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Introduction to High Energy Density Electron and Laser Beam Welding

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HIGH ENERGY DENSITY BEAM WELDING refers to electron or laser processes where a beam of electrons or photons, respectively, can be focused to power densities high enough to melt and vaporize the metals being joined. The high power densities and associated metal vaporization can be used to produce welds with high depth-to-width aspect ratios, small heat affected zones, and reduced distortion. In certain applications, high energy density beam welds can offer both high quality and cost effectiveness when compared to other welding methods. Although there are many similarities between electron and laser welding techniques, there are also many significant differences. This article provides a brief history of electron and laser beam welding, discusses the properties of electrons and photons used for welding, and contrasts electron and laser beam welding by way of an introduction to the sections that follow where each process is described separately. In addition, a section is included on the growing field of microjoining with electron and laser beams, which is becoming more important as miniaturization of components continues and microelectromechanical systems show great promise in the near future.

A Brief History of Electron Beams and Laser Beams used for Welding

The development of electron beams used for welding began in Europe in the mid to late 1950's. In Germany around 1958, scientist Karl-Heinz Steigerwald was conducting experiments on a transmission electron microscope and observed melting of the small samples as the beam current was increased [1, 2]. About the same time in France, Dr. Jacques-Andre Stohr was looking to weld reactive materials with x-ray tube systems, and began developing electron beam welding through work carried out by the Commissariat Energie Atomique (CEA) [3-5]. At the time, the science behind the production, acceleration, and focusing of electron beams in vacuum was well understood, so it was a relatively straightforward process to design and build systems large enough for welding practical materials once these initial ideas had germinated. The introduction of electron beam welding to manufacturing technology is important enough that one of the earliest electron beam welding machines from Steigerwald has been preserved and is on public display at the Deutsches Museum of Technology in Munich, Germany. By the early 1960's high voltage (125-150 kV) electron beam welding systems were being fabricated and sold by the Carl Zeiss Company in cooperation with Hamilton Standard, a division of United Technologies

Corporation, and low voltage (15-60kV) systems by Sciaky SA through license agreement with CEA which extended to Sciaky Bros. in the U.S.A. [3]. These early machines were fabricated mostly for laboratory and limited commercial use. By the 1970's electron beams became the welding method of choice for high quality precision welds. The driving force for new developments during this time came mainly from the nuclear and aerospace industries where 5kW to 100kW systems were developed for deep penetration welding [2, 6]. High voltage systems, 150-200kV, were developed to operate at less than 100mA of beam current while low voltage systems, 30-60kV, were developed to operate at higher beam currents of up to 1 A, with powers exceeding 50kW. The largest and most powerful electron beam welder to date was developed in Japan, reaching 300 kW at 600kV and was able to penetrate up to 12 inches of steel [7, 8].

Both high and low voltage electron beam welding systems were later integrated with computer numerical control (CNC) systems using both fixed and movable head electron beam welding guns in the 1970's and 1980's to access greater commercial applications. Other advances in electron beam welding technology included out-of-vacuum welding systems, seam tracking, and beam rastering, which spurred new applications for heat treating, drilling, cutting and cladding. Today, electron beam welding is the method of choice for larger components that require welds to be made in vacuum, such as with reactive materials and hermetic vacuum sealing, and for welds with penetrations greater than about 12 mm. Electron beam welding continues to evolve through the development of new applications, such as free form fabrication with wire or powder filler metals [9] and rapid deflection optics to scan the beam in a way to allow a part to be simultaneously heat treated and welded with one beam, or allow multiple welds to be made using one beam [10, 11]. In addition, electron beam diagnostics are being continually improved to provide a greater measure of quality control for electron beams that was not available in the past [12-14]. These diagnostics are on par with diagnostics used for measuring power density distributions in continuous wave laser beams, and allow the two processes to be quantitatively compared. The number of electron beam welders appears to be approaching a steady state value, where a rough estimated number of installed electron beam welders in the world are on the order of 2,000 [3], which is approximately one-half the number of installed kW level high power lasers used for welding [15].

While electron beam welding was being developed in the late 1950's and early 1960's for commercial applications, lasers were being invented and discovered in research laboratories in the United States. Many good articles exist on the early development of "lasers", the term first given to represent <u>L</u>ight <u>A</u>mplification by <u>S</u>timulated <u>E</u>mission of <u>R</u>adiation by Gould in 1959 [16], so only a short introduction will be provided here. The invention of the laser can be traced to the pioneering work performed by A. L. Schawlow and C. H. Townes at Bell Laboratories for their work on infrared masers in 1958 [17]. The first working laser, which was a solid-state flash-lamp pumped synthetic ruby crystal laser that operated in a pulsed mode at 0.694μm wavelength, was developed in 1960 by Theodore Maiman at Hughes Research Laboratories [16]. Shortly afterward, gas lasers based on helium and neon, were developed at Bell Labs and were capable of being scaled to high powers due to easier heat management of the gas lasing medium [16]. In 1962, semiconducting laser diodes were also developed at Bell Labs, further demonstrating the wide range of mediums capable of generating laser light [16].

Early lasers were not much more than laboratory curiosities, and it took more than a decade for their real commercial potential to be developed in consumer products such as barcode scanners, compact disk players, laser pointers, laser printers, and materials processing applications. The majority of lasers used for welding today are either yttrium aluminum garnet (YAG) crystal solid state lasers doped with Nd or Yb or CO_2 gas lasers. However, direct diode lasers are now commercially available with high enough beam quality at high powers to be used for welding and other materials applications [18]. Nd:YAG and CO_2 lasers were both developed at Bell Laboratories in 1964, and although both operate in the infrared wavelength range, they have wavelengths that are an order of magnitude apart: 1,060 nm for Nd:YAG and10,600 nm for CO_2. This difference in wavelength results in different interactions with materials, and requires different types of optics and laser delivery systems to be used for each. These differences, and the ease at which gas lasers were scaled up in the early years, led to CO_2 laser dominance of high power laser applications, oftentimes competing with electron beams, while solid-state YAG lasers were used primarily for precision and low power applications. By the early 1970's, CO_2 lasers had reached the 20kW level, while flash lamp pumped Nd:YAG laser were limited to only 400W [19, 20]. Today, diode pumped Nd:YAG lasers are available with powers up to 4 kW, and direct diode lasers are available with powers up to 10 kW. CO_2 lasers dominate the gas laser market and are commonly used for welding and cutting with powers as high as 45kW [21].

New generation high brightness lasers are being developed with ever increasing powers Disc lasers are now commercially available with powers up to 16 kW, and fiber lasers are available with powers up to 50 kW for military and commercial applications, with 200kW powers planned for the near future [22]. Note that the term "brightness" will be used in this article as a descriptive term to refer to the quality of the laser beam, where higher brightness refers to higher quality beams. These new generation lasers use lasing media that are thin in at least one dimension so that heat can be removed from them efficiently. With less heating of the lasing media higher quality, higher brightness, beams are produced. In the case of disc lasers, the lasing crystal is a thin disk measuring only about 10 mm diameter and less than 1 mm thick. In the case of fiber lasers the active lasing media is a long thin fiber only 10 micron diameter.

High laser powers are now available from many suppliers, and after the overall power level for an application is established, the quality of the beam becomes the next important consideration. The quality of the beam affects how well the laser can be focused and delivered, and there are different ways to measure beam quality. One common measure of laser beam quality is the beam parameter product (BPP), which represents how tightly the beam can be focused under a limited divergence condition. BPP will be discussed in more detail later, but is used in Figure 1 to compare the beam quality of different types of lasers as a function of beam power up to their respective maximum powers. Lower BPPs refer to more tightly focused and less divergent beams, and are desired for precise cutting, deep keyhole welding, and long focal length conditions. Diode lasers have the largest BPPs, which makes them most attractive for lower power density applications where larger beam diameters and lower power densities are desired. Their high powers combined with large BPPs make them also very useful for non-welding applications such as large area heat treating and cladding. Diode and flash lamp pumped Nd:YAG rod lasers are available from many sources with BPPs between 10-20 mm-mrad at the 4 kW level. These lasers, along with CO_2 lasers have lower BPPs than diode lasers, and dominated the laser welding and cutting market until solid state disc and fiber lasers became commercially available. Disc lasers currently have BPPs on the order of 8 mm-mrad at the 8kW level, while single mode (SM) fiber lasers are now available with powers up to 10kW and BPPs at the limit of diffraction for 1060 nm beams of 0.37 mm-mrad. CO_2 lasers below 10 kW can have similar diffraction limited beam quality, but have BPPs approximately10x as large as fiber lasers due to their longer wavelength. At power levels higher than 10kW, CO_2 (up to 45kW) and fiber (up to 50kW), the BPP increases to the 6-8 mm-mrad range as less perfect multi-mode (MM) beams are required to generate these powers.

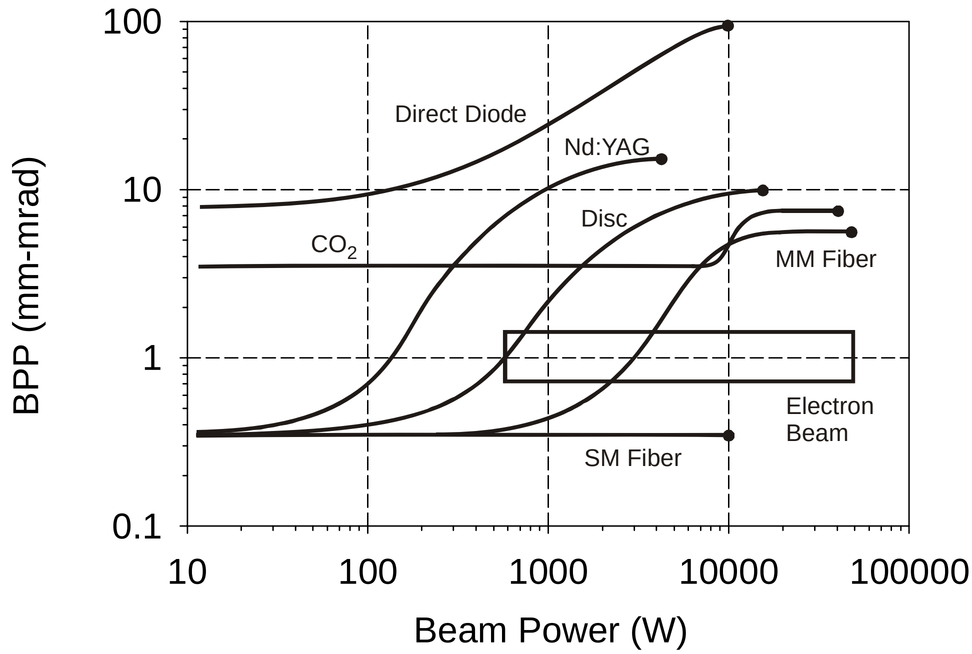

Figure 1: Beam parameter product (BPP) plotted versus laser power up to the highest commercially available power levels for six different types of lasers. SM and MM refer to single-mode and multi-mode fiber lasers respectively. The estimated BPP range for electron beams is shown for comparison.

While the quality of laser beams is typically measured using the BPP, electron beam technology has not traditionally used the same convention, making it difficult to compare the two processes directly. However, estimates of electron beam quality can be made using diagnostic measurements of the beam's power density distribution [23], and approximations of the beam divergence. Recent measurements of electron beams have been performed to determine the BPP of kW level electron beams, showing BPP values between 0.75 and 1.3 mm-mrad [11, 24, 25]. This range is plotted in Fig. 1 for comparison with lasers, indicating that an equivalent BPP for electron beams is smaller than that of CO_2 lasers, but larger than that of solid state single mode lasers. Additional work needs to be done to characterize electron beam quality using advanced diagnostics to determine the influence of operating voltage, cathode size and shape and electron gun design on beam quality. However, it is clear that the recent increase in the quality and power of solid-state lasers has resulted in a large overlap of welding capabilities between CO_2 lasers, solid state lasers, and electron beams, providing users with many options when selecting high energy density beam welding processes.

The Properties of Electron and Laser Beams

Electron Beams

Electron beams are composed of electrons which are charged particles that have a rest mass (m) of 9.1×10^{-31} kg and can be accelerated in electron guns to relativistic velocities giving them high kinetic energies. At 10kV, electrons travel at approximately 20% of the speed of light while at 200kV they travel at approximately 70% the speed of light [2, 26]. The kinetic energy is the source of heat used for welding as the electrons in the beam rapidly slow down and deposit their energy into the substrate. The depth that the electrons penetrate into a substrate depends on the energy of the electron and the properties of material being welded, and most importantly is inversely related to the atomic number, Z. The penetration depth is often calculated using Carlo methods to account for multiple atomic collisions as the electrons continuously slow down [27]. These calculations indicate that 150 kV electrons penetrate 10-100 μm in metals [26], thus the majority of the electron's energy is deposited in a rather thin surface layer. Electrons, being charged particles, interact with all types of matter which places restrictions on how they are focused and delivered to the parts being welded. Unlike lasers, electron beam focusing is performed using magnetic lenses that do not function to the same degree of precision as optics for lasers. However, this magnetic lens property does allow for dynamic adjustments of beam deflection and focus through computer control. Caution should also be used when working with magnetic and ferromagnetic materials and weld tooling so that the beam does not inappropriately deflect from the intended target. In addition, electron beams interact with gas molecules to the extent that a 100 kV beam will lose 90% of its energy after propagating through only 18 inches of air [26]. Electron beam welding is therefore most typically performed under medium-to-high vacuum conditions of 10^{-4} to 10^{-6} torr in large vacuum chambers to accommodate the welding of large structures [2, 6, 7]. This vacuum environment is advantageous for welding materials that are reactive or refractory, or require low levels of atmospheric contaminants. On occasion, electron beam welding is performed under non-vacuum conditions, but the beam must be kept very close to the surface of the part. Although the depth of the weld is significantly reduced compared to vacuum welding, numerous applications, particularly in the automotive industry, are found for out of vacuum electron beam welding [6, 28].

After electrons strike the substrate, they primarily lose their energy through elastic and inelastic scattering with atoms, causing the electrons to slow down as they deposit their energy into the material being welded [26, 27]. In the process of slowing down, the electrons produce a spectrum of electromagnetic waves, particularly X-rays, which present a health and safety hazard that requires adequate shielding to protect the operator. Some of the electrons are backscattered from the surface, resulting in energy that is not deposited into the substrate. The fraction of backscattered electrons increases with atomic number, from about 0.1 for low Z materials like aluminum, to nearly 0.5 for high Z materials such as tantalum [2]. Electrons can also be treated as waves, instead of charged particles, according to the de Broglie equation $\lambda = h/p$, where λ is the wavelength of the electron, h is Planck's constant, and p is the electron's momentum (mV) [29]. Using this relationship and the relativistic velocity of the electrons to account for their increased mass at these speeds [29], the wavelength of electrons used for welding are smaller than atomic dimensions, ranging between $\lambda = 0.0123$ nm at 10 kV and $\lambda = 0.0025$ nm at 200 kV [29]. These wavelengths are significantly less than photons used for laser welding, and this difference represents a fundamental difference between how electron and laser beams interact with materials.

Laser Beams

Lasers are devices that emit light (photons), typically in a narrow wavelength range (monochromatic) that is spatially coherent (in phase). These properties allow lasers to be focused to much higher power densities than would be possible from incoherent multispectral light sources, giving lasers the ability to be used for a wide variety of materials processing applications such as welding, cutting, drilling and micromachining. Laser beams can be transported through air or inert gasses and thus do not require the large vacuum chambers used for electron beam welding, which opens up host of possibilities not readily accessible to electron beams. One of the most fundamental properties of laser beams is wavelength, which can vary from the ultraviolet to the visible and the near and far infrared regions of the electromagnetic spectrum. However, the majority of lasers used for welding have wavelengths close to either λ=1060 nm (solid state lasers) or λ=10,600 nm (CO_2 lasers), representing a factor of 10^5 to 10^6 longer wavelengths than electron beams used for welding.

The minimum spot size of focused laser beams, and electron beams, operating under ideal conditions is ultimately limited by diffraction [29, 30]. The minimum or diffraction limited spot size for an ideal beam is given by $d_{min}=2.44\lambda(f/x_c)$, where d_{min} is the smallest spot size of the laser beam, f is the focal length of the lens, and x_c is the coherence length of the beam taken to be the collimated beam diameter [30]. Since the smallest diameter spot is directly related to the wavelength of the beam, λ, smaller wavelength electron beams can in principal be focused to many orders of magnitude smaller spot sizes than laser beams. However, the combination of the large size of the cathodes that emit the electrons, the comparatively poor quality of electron optics used for welding, and the mutual repulsion of electrons (space charge effect), prevents high power electron beams used in welding from being focused to their diffraction limit. In fact, the sharpest focus conditions for most electron beam welders produce spot diameters on the order of 200 μm [12-14]. On the other hand, high power laser beams that can be focused to diameters less than 100 μm for solid state lasers with small f-number (ratio of focal length of lens to collimated beam diameter) optics [30]. High power CO_2 lasers, because of their longer wavelength, are at a disadvantage compared to solid state lasers. However, their ability to produce Gaussian-like TEM_{00} modes with low M^2 values at powers approaching 10kW enables CO_2 lasers to maintain low BPPs and produce smaller spot sizes at high powers than Nd:YAG lasers, and similar spot sizes to fiber lasers at the 10kW level.

Characterization and definition of laser beam propagation is important in order to compare different lasers and different optical configurations. This subject is discussed in many references and is detailed in ISO Standard 11146 [31]. A schematic drawing of the propagation of a laser beam is shown in Fig. 2, which illustrates several important beam characteristics. As the beam is focused, the circular cross section, defined by either the second moment, or 86% width [31], decreases in size as it converges to the waist of the beam where the sharpest spot occurs. The beam radius as a function of Z-axis position, R(Z), reaches a minimum radius, R_o, at the beam waist. The Rayleigh Length, Z_{RL}, is the Z-axis distance above or below the minimum beam radius where the radius at that point, R_{RL}, increases by a factor of square root of 2 and the area of the beam is doubled. The beam diverges at a half angle of θ in the far field, with the full beam angle of Θ=2θ. The beam parameter product, BPP, is defined as the product of the half-width (beam radius) at the beam's cross-over location and the beam divergence angle (BPP=θ*Ro) and has units of mm-mrad [31, 32]. Note that the half-divergence angle, θ, is used and not the full divergence angle for this calculation. The BPP is often used as a measure for comparing the quality of different lasers beams, and is a fundamental property of the beam and is not affected by the configuration of the output optics. Another common measure of the beam quality is M^2, which is a dimensionless number defined as the ratio of the true BPP to the ideal BPP for a perfect Gaussian beam, and indicates how far the beam is from an ideal, diffraction limited, beam. Alternatively K , which is defined as the reciprocal of M^2 ($K=1/M^2$) is used as yet one more measure of beam quality as a matter of convenience. These definitions, and more details of beam quality, can be found in standard laser beam texts or beam quality references [31].

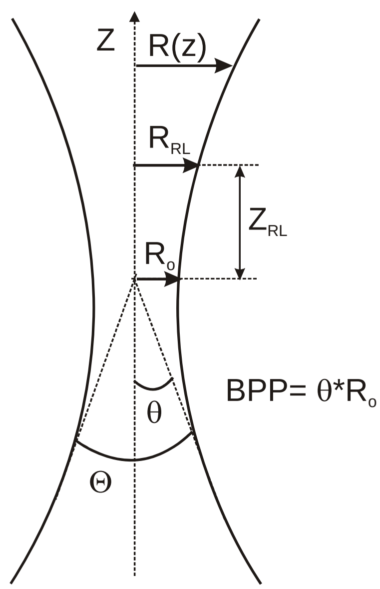

Figure 2: Illustration of the propagation of a focused laser beam as the beam radius, R(z), varies along the Z axis. The beam parameter produce (BPP) is a fundamental property of the beam, and is a useful way to compare different laser beams.

Solid state lasers operating at or near 1 μm wavelength have rapidly evolved over the past decade from flash lamp pumped and diode pumped rods, to disk, fiber, and direct diode lasers used for materials processing. These advances in technology have created commercial products with a wide variety of beam qualities and power levels, which are finding applications from low brightness applications for welding of plastics, soldering and brazing, to high brightness applications such as keyhole welding. Figure 3 plots these different regions on coordinates of beam parameter product (BPP) versus laser power, as redrawn and modified from reference [18] to include keyhole welding, cutting and drilling. Since the BPP is defined as the product of the beam radius at the beam waist with the far-field beam divergence, smaller numbers correspond to brighter beams that can be focused to higher power densities. More than three orders of magnitude of BPP are plotted in this figure, which cover a wide range of materials processing applications from large area heat treating of metals at high powers without melting the substrate, to intense beams used to keyhole welding, cutting and drilling. Although the regions of interest are only approximate and may vary by application, the overall plot is a useful starting point when considering the type of laser and optical configurations required for a given job. Even though high brightness lasers can be defocused to low beam intensities, the higher cost of these systems may make less expensive, lower brightness, lasers more cost effective for selected applications.

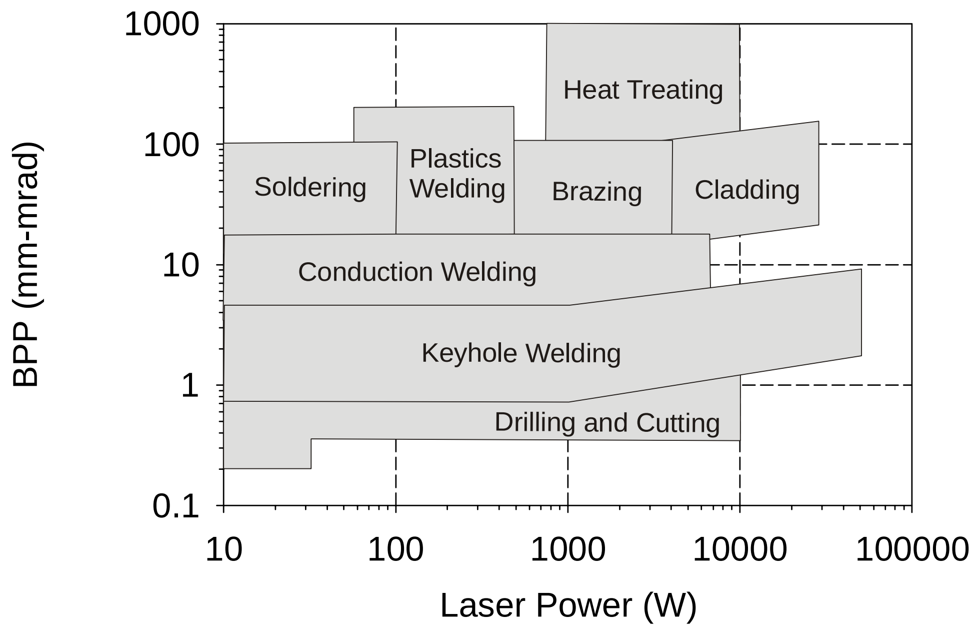

Figure 3: Beam parameter product plotted versus laser power, showing typical regions used for low and high brightness laser applications.

Just as electron beams can be described in terms of either energy or wavelength using the de Broglie equation, so can laser beams. Since photons have no mass and travel at the speed of light, the relationship is simplified to $E=1.240/\lambda$, where λ is in nm and E is in keV. Thus the energy of a 1,060 nm Nd:YAG laser beam is only 0.00116 keV (1.16 eV), and that for a 10,600 nm CO_2 laser is 0.116 eV; both being considerably smaller in energy than their electron beam counterparts. The lower energy and longer wavelengths of lasers beams compared to electron beams results in significantly different beam/material interactions, particularly the fraction of energy that is absorbed by the substrate, which strongly depends on both the laser wavelength and the material properties [33]. In addition, other factors such as temperature, beam intensity, polarization, angle of incidence, alloy composition, surface roughness, oxide layers and contamination contribute to the absorption of laser beams [33].

Laser absorption increases as the wavelength decreases, and this factor is important when selecting the type of laser to use for a given application. The absorption for CO_2 lasers operating at 10,600 nm is 1/5 to 1/10 that of solid state lasers operating at 1,060 nm on metal surfaces. Even for solid state lasers, with wavelengths of 1,060 nm, the absorption is rather low. For example, absorption at 1,060 nm is less than 0.5 for the highest absorbing metals such as titanium, and less than 0.05 for highly reflective materials such as silver and gold at room temperature [33]. Significantly higher laser absorption on highly reflective metals such as Au and Cu can be achieved by decreasing the wavelength into the green at 532 nm [34] or even lower wavelengths. These lasers are just now becoming commercially available in small packages with 10 W level powers that are ideal for microelectronic and small component applications.

For material/laser combinations where the absorption is low, the fraction of energy not absorbed by the substrate is reflected and may or may not contribute to further heating of the material depending on the weld geometry. The beam energy is absorbed in a very narrow surface layer because the photons interact only with electrons at these energy levels. This depth of penetration of the photons, or attenuation length, is inversely related to the material's absorption coefficient, α. The penetration depth of the photons is on the order of 10^{-1} to 10^{-2} μm in metals, which is less than the wavelength of the laser beams. This shallow penetration is considerably smaller than that of electrons used for welding, which allows laser to vaporize materials more easily, and is one reason why lasers are preferred over electron beams for precision cutting, drilling, scribing, marking and micromachining.

Comparison between Electron and Laser BeamWelding

Beam quality measurements such as BPP are a good way to compare the brightness and focusing ability of different laser and electron beams. However, the power density, which is defined as the ratio of the absorbed power to the area of the beam, is the important parameter for determining how the beam will interact with a given material. High power density beam welding requires beams with power densities that exceed approximately 10^5 W/cm^2, which is the level at which most metals will begin to vaporize rapidly beneath the beam [35]. As the power density increases above this level, the rate of vaporization increases, producing deeper welds with little increase in the weld width. At a power density of 10^6 W/cm^2, the depth-to width ratio of the weld can exceed 10:1. Further increases in power density above 10^7 W/cm^{2}can create such intense vaporization that metal is ejected from the keyhole, and the beam begins to enter a cutting rather than welding mode.

The power density is, primarily controlled by the focal spot diameter and the beam power. Fig. 4 plots this relationship, showing the power required to achieve a given power density as a function of beam diameter. For example, to achieve a power density of 10^6 W/cm^2, a 200 μm diameter beam only requires approximately 300 W of power, whereas a 1 mm diameter beam requires approximately 8 kW of power. Both laser and electron beams easily achieve the power density required for rapid vaporization and keyhole welding. To reach the higher power density limit of keyhole welding of 10^7 W/cm^2, continuous beams of 5 kW would need to be focused to a diameter of approximately 250 μm. This diameter and power combination has been easily achieved by electron beams for decades, and is now being equaled, and surpassed, by solid state lasers that can deliver these power levels through 100 μm diameter fibers with similar or smaller focused spot sizes depending on the optics. These tightly focused laser beams now have the ability to produce power densities too high for welding and may need to be lowered in intensity by stepping up to larger diameter fibers, using longer focal length lenses, and/or defocusing the beam to produce acceptable welds.

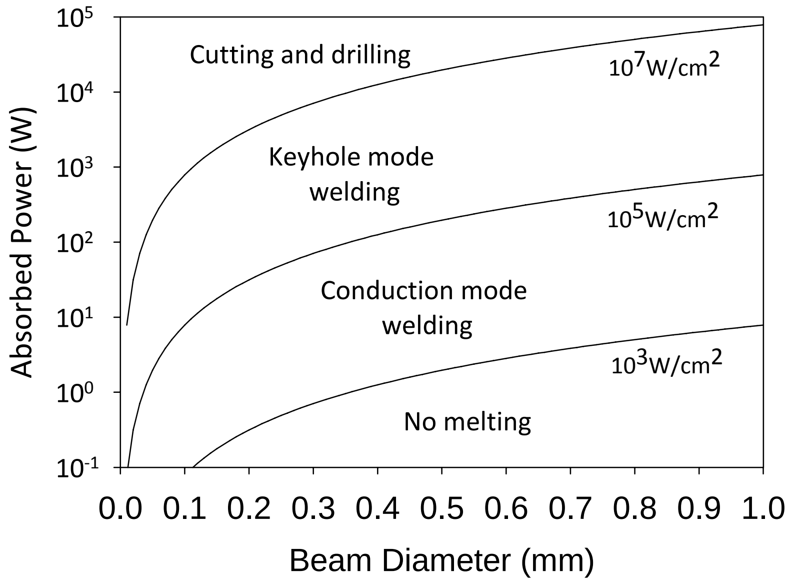

Figure 4: Constant power-density boundaries showing the relationship between the focused beam diameter and the absorbed beam power for approximate regions of keyhole mode welding, conduction mode welding, cutting and drilling.

When a beam interacts with a surface, not all of the beam power is absorbed by the substrate, and one of the largest differences between laser and electron beams is the difference in absorption characteristics for lasers of different wavelengths and electron beams. Absorption of the beam is typically less for photons than electrons under most circumstances, and the differences can be large. Since the material must first absorb enough energy to melt before it can vaporize to form a keyhole, there is a power density level below which welding will not occur. This power level is highly dependent on the absorption as well as the thermophysical properties of the metal. While electrons instantly begin to penetrate the substrate and form a keyhole at 10^5 W/cm^2, lasers may not if the reflectance is high enough to prevent a substantial portion of the beam from being absorbed. For electrons, where absorption is high, calculations show that materials with low thermal diffusivity, such as stainless steel and titanium alloys, will begin to melt at 5-10x lower power densities than high thermal diffusivity metals like copper and gold [7]. For lasers, though, this threshold value may be as large as two orders of magnitude between high reflectivity and high conductivity metals, or between low conductivity and low reflectivity metals [7]. Pulsed lasers minimize the absorption problems at low powers by producing higher peak power densities than their continuous wave counterparts, while maintaining the same average power. Electron beams can be pulsed modulated for hole drilling, which is occasionally used for keyhole stability. However, pulse modulation does not increase the peak power density of electron beams and is not a technique used for initiating a keyhole in welds.

Travel speed plays the other major role in how the beam interacts with the substrate since the energy density, rather than power density, is the parameter that ultimately controls the response of the material to the beam. The faster the beam moves the less energy is deposited per unit length of weld, and the penetration decreases. The energy deposited per unit length of weld (J/mm) is defined by the beam's power (W) divided by the travel speed of the weld (mm/s), and is one measure of how the travel speed influences weld behavior. Analytical solutions to heat flow relationships in high power density welding [20, 36, 37] can be used to estimate the influence of welding speed on the threshold for surface melting, and vaporization that leads to deep penetration conditions, while more advanced models are continually evolving to predict the complicated relationships between welding variables and keyhole weld shape. These advanced numerical models use a coupled thermal-fluids approach to solve the equations of conservation of mass, momentum and energy in three dimensions, and must calculate the temperature distribution on the inside surface of the keyhole wall. In the case of lasers, multiple reflections of the beam off of the keyhole wall need to be considered in how the keyhole is established and maintained [38]. In the case of electron beams, the presence of welding in vacuum must be considered [39]. More details about the numerical modeling of high power density beam welding can be found elsewhere in this handbook.

A number of articles that compare laser and electron beam welding processes have been written. However, many of these comparisons are more than a decade old and have not kept pace with the recent advances in these technologies [40-45]. Nevertheless, much of the reasoning behind the comparisons is still valid. For example, electrons require a vacuum in order to propagate the beam, and they generate large amounts of x-rays. Lasers on the other hand, may require shielding gases, have higher reflectance, and present hazards in other ways. Concerning capital equipment and operating costs listed in some of these comparisons, it is important to note that the price per kW of power has decreased significantly for lasers as higher average power lasers are being produced in more compact systems with smaller footprints and lower utility costs. Factoring in all the types of lasers used for welding and all types of electron beam configurations creates too many variables to compare and contrast in this article. However, it's safe to say that either method will work well for many applications, but certain applications still tend towards one method or another. For deep penetration welds over 12mm, for highly reflective metals, for welds on highly reactive materials that require vacuum conditions, and/or for welds that require hermetic sealing in vacuum, electrons beams are most often the preferred method. Lasers, on the other hand, have more flexible delivery options and superior versatility that allows them to be directed into areas that are difficult to access with electron beams. This versatility allows lasers to be more easily configured and integrated into multiple use workstations with associated potential cost savings. Since lasers do not require vacuum operation, tooling is oftentimes simpler to fabricate and use, and production rates are oftentimes higher. In addition, lasers can be used to heat and melt non-electrically conductive materials, and they are not affected by magnetic or ferromagnetic base materials and tooling that tend to deflect and/or interfere with electron beams.

Summary

High power density welding with lasers and electron beams can produce deep welds with small heat affected zones and minimal disruption to the surrounding base metal. These attributes make both processes attractive for high value added welded components in the nuclear and aerospace industries, as well as high volume manufacturing in other industries. Recent advances in laser technology have given rise to high power multi-kW solid state lasers with power densities matching and sometimes exceeding those of electron beams used for welding, which provides users with multiple options for high power density welding techniques. Electron beam welding and laser beam welding will be discussed separately in the sections that follow, with articles describing welding equipment, welding procedures, design of weld joints, beam diagnostics, quality control and appropriate codes, non-destructive evaluation, and non-traditional uses for both processes. These articles are intended to provide a broad overview of high power density electron-beam and laser-beam welding with numerous citations for specific details about this large and important field of welding. A final section is included to discuss recent advances in microjoining with electron and laser beams, which has been a growth area over the past decade as microelectronics, implantable medical devices, sensors, optoelectronics, and micromechanical systems are becoming more compact and require joining on the sub-millimeter scale. Although many of the principals are the same between macro- and micro-joining, many new areas exist for research and development in the microjoining field. When weld dimensions become less than a millimeter, spot size, beam control and part manipulation become more challenging, joint preparation and cleanliness become more important, and not all of the material properties scale at the same rates. These factors bring new challenges to both the technological and metallurgical aspects of microjoints made by electron and laser beams.

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References

1. K. J. Miller and T. Takenaka, “Electron Beam Welding,” Welding Research Council Bulletin, New York, No. 100, 1964.
2. Electron Beam Technology, by S. Shiller, U. Heisig, and S. Panzer, English Translation from German Edition, Published by John Wiley and Sons, 1982.
3. An International History of Electron Beam Welding, by K.H. Steigerwald, G. Sayegh, D. Powers, R. Bakish, O.K. Nazarenko, W. Dietrich, H. Irie, D. Wyatt and D. V. Dobeneck – Published by Pro-Beam AG & Co. KGaA , pp.32-89, 2007.
4. Stohr J.A., Fuel Elements Conference, Nov. 1957, Paris, TID 7546, Book 1, US Atomic Energy Commission, pp. 0-17, 1958.
5. Stohr J.A., CEA Sacley, patent 1.41.535 Paris, 1956.
6. M. Schwartz, “Electron Beam Welding,” Welding Research Council Bulletin, New York, No. 196, 1974.
7. Y. Arata, “Development of Ultra High Energy Density Heat Sources and Their Application to Heat Processing," in Plasma, Electron and Laser Beam Technology, edited by Y. Arata, The American Society for Metals, p. 3-27, 1986.
8. T. W. Eagar, "Electron Beam and Laser Beam Welding in Japan," *Welding Journal*, 57(7), p. 19, 1986.
9. Lachenberg, K.W. and Stecker, S. “Manufacturing Advantages Using Electron Beam Welding / Free Form Fabrication (EBFFF),” AWS/Fabtech 2008 Conference Presentation, Las Vegas Convention Center, October 8, 2008.
10. Private communication, Dr. Michael Mücke, All Welding Technologies AG, June 2009.
11. U. Clauss, “Fast Beam Deflection and Beam Quality-Keys to Economic High Quality Electron Beam Applications,” Presented at the *2nd International Electron Beam Welding Conference*, held at Fabtec Convention, Chicago, IL, November 2009.
12. G. R. LaFlamme and D. E. Powers, “Diagnostic Device Quantifies, Defines Geometric Characteristics of Electron Beams,” *Welding Journal*, 70(10), pp. 33-40, 1991.
13. U. Dilthey and J. Weiser, “Study of the “Tool” Electron Beam – Part 1: Comparison between the Arata Beam Test and Diabeam Beam Measurements,” *Schw. and Schn*., 47(5), pp. 339-345, 1995.
14. T.A. Palmer and J.W. Elmer, “Improving Process Control in Electron Beam Welding Using the Enhanced Modified Faraday Cup,” *Journal of Manufacturing Science and Engineering*, 130(4), 041008, 2008.
15. Private communication, D. Belforte, PennWell Corporation, Tulsa, Oklahoma, USA, December, 2009.
16. The Laser in America 1950-1970, by J. L. Bromberg, MIT Press, 1991.
17. A. L. Schawlow and C. H. Townes, “Infrared and Optical Masers,” *Physical Review*, 112(6), pp1940-1949, 1958.
18. A. Eltze, “High Power Diode Lasers for Brazing, Welding, Cladding and Hardening,” presented at the Laser World of Photonics, Munich, Germany, June, 2009.
19. M. Schwartz, “Laser Welding and Cutting,” Welding Research Council Bulletin, New York, No. 167, November, 1971.
20. D. T. Swift-Hook and A. E. F. Gick, “Penetration Welding with Lasers,” *Welding Journal*, 52(11), pp 492s – 499s, 1973.
21. M. Kido et al, “Development of 45-kW Laser Welding System for Continuous Finish Rolling,” Nippon Steel Technical Report No. 89, pp 91-95, 2004.

22. V. Gaspontsev, V. Fomin and A. Yusim, "Recent Progress in Scaling High Power Fiber Lasers at IPG Photonics," Presented at the 22nd Annual Solid State and Diode Laser Technology Review, Newton, MA, USA, July, 2009.
23. T. A. Palmer, J. W. Elmer, K. D. Nicklas, and T. Mustaleski, "Transferring Electron Beam Parameters Using the Enhanced Modified Faraday Cup," *Welding Journa*l, 86(12), pp 388s-398s, 2007.
24. C. Menhard and T. Löwer, "The Electron Beam Geometry—Definition, Measurement, and Significance for the Welding Process," *Welding and Cutting*, 8(3), pp 138-142, 2009.
25. M. Boyd and J. Vaja, unpublished research acquired on a 120 kV electron beam at the Atomic Weapons Establishment, Aldermaston, England, December, 2009.
26. A. C. Smith, Jr., E. E, Nolting, and W. M. Fawley, "An Overview of the High Energy Electron Beam Science," Conference Proceedings of High Energy Electron Beam and Welding and Materials Processing, Edited by J. Danko and E. Nolting, pp 1-41, American Welding Society, September, 1992.
27. Monte Carlo Transport of Electrons and Photons, edited by T. Jenkins, W. Nelson, and A. Rindi, Plenum Press, 1987.
28. Y. Arata, "Some Fundamental Properties of Nonvacuum Electron Beams," in Plasma, Electron and Laser Beam Technology, edited by Y. Arata, The American Society for Metals, p. 71, 1986.
29. Transmission Electron Microscopy, a Textbook for Materials Science, by D. B. Williams and C. B. Carter, Plenum Press, 1996.
30. Fundamentals of Laser Optics, by K. Iga, Plenum Press, 1994.
31. BS EN ISO 11146-1: 2005, "Lasers and laser-related equipment—Test methods for laser beam widths, divergence angles and beam propagation ratios," British Standard, 2005.
32. Encyclopedia of Laser Physics and Technology, Vol. 1, R. Paschotta, Wiley-VCH, Verlag Gmbh&Co. KGaA, 2008.
33. Laser Processing and Analysis of Materials, W. W. Duley, Plenum Press, 1983.
34. M. Greenstein, "Optical absorption aspects of laser soldering for high density interconnects," *Applied Optics*, V28, N 21, p. 4595, 1989.
35. Welding Handbook, Volume 3: Welding Processes Part 2, ninth edition, American Welding Society, 2007
36. P. G. Klemens, "Heat Balance and Flow Conditions for Electron Beam and Laser Welding," *Journal of Applied Physics*, 47(5), pp 2165-2174, 1976.
37. H. E. Cline and T. R. Anthony, "Heat Treating and Melting Material with a Scanning Laser or Electron Beam," *Journal of Applied Physics*, 48(9), pp3895-3900, 1977.
38. R. Rai, J. W. Elmer, T. A. Palmer and T. DebRoy, "Heat Transfer and Fluid Flow During Keyhole Mode Laser Welding of Tantalum, Ti-6Al-4V, 304L Stainless Steel and Vanadium," *Journal of Physics D, Applied Physics*, 40, pp 5753-576, 2007.
39. R. Rai, T. A. Palmer, J. W. Elmer and T. DebRoy, " Heat Transfer and Fluid Flow during Electron Beam Welding of 304L Stainless Steel Alloy," *Welding Journal*, V88(3), pp 54s-61s, 2009.
40. R. C. Hanson, "High Energy Beam (EB/Laser) and Overview Comparison," First International Conference on Power Beam Technology, The Welding Institute – Brighton, 10-12 September, 1986.

41. Electron and Laser Beam Welding, Proceedings of the International Conference held in Tokyo, Japan, L'Institute International De La Soudure and The International Institute of Welding, Pergammon Press, July, 1986.
42. D. E. Powers and G. R. LaFlamme, "EBW vs. LBW—A Comparative Look at the Cost and Performance Traits of Both Processes," *Welding Journal*, 67(3), pp.25-31, 1988.
43. P. Anderl, "Comparison of Laser With Electron Beam Welding," in German, Chem.-Ing.-Tech. 61 (10) pp767-774, 1989.
44. The Laser and The Electron Beam in Welding, Cutting and Surface Treatment State of The Art, edited by R. Backish, Bakish Materials Corporation, Englewood, NJ, 1991
45. C. O. Brown and C. M. Banas, "High-Power Laser Beam Welding in Reduced-Pressure Atmospheres," *Welding Journal*, 65(7), pp.48-53, 1986.