6328Å 1.15 μm 3.39 μm	Metrology, optical research and demonstration, microscopy, space communications, photography	Gas lasers can furnish very stable, continuous, visible, or infrared energy which has high spatial and temporal coherence
Argon Numerous other gases	Usually CW (can be pulsed)	Several lines in the blue-green region (some in infrared)	Medical research, micrometalworking	Higher average powers are available from the argon system (1-10 W)
Semiconductor (injection) Gallium arsenide (most common) Others	P (up to 1 kHz) + CW	Numerous infrared	Space communications and navigation, metrology	Complete unit (diode + power supply) can be housed in a small, lightweight package—requires only low voltages and currents—several watts of output power are available promising potential as a microwelder and in other uses requiring higher powers—most designs require liquid nitrogen cooling of diode
Other types Some operating systems are available using plastics (chelates) or liquids as active media. Research in these and other media is being carried on	P + CW	—	May serve purposes similar to gas or injection systems	

Table 2. Operating characteristics of the three common lasers (from Ref. 10)

Laser type	Seniority and experience	Performance reliability in a production environment	Usefulness for metallic welding	Usefulness for transparent materials welding	Cost per zap including depreciation	Maximum economic weld size	Ambient control required
Pulsed ruby	A	A	A	F	2–5¢	1 mm^3	No
Pulsed neodymium glass	B	C	B	D	2–5¢	1 mm^3	No
Continuous CO_2	C	D	D	A	Not established	25 mm^3	Yes
	Comparison of features of laser systems			A: best F: worst			

plus typical applications and other considerations. Table 2 presents data on three common lasers; namely, the pulsed ruby, the pulsed neodymium glass, and the continuous CO_2 laser. This table basically compares the features of each of these systems with respect to their applicability in welding, their costs, etc., Ref. 10.

The laser has been the subject of theoretical considerations and test programs with regard to its applicability to welding. Adams and Fairbanks, Ref. 11, approach the capability of laser beam fusion welding from a theoretical standpoint. They followed this up with metallographic observations concluding that materials with high thermal diffusivity, such as copper, silver, and gold, are ideally suited to laser welding. In addition, they stated the future of laser welding generally appears bright. Many other investigators have continued efforts to evaluate the capability of the laser as a welding tool, Refs. 5, 7, 12, and 13. These investigations included not only metallurgical examination but strength determinations, and in those areas where the joining for electronics was a consideration, joint resistance was also determined. Some of these data are discussed in Section IV of this report.

Since the reflectance of the material being welded is such a prime consideration in laser welding, it has been found that the lap or parallel-wire joint is the most optimum type of joint for laser welding. Figure 3 compares the advantages of a parallel-wire joint, as opposed to the cross-wire joint. This depicts an important consideration when using a light beam, such as available from a laser source. Care must be exercised in utilizing a laser for welding, since there is a limit to the power intensity that can be tolerated in welding, Ref. 14. If this intensity is too high, boiling occurs on the surface and vaporized metal is emitted resulting in laser drilling. By controlling the intensity supplied to the metal surface, welding occurs. For most common metals this is around 10^5 to 10^6 W/cm^2, Ref. 14. It should be noted that the laser, on impinging the metal surface, creates a molten area, and its depth of penetration is gained by the thermal properties of the materials being welded, Ref. 8. Thus the laser, in its present state of development, is limited to the thicknesses which it can weld. These thicknesses, however, are such that application to microelectronic circuitry can be achieved with presently available equipment. The intensity of the beam at the surface of the metal must be sufficient to raise a temperature up to the fusion point, but below the vaporization point. Also, the energy must be supplied in a short enough length of time to permit localized heating, but also long enough to permit penetration of the molten zone by thermal conduction, Ref. 8. This requires control of the total energy, the rate of energy delivery (the pulse shape and pulse duration) and the power density at the surface (the spot diameter), Ref. 8.

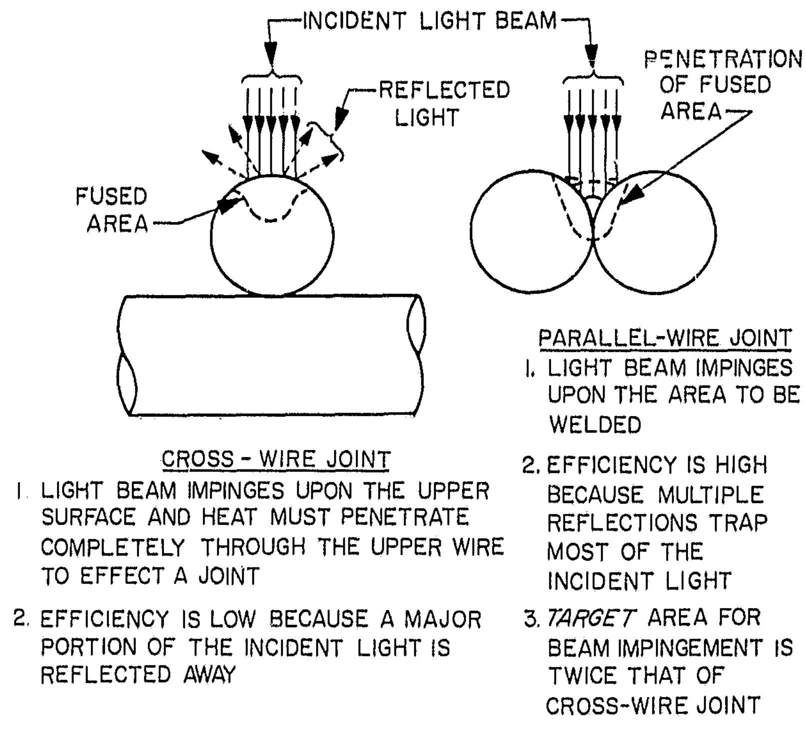


Fig. 3. Advantages of the parallel-wire joint over the cross-wire joint when welded with a laser beam (from Ref. 3)

B. Electron Beams

The electron beam, although applied to welding more recently, has been recognized as a source of heat for years. In early years, this heating effect was regarded as a nuisance, especially by those involved with electronic tubes, cathode-ray tubes, and X-ray equipment. Some instances, such as in X-ray equipment, require water cooling to alleviate this unwanted effect. As early as 1907, Pirani designed a furnace and acquired a patent to melt tantalum and other refractory metals by the use of electron beams. It was not until 1957, through the work of Steigerwald, and as indicated in publications by Stohr, that electron beams were considered for welding. Since that time, this technique has undergone considerable development throughout the world, and is now considered a recognized technique, Ref. 15. Figure 4 is a schematic of a typical electron beam welding machine.

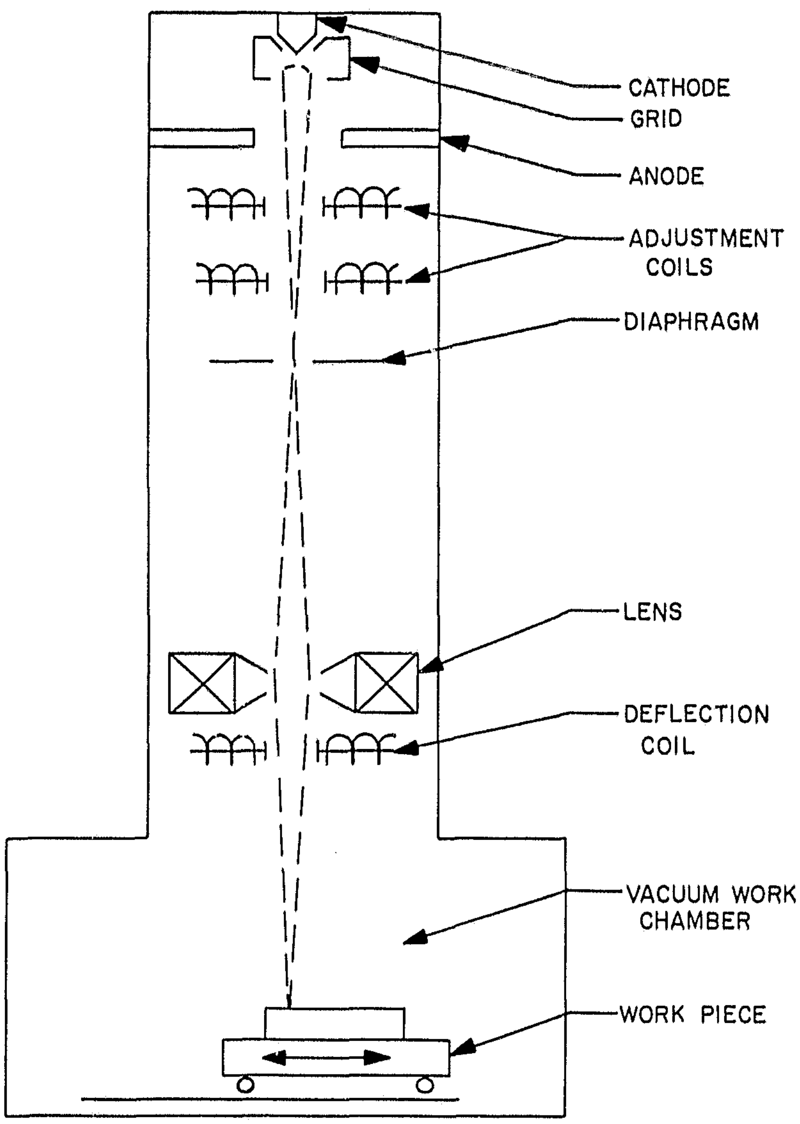


Fig. 4. Electron beam welding machine schematic (from Ref. 16)

Basically, the electron beam process consists of acceleration of electrons which are focused by electromagnetic and electrostatic means to a spot size and impingement of these electrons on the surface of a material to be welded. The kinetic energy of the electrons is instantly transformed into heat, Ref. 17. The beam is formed by boiling off electrons from a heated filament cathode, Ref. 18. Most equipment uses refractory metal cathodes, such as tungsten or tantalum; however, in Russian equipment lanthanum hexaboride is often used as the cathode material, Ref. 15. Electrons emitted from the filament are accelerated by an electric field developed between the anode and cathode. They pass through a hole in the anode and continue on toward the work, Ref. 17. The beam is focused to a small diameter by use of a magnetic focus coil or lens, as shown in Fig. 4. In addition, deflection coils to provide for movement on the X and Y axes of the workpiece are usually provided. This deflection is also magnetically induced. Controls are available to regulate a number of variables that affect the weld schedule. These include accelerating potential, filament current, focus current, work or gun velocities, and positioning, Ref. 17. By means of deflection coils the beam can be scanned, moved from point to point, and oscillated, depending on the nature of the work. In addition, the beam can be pulsed and varied in intensity, Ref. 18. It should be pointed out that precautions are necessary in using or designing electron beam equipment since secondary emission in the form of X-rays can result. Therefore, the chamber in which this operation takes place must provide for adequate protection from any such happening, Ref. 15.

Electron beam equipment was originally developed for use in vacuum chambers. In early work, the vacuum chambers were a necessity; however, in recent developments partial vacuum and nonvacuum electron beam welders have become available, Ref. 19. However, due to the nature of the electron beam, such devices do not produce a very small spot size. The beam is first developed in a vacuum and is passed through consecutive chambers whose pressures are greater and greater, until it is finally emitted from the last chamber into the air, or into a gas atmosphere. When the beam passes from vacuum into the dense atmosphere, the electrons collide with the air or gas molecules and are thus scattered causing divergence of the beam, Ref. 19. As a result, the beam is not small in size, and the weld head must be in very close proximity to the workpiece. Estimates vary from 0.25 to 0.5 in., Ref. 15, and from 0.040 to 0.25 in., Ref. 12. Such an arrangement is far from optimum for use in microcircuit welding. Thus, nonvacuum or partial vacuum electron beams were not considered any further for investigation in this program.

The electron beam device has demonstrated over the years its capability to successfully weld structural members, as may be seen in the aerospace industry. Its capability of being focused to an extremely small spot, plus the fact that it can be automated make it very attractive to the electronics field.

III. Characteristics of Focused Energy Devices

Numerous characteristics of focused energy welding techniques were obtained in the search through the open literature and through contact with various organizations. These characteristics include both advantages and disadvantages in using laser beams or electron beams as a joining procedure in spacecraft electronic welding. Both processes exhibit similar characteristics in some respects; however, there are certain basic differences which will be discussed. In addition, a comparison of the two processes, with respect to these characteristics is also presented.

A. Advantages of the Laser and Electron Beam

The laser and electron beam, although imparting heat to the materials to be joined in a different manner, possess certain inherent characteristics which make them attractive for use in microcircuit joining of materials. One of the uppermost of these is the fact that the beams can be focused to an extremely small spot, thereby reducing the hazard of thermal damage to nearby sensitive components, Refs. 8, 14, 16, and 20–23. In addition, the small spot size permits welding of high density microcircuit components, Refs. 8 and 24, since a tool such as an electrode or soldering iron tip is not required to contact the joint. As mentioned earlier, the main difference in focusing of these two devices is that the laser merely requires simple optics, Refs. 1, 5, 24, and 25. Focusing with a laser is thus readily accomplished and is extremely accurate, Refs. 5 and 25. The electron beam device, on the other hand, requires sophisticated electromagnetic and electrostatic equipment in order to focus the beam to the desired spot size; however, very small spots are achieved, on the order of 0.0005 to 0.010 in., Ref. 1. Early reports cite the fact that a laser beam, 0.25 in. in diameter, was focused to a 0.005-in. size spot, using a standard 10X microscope objective, Ref. 26. Later work mentions that the laser beam is capable of being focused to a few thousandths of an inch, Refs. 7 and 27, with positioning as accurate, Refs. 7, 13, 20 and 27. In a more recent publication, the spot size is claimed to be focused down to 0.0001 in., Ref. 28.

In addition, these beams can be precisely aligned. Such alignment provides accessibility of the beam to areas considered difficult to reach using conventional techniques. This, coupled with the capability of providing an extremely small spot size, offers a great potential with respect to higher packaging densities. Areas which can not be readily reached by conventional joining techniques could be reached using laser or electron beam techniques.

As shown in Table 3, the laser and electron beam provide very high power intensities, as compared to other sources of heat. Such a high power intensity in turn provides for the development of extremely high temperatures in a localized area. This, coupled with the first advantage of focused energy devices discussed above, that of small spot size, provides for very small heat-affected zones in focused energy welding. Laser and electron beam equipment thus generate extremely high temperatures.

Table 3. Comparison of heat sources for welding (from Ref. 14)

Heat source	Power intensity, W/cm²
Laser	up to 10^9
Electron beam	up to 10^9
Electric arc (Argon—200 A)[a]	1.5×10^4
Oxygen-acetylene flame[a]	10^3
Oxygen-hydrogen jet burner[a]	3×10^3
Black body radiation,[b] °K	
6,500	10^4
11,500	10^5
20,500	10^6
36,500	10^7
65,000	10^8
115,000	10^9

[a]Experimentally determined for heat transferred to flat surfaces.
[b]Calculated.

The capability of generating such high temperatures makes welding of most materials possible, Refs. 5 and 26. In fact, the laser can melt or vaporize almost any known material, Refs. 3 and 22. It has been mentioned that it is as easy to make a hole in alumina as it is in copper, Ref. 29. Utilizing these techniques, materials otherwise considered difficult to join can be welded, Refs. 1, 7, and 27. Even dissimilar metals can be joined, provided their metallurgical characteristics permit such joining. In addition, metals with high electrical resistance can be joined, Refs. 7, 13, 20 and 27. Information gathered in the literature also shows that parts varying tremendously in mass and size have been welded using these techniques, especially the laser, Refs. 7, 13, 16, 20, 27, 28, and 30.

An additional advantage in using focused energy techniques is the fact that no contact is necessary between the joining media and the parts to be joined, Refs. 1, 8, 10, 12, 16, 20, 23, and 25. This, of course, is the main difference between focused-energy techniques and the conventionally used techniques in the electronics joining field. Because no contact is necessary, there is no possibility of electrode contamination as found when resistance welding is used, Refs. 8, 12, 20, and 28. In addition, the focused energy technique provides for freedom from high electrical currents, which may cause component damage, Ref. 8, as may also be experienced in welding where conventional resistance techniques are used. Again, accessibility is a prime consideration due to the fact that no contact is necessary, Refs. 7, 13, 14, 21, 27, and 31. As a result, packaging density is increased considerably, Ref. 1. Also, as compared to solder joining techniques focused energy welding does not require the addition of any foreign materials which can cause variations in the joint, Ref. 12. The laser and the electron beam processes also are not sensitive to surface irregularities or impurities, Ref. 1. By eliminating contact between the heat source and the parts to be joined, parts are not physically displaced, Refs. 12 and 29. In addition, no strains or mechanical deformation result, Ref. 25.

Another advantage in using focused energy welding is the fact that both processes can be automated, Refs. 1, 8, 21, 28, and 30. Automation with precision accuracy can be attained using electron beams since they have the ability to be precisely controlled with regard to beam parameters and location, Ref. 1. Since lasers are capable of being focused optically, they too have the same advantage. Optical focusing, being simpler, may prove the laser to be easier to automate. Relative motion between the welding device and the parts to be welded is an important consideration in automation. Using resistance welding, movement of the welding tool, the work, or both can be accomplished. With the electron beam technique the same is true; however, the electron beam has the added advantage in that the beam can be deflected by magnetic means, Ref. 30. In addition, electronic programming of the beam is also possible, Ref. 30. To some extent, the laser beam can also be manipulated, since it is a light beam and can be reflected by mirrors. Present laser welding uses pulsed techniques and, as a result, assembly line techniques are possible. Parts could be automatically positioned under the laser and the beam tripped by a microswitch, Ref. 21. Also, the laser requires a minimum of fixturing, thus mechanization could be easily accomplished, Ref. 28.

Because they are a welding process, lasers and electron beams provide better electrical contact and also provide high reliability joints, Refs. 16 and 24. At a given welded junction, lower resistance is presented to the flow of electrical current, since the interface between welded metals is minimized or eliminated. A solder joint which exhibits several interfaces could result in current flow through several layers. This is eliminated using welding techniques, Refs. 1 and 16. The electron beam welding process proves to be very reliable, since welding also improves reliability over solder connections because they are less susceptible to contamination during joining. Also, the electron beam, requiring a vacuum to weld, further minimizes oxidation. The nugget structure thus formed improves the connection from the standpoint of resistance to vibration, stresses, and fatigue damage, Ref. 16. The laser also forms a nugget type weld, however, it is not necessary to accomplish the weld in a vacuum.

One of the basic differences between laser and electron beam welders is that the electron beam technique requires a vacuum in order to operate in the manner which we desire for electronic welding. As mentioned earlier, nonvacuum electron beam techniques have been developed, but, due to the diversion of the beam on entering an air or gas atmosphere, the control of the beam focus to the desired small diameter becomes very difficult. Welding in a vacuum results in certain attractive attributes. The vacuum in the electron beam welding technique promotes cleanliness, Ref. 15. In the first case, parts are cleaned prior to enclosing in the vacuum chamber. Decreasing the pressure in the chamber results in outgassing or removal of any materials whose vapor pressures are such that they become unstable in the vacuum environment. This adds an additional cleaning procedure, so to speak, in the electron beam process. Second, welding in the vacuum provides a high purity atmosphere in which the weld is melted and resolidified, Ref. 32. This high purity atmosphere eliminates many contaminating elements which are a detriment to joint quality, Ref. 1. Another factor associated with welding in a vacuum is the fact that metals which are easily damaged on heating in air can be electron beam welded with confidence, since the vacuum is used, Ref. 30.

Lasers, on the other hand, do not require a vacuum environment to operate, Refs. 1, 26, and 32–36. In fact, the laser can operate in any atmosphere which allows passage of the beam, Refs. 5, 7, 23, 25, 28, and 31. Welding can also be accomplished inside a chamber or other object with the laser head on the outside provided a port, made of a transparent material such as glass, is available through which the beam can be focused, Refs. 5 and 25. Any transparent materials can be used to transport the laser beam, Refs. 7, 28, and 31; even certain liquids, Ref. 28. Some difference of opinion exists with regard to the welding of reactive materials with the laser. Early reports recommend the use of inert gas to shield such materials and avoid any contamination or oxidation, Refs. 20 and 32. Later reports mention that no vacuum or shielding is required when welding reactive materials with a laser, Refs. 9 and 37. No explanation is offered in these reports as to the reason this can be accomplished; however, it may be the result of the laser weld being accomplished in a very short period of time, in the order of ms. Thus, the contamination or oxidation associated with these reactive materials does not have adequate time to occur to any great degree. This of course would be applicable only to a pulsed laser. Early reports have mentioned that rapid cooling rates associated with the laser may have certain metallurgical benefits, Ref. 5. This nonreaction of normally reactant materials may be one of those benefits.

With the laser welder, another advantage is the fact that operations are very much simplified, Refs. 20 and 21. Early laser welders were very difficult to manipulate, however, later devices have built-in characteristics which require merely aiming the device and pushing a button in order to fire the device. Since the laser is not subject to certain physical characteristics of materials, it does not require extensive preproduction weld schedule testing. The same is true of the electron beam, although it is not as easy to operate as a laser device. As opposed to the resistance welding process, which is controlled by the properties of the materials to be welded, including resistivity, heat capacity, thermal conductivity, and melting point, the laser and electron beam are not affected by such characteristics. This brings us to another feature of the focused energy welding procedures. By welding with a laser or an electron beam device a nugget is formed, instead of the type of joint found with a resistance weld. Resistance welding is very dependent on the resistivity of the materials being joined. This is not the case with the laser or electron beam, thus a critical property is eliminated from the process. Because resistivity governs, to a great extent, the resistance welding process, the type of joint formed by this process varies with the materials being joined. Microsectioning is required to determine joint quality, therefore requiring extensive tests to determine repeatability before proceeding with production welding. The inspector, in reality, never sees the weld in a production joint. Focused energy welding results in surface fusion between the materials being joined. This provides visible evidence that the welding has in fact occurred, resulting in easily inspected welds.

B. Disadvantages of the Laser and Electron Beam

Certain disadvantages also exist in the laser and electron beam welding processes, as in the case of any production process. Some of these are common to both techniques, while others are characteristic of either one or the other.

The major disadvantage associated with laser and electron beam welding is their high cost. This cost not only encompasses the initial cost, but also the operating cost of both devices. As early as 1964, the laser welding operation was estimated to cost approximately 2–5 cents per *pop* or laser pulse, Refs. 20 and 21. This value was based on 15,000 shots. A breakdown of this estimate is as follows:

Flashlamps	1.6 cents per shot
Utilities	0.01 cent per shot
Depreciation	0.32–3.2 cents per shot
Total	1.9–4.8 cents per shot

It is also noted that the basis to which this estimate was made is rapidly changing, Ref. 21. Later reports vary somewhat in their estimates on cost of laser welding. One mentions that the cost has been reduced to 1 cent per shot, Ref. 28, while another report again mentions 2–5 cents per shot, Ref. 10. A difference of approximately 1½ yr exists between these two estimates; the higher being the latest estimate. However, the basis of these estimates is not known, since no cost breakdown is included. An estimate of the cost of an electron beam device for use on small jobs, such as microelectronic welding, is $30,000 for an initial cost, Ref. 30. It should be noted that the author in this case breaks down the cost with respect to tooling, the cost of the electron beam gun, and the cost of the vacuum chamber. Tooling costs were not considered in the initial cost of the equipment since they are considered common to other welding techniques. A comparison of electron beam and laser weld costs is given in Refs. 37 and 38. It is noted that the fixture and manipulation costs of electron beam welding are considered higher due to a greater amount of heat input from continuous operation, and thus there are more extensive fixturing requirements. Present laser welders, on the other

Table 4. Laser and electron beam equipment requirements (from Ref. 38)

Equipment	Electron beam welding system	Laser welding system
Inert gas required	—	—
Flashtubes	—	X
Filaments	X	—
Workpiece manipulator	X	X
Water cooling system	X	X
Power source	X	X
Welding head	X	X
Vacuum chamber	X	—
Diffusion pump	X	—
Holding pump	X	—
Roughing pump	X	—

hand, operate in a pulsed mode, and simple tooling such as wood thus can be used. Table 4 presents equipment requirements for the electron beam and laser welding systems. A cost comparison as taken from the same reference is given below, the comparison being based on the ability to weld material thicknesses up to 0.020 in., since the laser is somewhat limited in this respect. From Table 4, the flash tubes of the laser system and the filaments of the electron beam system are considered to be equivalent from the cost standpoint and a replacement basis. Water cooling is required of both systems since the electron beam requires cooling of the diffusion pump used for creating vacuum, and the laser uses water for cooling of the laser head which includes the ruby rod and flash tube. Considering recirculation of the water, costs would be about equal. In considering power sources, the electron beam welding process requires such power as 20,000 to 60,000 V for low-voltage systems, and from 60,000 to 200,000 V for high-voltage systems. The laser power source, on the other hand, is a conventional capacitor discharge type and is considerably lower in cost.

Based on the power source requirements for both welding processes, the average cost estimate for the laser would be approximately 30% that for an electron beam. Proceeding further and comparing welding heads of both devices, an average electron beam gun would be approximately the same cost as an average laser head, except for the ruby rod in the head. This ruby rod, if destroyed through improper operation, would cost in excess of $1000 to replace. The exciting energy for the laser head is a flash tube which, if blown, costs on the average of $100 to replace. On the other hand, refractory alloy filaments used in electron beam guns cost an average of $3 to replace. The life expectancy of a flash tube is considered to be in the order of 30 times longer than that for a filament; therefore, a flash tube to filament cost comparison probably balances out. Backup equipment to make the processes possible is an additional cost. As a general rule, electron beam welding processes require complete evacuation systems consisting of a diffusion pump, a roughing pump, and holding pumps. In using a laser, on the other hand, vacuum chambers and associated equipment are not required. In comparing the two processess from this standpoint, a major imbalance occurs since the laser has no cost in this area, whereas the electron beam has extremely high cost, ranging up to about $10,000 for such a pumping system.

The second major common disadvantage in using electron beam and laser welding processes is the possibility of fixturing problems. Since both devices do not contact the materials they are being used to join, some means must be provided so that contact is maintained between materials being joined during the welding process. These may include simple clamps, etc. Due to the small spot size which laser and electron beam devices generate, it is essential that the parts being welded be in very close proximity to each other. For repair work the laser, as a matter of interest, has been demonstrated to be capable of bending a material so as to touch a second material at which time they could be joined, Refs. 13, 27, and 39. Bending is accomplished by impinging the beam on one side of the material to be bent.

The laser welding device presents a number of disadvantages. Many of these disadvantages are the result of its very recent development, and it is expected that many of its undesirable characteristics will be overcome in the future. The laser, basically a light beam, acts as light and can be reflected from highly polished surfaces, Refs. 29 and 40. Many highly polished metals can reflect 90% of incident light, Refs. 1 and 20. This results in a very low absorptance of the light, which in turn results in low heat and difficulty in welding. However, it is noted that once the material is molten, the absorptivity is constant, Ref. 20. It is known that the laser depends on the thermal diffusivity of the material to achieve depth of the molten zone. Thus, after the material has become molten by the impingement of the light, further light impingement is not varied to any great degree since that molten zone is of constant absorptivity. Further growth of the molten zone is dependent on thermal diffusivity of the materials involved. The reflected light of the laser also presents a problem with regard to personnel safety since eye damage could result, Ref. 1. It is expected that the operator of a laser should become as familiar with his piece of equipment as the operator of any other metal working equipment. In this case, familiarity will help to alleviate any possible eye damage. In addition, many present lasers have protective devices for operator safety, thus precluding the possibility of eye damage. In the search of the literature, a technical article covering safe laser welding was found, Ref. 41. The following is a short summary of guidelines for safe laser welding:

(1) The laser beams should be discharged into a background that is nonreflective and fire resistant.

(2) Personnel should be cleared from a reasonable distance on all sides of the anticipated path of the beam.

(3) Looking into the primary beam must be avoided at all times. Equal care shall be exerted to avoid looking at specular reflections of the beam, even those from lens surfaces.

(4) Avoid aiming the laser with the eye. Looking along the axis of the beam increases the hazard from reflections.

(5) Work with lasers should be done in areas of high general illumination to keep the pupils of the eyes constricted, and thus limit the energy which might inadvertently enter the eyes.

(6) Some laser electronic firing systems may store a charge. Caution should be exercised to avoid accidental pulsing of the laser to avoid electrical shock.

(7) Individuals working in laser test procedures, laser weld operators, and others frequently exposed to laser discharges should be included in a program which covers occupational vision, including thorough general eye examination at regular intervals. Safety eye wear designed to filter out specific frequency characteristics of the laser system will give protection, but it may only be partial.

In applying these guides, the following facts should be kept in mind:

(1) No acceptable threshold limit for exposure has been established.

(2) The effects of atmospheric diffraction upon the beam still remain to be measured.

(3) Atmospheric attenuation needs to be quantitated.

(4) Mirror reflections may cause as much biological damage as the original beam.

(5) Safety eye wear only offers limited protection.

It should be noted that this article was published in April, 1965, and some of the characteristics of present laser welders may present a more safe design than what was known then. However, looking at the laser beam or at the reflected beam should definitely be avoided.

Another outstanding disadvantage of a laser welder is its low power output or output efficiency. The output is affected by the temperature of the flash tubes and ruby rods; thus, adequate temperature controls are required, otherwise there is a degradation of the output of the laser, Refs. 1, 26, and 33. Inefficiencies in the laser are caused by crystal imperfections and cooling techniques. Laser efficiency (radiant energy output electrical energy input) ranges from 0.1 to 3%, Ref. 22. The low efficiency and lack of high output are mainly caused by three factors: (1) inefficient use of the energy from the pump by the laser crystal, (2) crystal imperfections and limitations, and (3) limited crystal cooling, Ref. 22. A number of programs are under way to improve much of this disadvantage, some of which are discussed in Section V of this report.

Another limitation to the laser is the fact that lasers presently designed for welding operations are pulsed devices rather than continuous working devices, and are therefore subject to intermittent operation, Refs. 26 and 42. The pink ruby laser and the neodymium-doped laser, both pulsed devices, are more conducive to welding because of their higher power. As discussed earlier, the laser also is limited in a thickness of welds that it may join. Estimates for the ruby laser are that welding can be accomplished up to 0.032 in., which does not make such a device very conducive to general structural welding. However, such a device certainly has the capabilities of welding on the microelectronic scale. Continued efforts are taking place in laser development with respect to the limited thickness capability and the pulsing characteristics. These will be discussed in a later section of the report.

With regard to the electron beam welder, one of the features considered an advantage by many people must also be considered a disadvantage. This is the necessity to operate such a device in a vacuum environment. From the standpoint of a production process, such a requirement must be considered a disadvantage since pumpdown time and the additional cost of equipment over and above that of the basic welding device contribute to a higher operational cost. Of course, on production line operations such a device may have consecutive chambers in which elements to be welded are stored prior to entry into the weld chamber, thus helping to reduce the time necessary for pumpdown.

IV. Evaluations of Focused Energy Welding

This section covers test programs, which were established to determine the feasibility of using laser and electron beam devices for welding of microcircuit joints.

A. Laser Weld Test Results

Early papers, covering the feasibility of welding with a laser device, covered the process from a standpoint of metallurgical examination. Some basic work, covering the weldability of Zircalloy-2, was conducted to determine the capability of achieving a weld and the depth of weld penetration, Ref. 34. In addition, other reports investigated the nature of the laser in regard to welding and machining, Ref. 5. Basically, metallurgical examination of the weld joints involved was the heart of the program. Later work conducted by the Linde Division of Union Carbide Corporation, Refs. 7, 14, 21, and 31, demonstrated much of the laser's capability. Shown in Table 5 are the properties of wire-to-wire laser welds of various materials. The processing parameters, such as laser output and pulse length, as well as joint strength and joint resistance are included in the table for different types of joints, including butt, lap, cross, and tee as defined by Fig. 5. It can be seen that the joint strength obtained is quite high, and the joint resistance in ohms

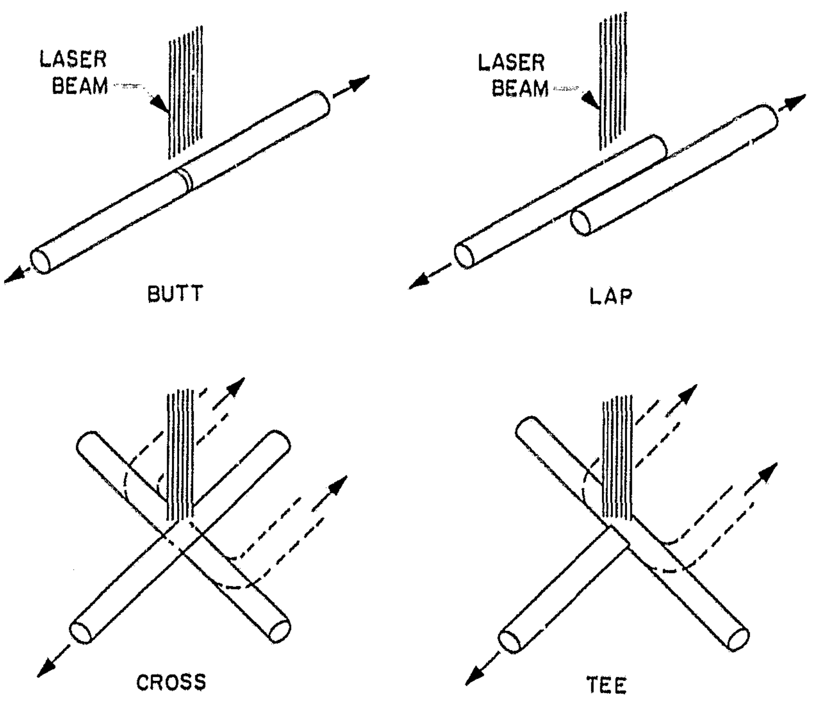


Fig. 5. Basic configurations for wire-to-wire laser spot welds (from Ref. 14)

Table 5. Properties of wire-to-wire laser welds (from Ref. 14)

Material	Joint	Laser output, J	Pulse length, ms (half power)	Joint strength, lb	Joint resistance, Ω
0.015 stainless	Butt	8	3.0	21.3	≤0.003
	Lap	8	3.0	22.8	≤0.003
	Cross	8	3.0	25.0	≤0.003
	Tee	8	3.0	23.2	≤0.003
0.031 stainless	Butt	10	3.4	31.8	≤0.002
	Lap	10	3.4	34.6	≤0.002
	Cross	10	3.4	40.0	≤0.002
	Tee	11	3.6	40.1	≤0.002
0.015/0.031[a] stainless	Butt	10	3.4	24.3	≤0.003
	Lap	10	3.4	24.8	≤0.003
	Cross	10	3.4	25.6	≤0.003
	Tee	11	3.6	22.0	≤0.003
0.015 copper	Butt	10	3.4	5.1	≤0.001
	Lap	10	3.4	3.2	≤0.001
	Cross	10	3.4	4.3	≤0.001
	Tee	11	3.6	3.2	≤0.001
0.020 nickel	Butt	10	3.4	12.2	≤0.001
	Lap	7	2.8	7.8	≤0.001
	Cross	9	3.2	6.8	≤0.001
	Tee	11	3.6	12.5	<0.001
0.015 tantalum	Butt	8	3.0	11.5	<0.001
	Lap	8	3.0	8.8	<0.001
	Cross	9	3.2	9.3	<0.001
	Tee	8	3.0	10.8	<0.001
0.025 tantalum	Butt	11	3.5	14.8	<0.001
	Lap	11	3.5	12.9	<0.001
	Tee	11	3.5	17.0	<0.001
0.015/0.025[a] tantalum	Butt	10	3.4	11.0	<0.001
	Cross	10	3.4	9.2	<0.001
0.015/0.031 stainless	Tee	11	3.6	26.4	<0.001
0.031/0.016 stainless	Tee	11	3.6	19.6	<0.001
0.015/0.025 tantalum	Tee	11	3.6	19.3	<0.001
0.025/0.015 tantalum	Tee	11	3.6	11.4	<0.001
0.015 copper 0.015 tantalum	Butt	10	3.4	3.8	<0.001
0.015 copper 0.015 tantalum	Tee	10	3.4	4.0	<0.001
0.015 copper 0.015 tantalum	Lap	10	3.4	5.3	<0.001
0.015 copper 0.015 tantalum	Cross	10	3.4	4.1	<0.001

[a]When two wire gages are used, the upper number in the size designation is the size of the top member of a cross or cross bar of a tee.

is very low; both are desirable characteristics for application in electronic welding. A number of different experiments were conducted to establish the reliability of laser weldments. The result of a first series of data, that of 100 lap welds on 0.018 in. nickel is shown below, Ref. 14.

Total number of welds:	100
Material:	0.018-in. diam nickel wire, lap joint
Highest strength:	16.8 lb
Lowest strength:	12.6 lb
Average strength:	14.78 lb
Standard deviation:	0.682 lb

All welds were made with an output of 11 J (joules). Welds are made individually with no further machine adjustments. Handloading was used with alignment or sighting occurring before welding. By conducting the program in this manner, inconsistencies could be the result of either operator or machine variations, or both, Refs. 4 and 14. Figure 6 depicts the results of experiments to determine the effect of laser output on joint strength. It can be seen that control of laser output is a requirement for commercial equipment, Refs. 4, 14, and 21. The effect of sample position was determined in two other series of tests. Defocusing was one of these,

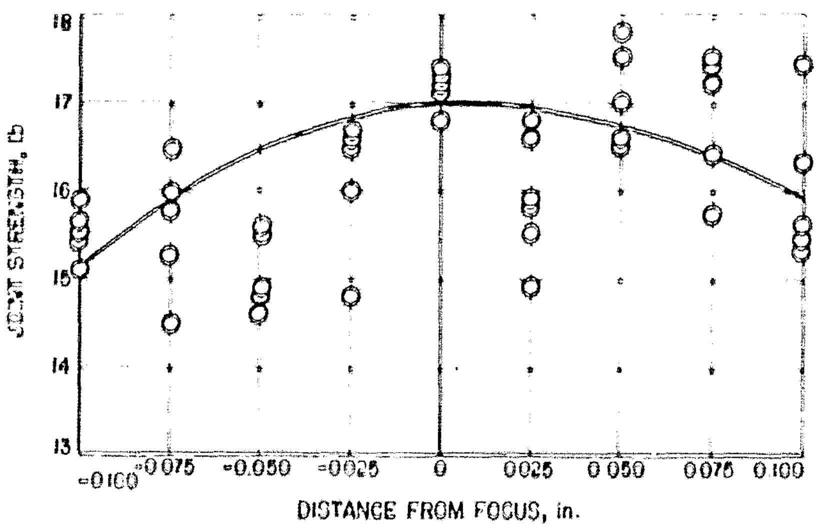


Fig. 7. Effect of distance from optical focal point on joint strength for lap weld between 0.020-in. diam nickel wires (from Ref. 14)

the results of which are shown in Fig. 7. In general, one can be about 0.050 in. out of focus without producing unacceptable welds, Refs. 7, 14, and 21. The second series of tests describes the effect of joint separation distance or gap on the joint strength of laser weldments as shown in Fig. 8. It appears that a gap of approximately 0.005 in. can be tolerated without major degradation of laser weldment strength, Refs. 7, 14, and 21. Since the laser is a light beam, the optimum output energy for welding depends on the physical properties of a metal

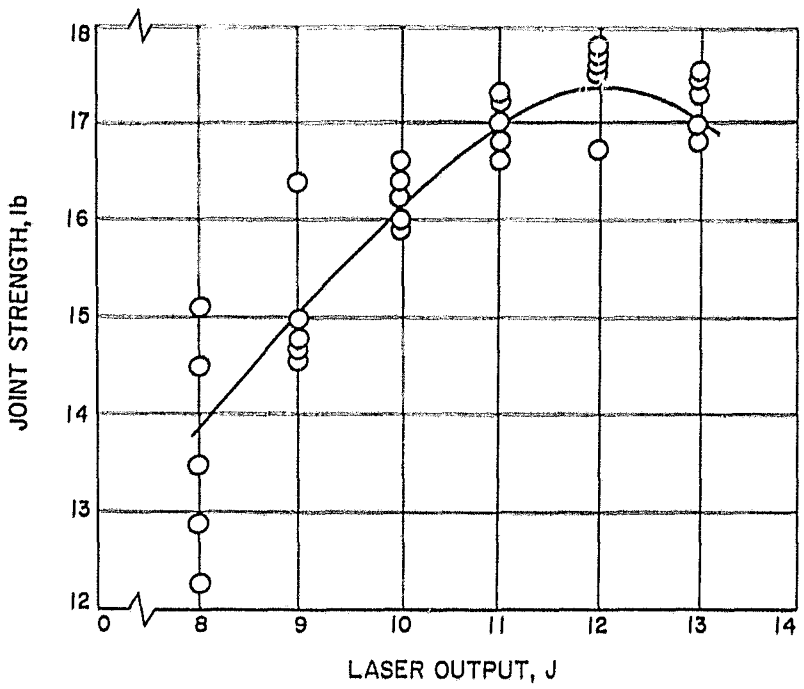


Fig. 6. Effect of laser output on joint strength for lap weld between 0.020-in. diam nickel wires (from Ref. 14)

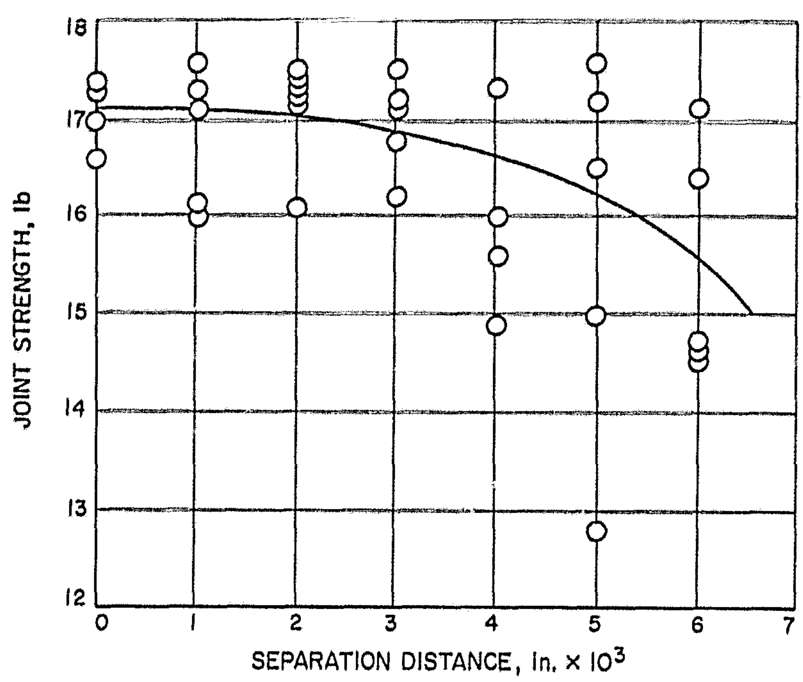


Fig. 8. Effect of joint separation distance on joint strength for lap weld between 0.020-in. diam nickel wires (from Ref. 14)

being welded, as well as the pulse length of a laser, Ref. 7. These properties include absorptivity, thermal conduction, density, heat capacity, and melting point. Since materials being considered for laser welding vary considerably in these properties, it is usually easier to make a few tests to determine the proper setting for the weld, rather than resort to theoretical calculations, Ref. 7. As a guide, the data shown in Fig. 9 were developed. The

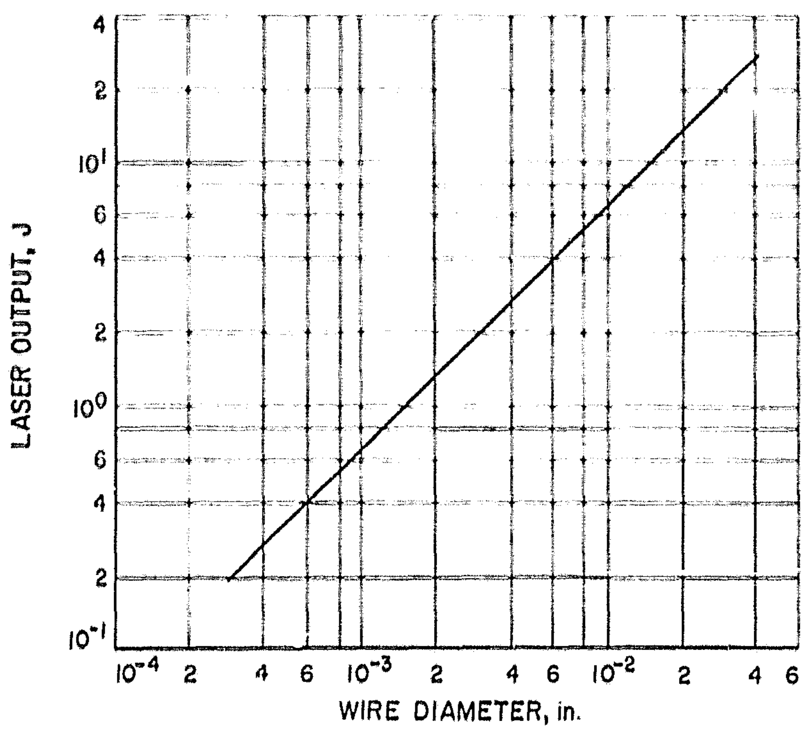
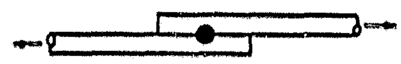


Fig. 9. Approximate laser output required for full-strength welds for various wire diameters (from Ref. 14)

data were derived empirically and depict the laser output required to weld a given wire diameter and obtain a full strength weld, Refs. 7, 13, 14, 21, and 31. Based on the foregoing information, it appears that the laser welder is a reliable piece of equipment for performing microcircuit welding. Rather large gaps between the metals to be joined, of the order of 5 mils, and considerable amount of defocusing can be tolerated without gross degradation of weldment strength. Of course, proper focus and no gap should be used to insure reliability. Table 6 depicts the results of further study on parallel wire joints which have been laser-welded. As expected, the greater number of spots or welds placed adjacent to each other, results in higher joint strength. The results of the further study on the effects of weld machine process variables are shown in Table 7. It is apparent in the table that a wide distribution of energy and pulse duration can result in adequate welds for the particular material combination covered, Ref. 22. An additional fact is that all of the 17 welds had

Table 6. Tensile-shear strength of parallel wire laser welds; material: 0.020 in. nickel wire (from Ref. 3)



Specimen No.	Description	Testing speed, in./min	Load, lb	Remarks
29-2	Single spot	0.5	6.11	
29-3	Single spot	0.5	6.26	
29-4	Single spot	0.5	6.56	
29-6	Single spot	0.5	5.18	
31-1	Single spot	0.5	5.04	Mean = 5.69 lb (25% of wire strength)
31-2	Single spot	0.5	4.51	
31-3	Single spot	0.5	4.70	
31-4	Single spot	0.2	7.00	
31-5	Single spot	0.2	6.22	
31-6	Single spot	0.2	5.27	
31-8	Triple spot	0.2	16.9	
31-9	Triple spot	0.2	16.3	Mean 16.4 lb (73% of wire strength)
31-10	Triple spot	0.2	15.9	
31-11	Quadruple spot	0.2	20	
Control	0.020-in. Ni wire	0.5	22.6	

Table 7. Energy and pulse length combinations that will weld phosphor bronze to palladium (from Ref. 22)

Energy, J	Pulse length, ms	Pull strength, lb
3.11	3.5	3.34 ±0.13
2.30	2.3	4.29 ±0.01
2.60	2.4	4.27 ±0.15
2.05[a]	1.8	3.63 ±0.05

[a]Because of difficulty of welding, data include only two samples.

pull strengths greater than that of the fully-annealed wire except one of the 1.8-ms welds, Ref. 22. A study on the use of the laser on welding 5-mil thick aerospace alloys, such as René-41 and D-36 columbium alloy, produced data which are not directly applicable to electronic systems but are still of considerable interest. Mechanical testing revealed high joint efficiencies and good ductility in the welds, while metallurgical evaluation of the laser welds did not reveal any differences in weld character, when compared to other types of welding techniques. The laser welds appeared to possess slightly finer microstructure and narrower heat-affected zones than did electron beam welds of the same materials, Ref. 43.

B. Electron Beam Weld Test Results

There was a lack of published information on electron beam welding specifically oriented to electronic joining. However, application of electron beam welding devices to microcircuit welding has been investigated by evaluation of mechanical characteristics through vibration tests, shock tests, pull-strength tests, thermal shock tests, thermal resistance tests, and bend tests, Refs. 16 and 44. In addition, metallurgical evaluation also has been carried out. The references cited cover separate studies on the same weld combination. The weld consisted of a copper ribbon welded to a metallized ceramic header, the metal being nickel. These studies demonstrated the electron beam welding to be a statistically predictable, exceptionally reliable joining process, Ref. 44. A summary of the evaluation is as follows:

Pull strength: None of the welds failed in the fusion zone, or at a load less than 200 g (grams).

Weld resistance: It was demonstrated that less than three out of 1,000 weld pairs would exhibit a resistance of 0.010 Ω, or greater, with 90% confidence.

Thermal shock: There was no degradation of pull strength observed after thermal shock. It was also demonstrated that no more than 5.5 out of a 1,000,000 weld-pair would exhibit an increase of 0.001 Ω, or greater, in joint resistance.

Extreme ambient temperature: Measurements of joint resistance from −55 to 200°C were below 0.010 Ω.

Vibration: No visible degradation occurred on vibration testing according to MIL-Standard-202.

Metallurgical examination revealed that the fusion zone had a very fine grain structure. In addition, the heat-affected zone was noted to be very narrow.

The above results are taken from the later literature, Ref. 44, which apparently was a follow-on to the program conducted in Ref. 16.

V. Applications to Electronic Circuit Joining

During the course of the literature search, numerous applications were found which either were for use in production or were under evaluation, for both electron beam or laser devices. Many of the applications were very unique in that they could be accomplished only by using laser or electron beam procedures. Certainly more applications have been evaluated, but due to the nature of these processes, some applications and evaluations are proprietary within various organizations. Tests have been accomplished by some of the manufacturers of welding equipment; however, they themselves did not know what the ultimate application was, only that they were given two pieces of metal to weld. A summary of those applications found in the literature which were not considered proprietary follows.

A. Welding Applications for Laser Devices

The first, and most obvious, application is the wire-to-wire weld. Various types of wire-to-wire welds have been investigated, some of which have been shown in previous sections of this report. Based on the information gathered, it appears that lap welds are the best recommended practice for making wire-to-wire joints, due to the adjacency of the materials to be welded. On a cross-wire weld, one material must be melted through before joining can take place, whereas with wires adjacent to one another, as in the lap configuration, the beam strikes the interface, Refs. 7, 13, 14, 20, 21, 27, 28, and 31. The references cited have investigated not only dissimilar metal welds, but also welds of large dimensional differences. Similar and dissimilar metal joints have been made with various materials, including copper, nickel, tantalum, stainless steel, Dumet, Kovar, aluminum, tungsten, titanium, and columbium, Ref. 14. Test data on some of these joints appear in Table 5 of Section IV.

Another configuration which has seen much investigation, is the joint between an integrated circuit flat pack and a circuit board. Investigations have been carried out to determine a good joint design for integrated circuit welding. One investigation evaluated the end, center, and plug configurations, as shown in Fig. 10. Welding ease, in order of configurations are plug, end, and center. The plug-type weld requires a pre-drilled lead on the flat pack. However, the beam strikes both the flat pack lead and the printed circuit board pad, thus fusion of both materials takes place. The same effect is achieved on the end weld. The center weld configuration, on the other hand, requires transfer of energy through the flat pack lead across the interface to the circuit board pad, thus necessitating intimate contact between the two members being joined, Refs. 13 and 27. Because flat pack to circuit board welds are not self-fixturing, further investigations have attempted the use of slotted printed circuit boards to achieve the weld more readily. In this case, the leads from the flat pack are placed in slots provided on the circuit boards, and the laser beam strikes the edge of the flat pack lead and the slot simultaneously, thus performing the weld operation, Refs. 4 and 8. This takes advantage

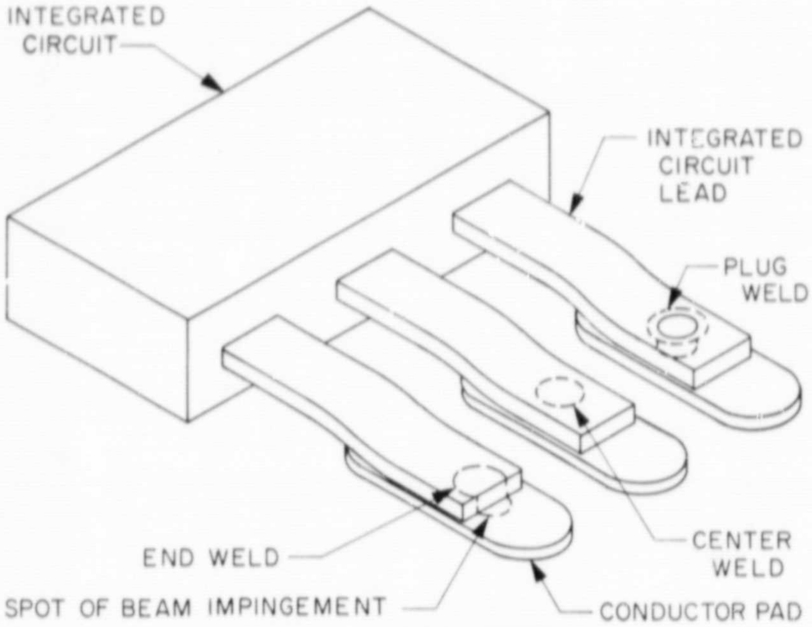


Fig. 10. Joint designs for integrated circuit welding (from Ref. 27)

of the preferred lap configuration for laser welding, and also provides for self-fixturing since intimate contact is automatically provided. Investigators have also evaluated the laser welder with respect to possible damage to substrates on printed circuit boards because the heat input to the flat pack lead is near the theoretical minimum with laser welding. Also, the welds can be inspected visually with high reliability and the laser is not sensitive to changes in lead composition and thickness as with other techniques, Ref. 28. A comparison of the effect of laser welding and parallel gap welding on the substrate of a printed circuit board after welding flat pack leads, is shown in Fig. 11. In this case, a hold-down technique was

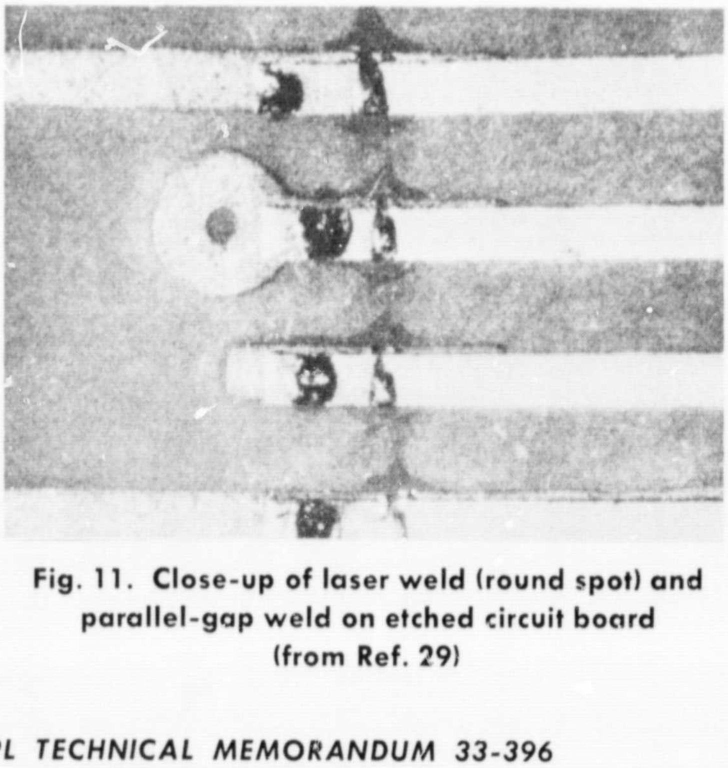


Fig. 11. Close-up of laser weld (round spot) and parallel-gap weld on etched circuit board (from Ref. 29)

used to provide intimate contact between the flat pack and the circuit leads. Figure 11 indicates the small amount of heat penetration allowed by a laser, as compared to the large amount revealed by the parallel gap weld. The dark area around the parallel gap weld is fused epoxy resin, Ref. 29.

Another interesting application of laser welding is the joining of fine wires to miniature magnetic devices, such as inductors and transformers. In many of the investigations, either insulated or bare copper wire is joined, Refs. 4, 8, and 28. In the case of insulated wires, the insulation is not stripped off prior to laser welding. The laser first vaporizes the insulation and then achieves the weld between the wire and the terminal. Insulated wire-to-wire welds have also been achieved by this technique, Ref. 28.

The use of laser devices for joining fine wire to thin films has also been investigated. In one investigation 0.003-in.-thick gold was joined to 2,000-Å-thick gold, which had been deposited on a silicon substrate, Refs. 4 and 8. Other investigators have welded 0.002-in.-thick nickel to a chromium-copper-gold thin film deposited on glass, Ref. 12, and 0.005-in. thick copper interconnect to the same film on glass, Ref. 29. Good weld joints were also achieved between nickel interconnecting ribbon and silk-screened silver paint, Ref. 12.

An application to which laser welders seemed almost perfectly fitted is the joining of wire to Polyweld, Refs. 4 and 8. Polyweld is a circuit board to which small tubelets are applied for joining purposes. These tubelets help control lead positioning and their use results in a large contact area between leads and tubelets, which ultimately result in a large reliable weld, Ref. 8. There are two major problems inherent in laser welding to Polyweld circuitry: (1) waviness in the supporting substrate which causes the weld area to be at a point other than the focal point of the beam, and (2) weak welds which are the result of leads that extend excessively above the tubelets, Ref. 8.

Other interesting applications of lasers in electronic circuitry joining includes interconnections to ceramic micromodules and wire matrix interconnections, Ref. 29. In addition, laser welding has been used to seal relay cans and has been used for the tack welding of aluminum wave guides, Ref. 4.

A very unique approach was demonstrated in the welding of integrated circuit chips to an interconnection pattern, Ref. 24. In this case, interconnection lands are evaporated on the integrated circuit chips. In addition, an interconnection pattern is evaported onto a glass substrate for the proposed system of integrated circuit chips. The chips are then placed with the lands up, and the glass substrate placed with the pattern down onto the chip. Pressure contact was made and the laser beam focused through the glass substrate onto the contact area. Joints were thus accomplished. It is unfortunate that this program was carried out early in the development of the laser and was not as successful as desired due to poor energy control on the unit used since the ruby was uncooled, yet the idea has considerable merit.

An electronic sensing package and a thermistor assembly have also been production-welded by use of a laser, Refs. 38 and 45. On the thermistor assembly the small heat-affected zone achieved with a laser was demonstrated, since the ceramic insulation used was within 0.050-in. of the laser weld and was not subjected to damage. Another interesting application in the same references was the welding of a Type 321 stainless-steel heat shield to a Type 440C stainless-steel bearing housing. Although not an electronic joining application, this approach demonstrates the control and small heat-affected zones achieved with a laser weld. Prior to laser welding, three other joining processes, tungsten–inert gas (TIG), resistance welding, and electron beam, had been tried without success. Yet, the use of a laser welder accomplished the necessary joint with a great degree of success, Refs. 38 and 45.

B. Welding Applications for Electron Beam Devices

Certainly many of the applications mentioned above, which have used or evaluated the laser welding technique, could also utilize an electron beam device. These might include such applications as wire-to-wire welds, welding integrated circuits to circuit boards, the joining of fine wires to terminals of miniature magnetic devices, the sealing of relay cans, and others. Those specific applications found in the search of literature are discussed below.

One of the first applications covered microelectronic joining techniques, utilizing stacked wafers and interconnection ribbons as shown in Fig. 12. The wafers are 96% alumina, edge-metallized with molymanganese, over which nickel in a thickness of 2 mils was electroplated. The ribbons welded to the wafers were [illegible] mil OFHC copper. Electron beam welding was also [illegible] for buildup of the wafer circuits. The same substrate and metallized area were used as well as nickel plating. Microcomponents welded to the wafer included transistors, microdiodes, microcapacitors, and resistors. The wafers were also joined to a motherboard in vertical fashion. Finally, a steel cover was welded to a low alloy steel header to form

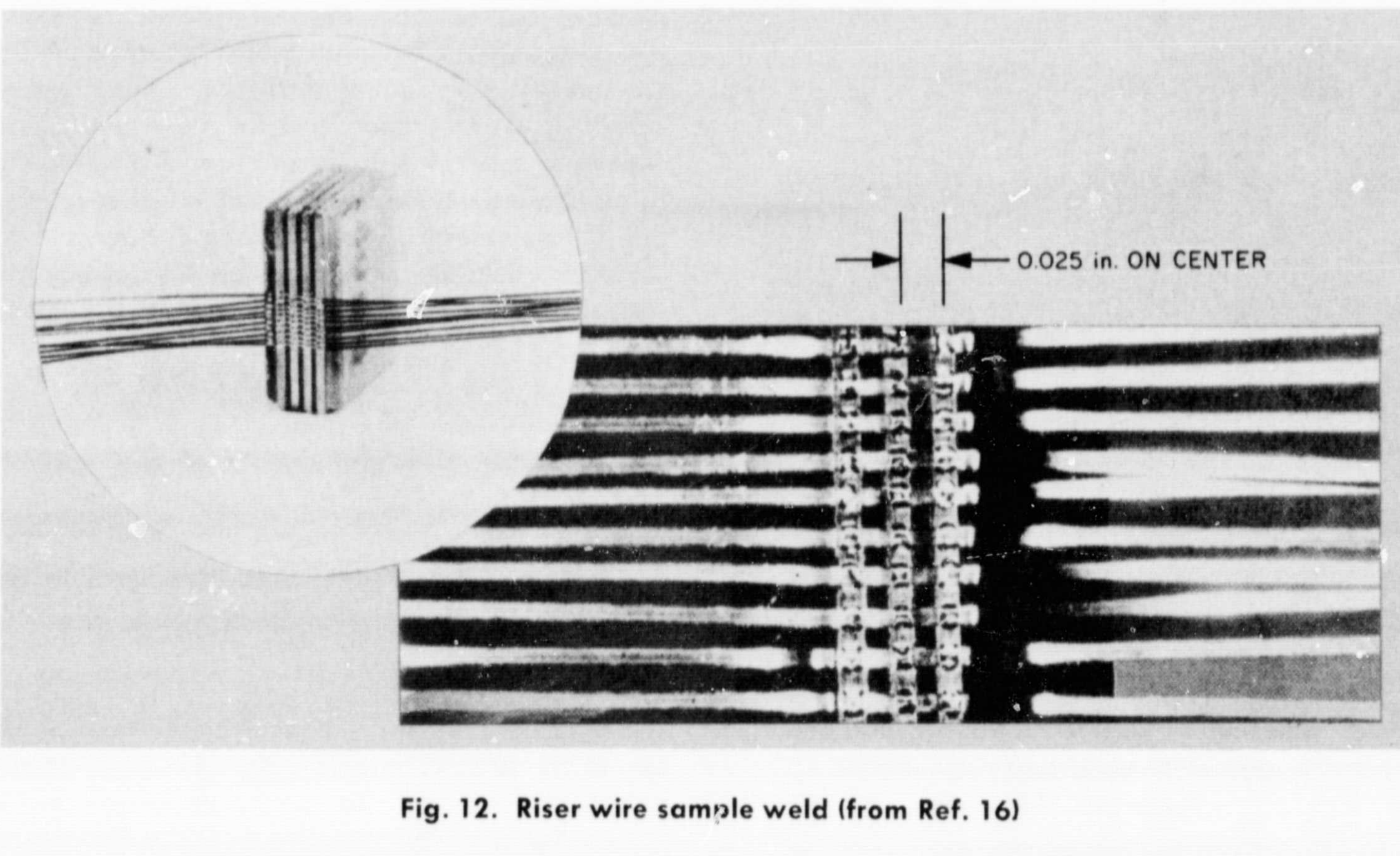


Fig. 12. Riser wire sample weld (from Ref. 16)

the all-welded module, Ref. 16. Various fixturing techniques are discussed in Ref. 16 to provide for precise location and for intimate contact in performing the welding process.

A similar microcircuit module also utilized electron beam joining techniques. The difference in this case is that integrated circuit chips are used. They are bonded to the wafers by gold silicon eutectic methods. The edges of the wafers have conductors bonded to them. The joints, which go from wafer to wafer and utilize an interconnection ribbon on these conductors, are welded by electron beam techniques. Welding is fully automated and the electron beam welding machine, loaded and programmed, can make 76,000 welds in 4 h, Ref. 18. A matrix consisting of a number of wafers, 10 in this case, is positioned and welding takes place. After all the stacks are welded, the fixtures are unloaded and excessive ribbon is trimmed. A transfer wafer-to-header subassembly serves as the plug-in base for the module. The transfer wafer is brazed to the header; the stack, however, which was previously welded by electron beam techniques, is welded in the same manner to the wafer. After this is accomplished, the can and header are hermetically sealed by electron beam weldments.

No fluxes or encapsulants are necessary, because the circuits are sealed in a vacuum. Contaminants are minimized and stresses associated with potting are avoided, Ref. 17.

The next application of electron beams for welding is unique in that the beam performs a multiple weld in a single pass. In manufacturing core- or memory-arrays for computers, the core frames are interconnected to those directly above and below until a given stack height is reached. Thus, thousands of interconnections must be made to complete an array, Ref. 46. A typical array contained over 9,000 external connections that were made between 36 core frames. Prior to using electron beam techniques, the joints were made using a resistance braze-welding technique. Such a technique results in a relatively slow rate of joining; in addition, process control and automation are difficult. Inspection is also complicated because blind joints are characteristic of the process. To automate the resistance welding process would require considerable floor space and extensive equipment. Utilizing the electron beam technique, the time required to weld each terminal is upgraded tremendously, since groups of terminals are welded simultaneously while the array is traversed continuously past the beam, Ref. 46.

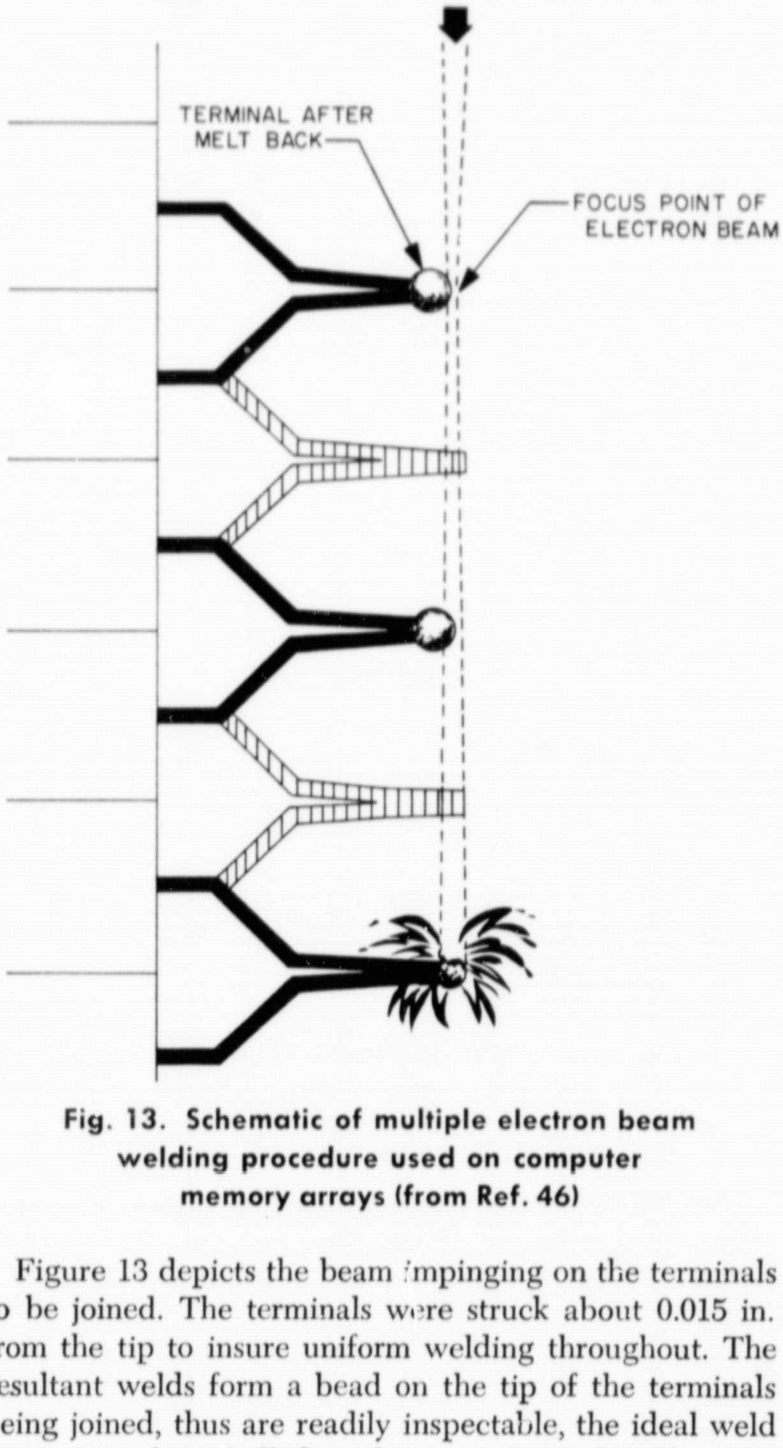


Fig. 13. Schematic of multiple electron beam welding procedure used on computer memory arrays (from Ref. 46)

Figure 13 depicts the beam impinging on the terminals to be joined. The terminals were struck about 0.015 in. from the tip to insure uniform welding throughout. The resultant welds form a bead on the tip of the terminals being joined, thus are readily inspectable, the ideal weld being a uniform ball-shaped nugget located at the very tip of the terminal. Visual acceptance criteria were based on an investigation which correlated the strength of joints with their visual appearance. Thus, inspection was readily carried out in a simple manner. One difficulty encountered was that, on occasion, some weld spatter would occur and cause shorts. This was easily rectified by protecting adjacent surfaces with aluminum foil, Ref. 46.

A unique device which utilized an electron beam, although not for welding, was that which processed thin-film components. In this case, the electron beam is used to vaporize metals for a continuous deposition of thin film materials, Ref. 47. Interconnected vacuum chambers are used in the process, thus reducing pumpdown time. The electron beam is not only used for vaporization of materials to be deposited, but also for trimming of the devices, such as balancing resistors. In this case, the beam is used as a machining tool to scribe the geometry in a resistive film. This process was fully automated with the devices being pushed by electromagnetic devices, Ref. 47.

C. Recent Developments

One of the basic approaches to increase laser efficiencies is to improve pump performance and crystal quality. Pump performance, Ref. 22, can be improved in four general ways:

(1) Develop pumps that emit only the absorption spectrum of the laser.

(2) Develop laser materials that will absorb a broader spectrum, using existing pump lamps.

(3) Develop new, broader spectrum pumps.

(4) Develop the efficiency of the transfer of energy from the pump to the laser crystal.

Crystal quality is also the study of further development, with investigation toward growth mechanisms and studies of new materials, Ref. 22.

Work is underway toward development of CW (continuous wave) lasers for welding. Development efforts have been undertaken at Linde[1] on a solid-state continuous device with some success on 0.025–0.030-in.-thick joints. Also, Linde's previous pulsed laser had pulse length selections of 2.5 and 3.5 ms. The same device[1] is now available with 0.5-, 2.5-, 3.5-, 4.2- and 5.0-ms pulse lengths.

Raytheon has a system[2] with a closed circuit television including automatic repetition rates of 1 pulse/s, 1 pulse/5 s and 1 pulse/10 s.

Some typical users have also expressed interest in laser welding, however no extensive work [3,4] is presently under development. Interest has been expressed in a continuous gas laser.[4]

[1]F. Winkler, Union Carbide Corp., Linde Div., private communication, Nov. 10, 1967.

[2]A. Leonardi, Raytheon Company, private communication, Nov. 9, 1967.

[3]J. Boros and T. Hogan, Autonetics, A Division of North American Aviation, Inc., private communication, Nov. 13, 1967.

[4]R. Conti, General Dynamics Corp., Pomona Div., private communication, Nov. 14, 1967.

VI. Conclusions

Based on the foregoing information, a number of conclusions can be drawn concerning lasers and electron beam devices with respect to their application to electronic circuitry joining.

Both techniques have been demonstrated to have the necessary capabilities for use in joining electronic circuitry: producibility, inspectability, repairability and reliability. In addition they exhibit certain attributes which no other joining processes possess: the capability of being precisely aligned and focused to an extremely small spot, accessibility to the joint, no contact requirement, and ease in inspection.

The major drawback of both the laser and electron beam is their high cost, both initially and operating However, both have been used to replace conventional techniques as demonstrated by the memory core multiple weld (electron beam) and the high temperature bearing weld (laser). This shows that these techniques can now be used where certain of their unique attributes warrant such use, even though, initially, the cost may originally seem higher. Faster and easily automated production and less rejects certainly lower costs in the long run.

If the rapid development of these devices continues, especially of the laser, it is expected to result in lower costs in the future, thus making their use more attractive.

Present joining techniques used in electronics certainly can accomplish capably the desired result. Thus, it appears that for the present laser and electron beams are only useable where other techniques cannot be used. This is true only if present packaging designs are continued to be employed. Many packaging designs now use conventional joining techniques as their basis, thus direct comparison to these techniques is not fair. Consideration must be given to the characteristics of the focused energy devices to develop an optimum design. Certainly, as high reliability with increased packaging densities such as semiconductor devices become more prevalent, unique joining capabilities will be required. The laser and electron beam possess these characteristics.

The laser has the advantage of being capable of joining without use of vacuum; however, at present it cannot weld continuously or to great thicknesses, and thus the two devices enhance each other.

Neither device is a panacea to metallurgical problems encountered in joining.

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