Differences of CO_2 and Solid-State Laser Welding in Industrial Flat Steel Production

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Solid-state lasers (SSLs) are increasingly becoming acknowledged as state of the art for welding of flat-rolled sheet. This trend has developed because of its reduced service requirements and operating costs associated. The current coil joining process has to be more flexible, robust and reliable to meet the industry's demands. Flexibility in joining of different grades, thicknesses and varying coatings is mandatory. This presentation deals with the differences in joining results and boundary conditions of the competing laser technologies of traditional CO_2 vs. the SSL. A comparison of the critical factors related to the different associated wavelengths will be reviewed.

Companies within the steel industry started installing welding machines with CO_2 lasers for coil joining in processing lines in the 1980s. Compared to the established flash butt welding machines, laser welding machines were able to realize gains in production flexibility, scheduling and welding capability. In the following years, CO_2 laser sources improved their reliability while continuing to meet the growing challenges of new steel grades in the production of steel strip.

Over the last few years, another laser type began earning more attention for this application. The solid-state laser (SSL) was developed with power capacities comparable to the 15-kW CO_2 gas lasers being applied to this application. The development of the SSL had improved their power, beam quality and robustness.

The SSL's comparatively low cost of ownership raised interest in its use; however, this was tempered by the increased safety hazard posed by its shorter operating wavelength.

The difference in wavelength of the CO_2 laser (10.6 µm) in comparison to the near-infrared SSL (1.03–1.07 µm) changes not only the hazards, but also the welding behavior of the laser. The wavelength significantly effects the interaction of the photons with materials, process gases and (sometimes) plasma, which ultimately determine the characteristics of laser welding behavior.

Aim and Scope

This paper focuses on the differences in laser welding of steel products with a CO_2 laser vs. SSL. It will address the different aspects to be considered when selecting between these types of lasers for a coil-joining application. The main aspects of setup, interactions and performance of both laser types will be reviewed.

Laser Technology Selection Factors

Today both types of laser sources have shown their capabilities in different applications, and several factors must be weighed in the decision to determine which is best suited for a new installation.

The points mentioned in Fig. 1 represent the most important selection criteria when choosing between CO_2 and SSL. This paper will focus on the points that appear in black.

Both laser types have advantages and disadvantages and cannot be defined without a detailed analysis of the application. This can be

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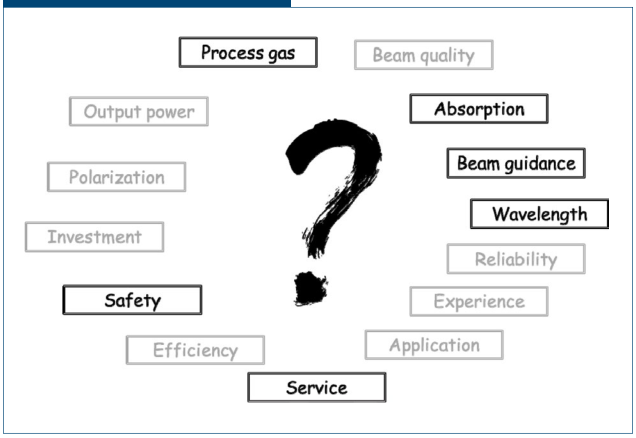
Figure 1



Factors in choosing laser type.

influenced by the environmental conditions, technological experience, the cost of investment and operational readiness. Added to this are the factors of process stability and service support.

Since the CO_2 laser technology has proven itself over the years, it is absolutely necessary to weigh the advantages of a newer technology against the risks.

Laser System Technology

Laser Resonator — For CO_2 laser sources, two types of resonators are feasible for coil application: fast-flow system and a diffusion-cooled (DC), or slab laser, system. For both types of gas lasers, the laser medium is a mixture of carbon dioxide, nitrogen and helium. Fig. 2 shows a schematic overview of both types.

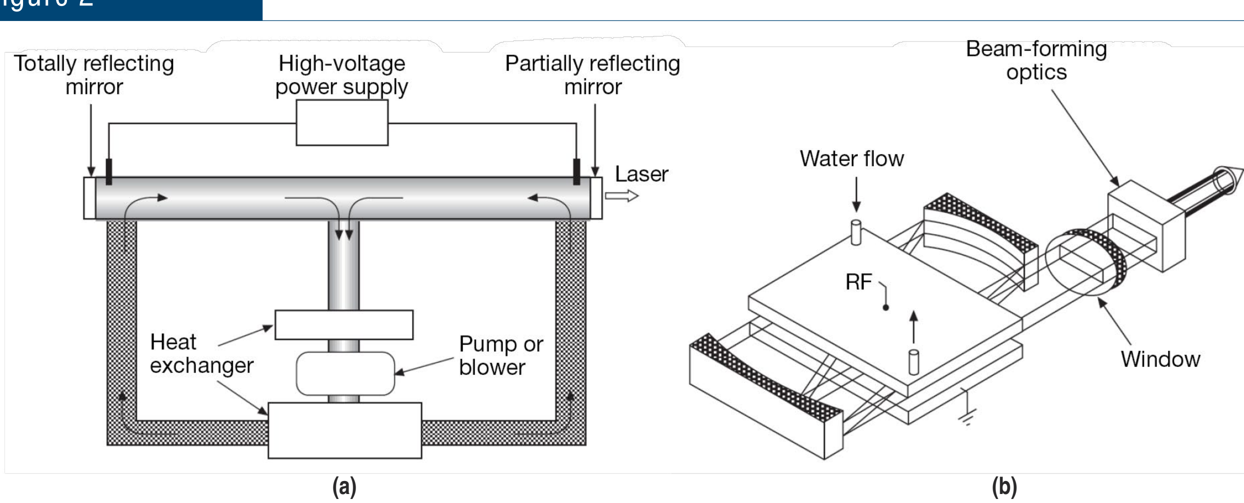
The resonator is the section between the two mirrors. The length of the resonator is derived from a multiple of the laser's wavelength. The laser gas mixture in the resonator is exposed to a high-frequency voltage field, which causes the electrons of the atoms or molecules located there to jump to a higher energy level. The electrons emit a photon of a 10.6 µm wavelength when falling back to their base level. This causes a cascade effect that stimulates other electrons to emit a photon with the same properties and direction. An output coupler mirror on one end of the resonator is partially transmissive. It releases a portion of the laser beam out of the resonator to the beam guiding system.

Fast axis flow lasers continuously circulate gases at high flowrates by means of high-speed turbines. High-power lasers up to 15 kW with good beam quality are available in this type of laser.

Slab lasers are classified as no-flow lasers, because they have no moving parts. The laser medium is also excited by RF-power in a narrow space between two water-cooled electrodes. The wide discharge area and efficient heat removal through the wide electrodes enable high power and high beam quality to be generated. High-power lasers up to 8 kW are available using this technology.

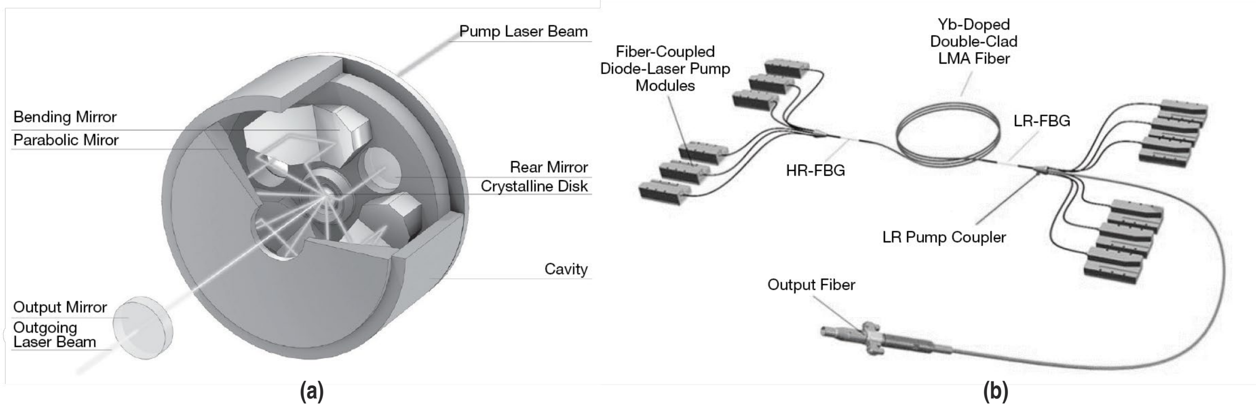
SSLs also create their laser radiation through the use of a resonator. The length of the resonator is again set to a multiple of the wavelength of the photons emitted from its medium. A common laser-active medium used in an SSL is a crystalline solid of yttrium aluminum garnet (YAG) doped with atoms of neodymium (Nd) or ytterbium (Yb). The photons generated from this resonator emit a wavelength of 1.06 µm.

Figure 2



Most common setups for CO_2 laser resonators, fast axis flow laser (a)[2] and DC laser (b).[1]

Figure 3



Two kind of laser resonators: solid-state laser (SSL) disc laser[3] (a) and fiber laser[4] (b).

Today's SSLs stimulate the electrons with laser diodes that radiate the crystal in one wavelength delivering the energy exactly in the required range. This greatly improves efficiency and significantly reduces the cooling requirements. The long-life diodes reduce maintenance needs.

Two types of SSL resonators are shown in Fig. 3: the disc laser in which the crystal is shaped like a flat disc, and the fiber laser in which the crystal forms a thin fiber. High-beam-quality lasers generating powers up to 16 kW are available from these systems.

Beam Guiding Technology — An outcoupling window is integrated into the CO_2 laser that separates the beam guiding system from the internal resonator. The beam guidance in the CO_2 laser is a permanently installed tube system with deflecting mirrors. The deflecting mirrors made from copper need to be cooled. The tube is purged with nitrogen or dried air to protect the mirrors from vapor or prevent dust contaminants from entering. The mirrors need to be perfectly aligned to one another, which is in itself a painstaking process. At the end of the beam tube is the laser optic. The beam is focused by means of a parabolic mirror of a fixed focal length that is targeted to the workpiece surface.

The beam guidance in the SSL is much simpler. The short wavelength of this type of laser makes it possible to use an optical fiber to transmit the laser radiation. The fiber allows the laser source to be positioned away from the machine, which simplifies the machine design considerably. The fiber doesn't require purge air to keep contaminants out. It eliminates the need for deflection mirrors and their associated cooling and alignment requirements. The SSL still needs to focus the beam onto the strip, but uses an optical lens for this purpose.

Interaction With Material — The different wavelengths of CO_2 and YAG have a corresponding effect on the energy absorption characteristics of the material. This has a significant effect on the welding behavior and quality of the seam. An understanding of the interactions of the laser with the material and the plasma within the keyhole is useful in determining how to manage the results.

For technical applications, melting and evaporating of material occur in very short times, which influences the absorption rates significantly. The material is vaporized instantly at high temperatures to create a keyhole. The resulting metal vapor pressure within the keyhole is partly responsible for the dynamics in the welding process. Since both wavelengths interact differently with the metal vapor, it is affected differently.

During CO_2 laser welding, the laser beam interacts with the vapor jet to form a laser-induced plasma within the keyhole and just above it. An increase in the proportion of CO_2 laser energy is absorbed by the plasma based on physical effects of inverse bremsstrahlung.[5,6] The built-up plasma expands, keeping the keyhole open during welding. The heat is also transferred via the plasma to the material. The resulting process is less influenced by variations in material and is therefore very stable.

The Nd-YAG laser has a wavelength one-tenth of the CO_2, which results in very different behavior concerning its interaction with the vapor plume. First, as the inverse bremsstrahlung absorption coefficient of an ionized gas with a given electron density follows a λ^2 scaling law, one can consider that this absorption mechanism is not at all relevant at 1.06 μm, for incident laser intensities characteristic of welding processes. As a consequence, the temperature of the vapor plume follows the temperature of the surface where the evaporation process occurs; in fact, this plume temperature may be even lower due to its expansion into the ambient atmosphere and because its reheating cannot occur due to the very low absorption coefficient. These vapor plume temperatures are rather low, in the range of and above the evaporation temperature of the material at atmospheric pressure. The laser energy is therefore not absorbed in the plasma and hits directly on the workpiece surface. This causes local evaporation of the material. These jets of vapor keep the keyhole open during the process. Since the evaporation is very dynamic, it leads to a much more dynamic process compared to the CO_2 laser.

The second aspect of the laser–plume interaction concerns the important role of particles (droplets of molten material) ejected back toward the laser along the direction of the beam. These particles have a very wide range of diameters that can vary from a few nanometers to micrometers. Because this size of particle is equal to or smaller than the SSL's 1.06 µm wavelength, it is expected that scattering and absorption by these small particles may play a much more important role than with the CO_2 laser's 10.6 µm laser wavelength. Reference 7 has shown that for welding conditions at 1.06 µm, the average particle size inside the vapor plume varied from 20 to 50 nm when He or Ar shielding gas was used, while for CO_2 laser welding, this size was typically 10 times smaller; this likely results from the strong difference in the plume temperature between these two types of welding.[8]

Service Technology and Consumptions

For CO_2 laser welding, there are three main system parts: the generator, the resonator and the beam guiding system. All these components require maintenance to ensure the safe and reliable performance of the laser system. The beam guiding system consists of a length of tube with a focusing mirror and possibly with some deflection mirrors in between. It is open-ended and flushed with nitrogen or dried air. This flushing gas inhibits the contamination of the optics from the vapor or dust. The focusing mirrors need to be cleaned approximately every 4 weeks. The deflection mirrors need cleaning as well but on a less frequent basis. Cleaning requires removal of the mirrors and possibly the realignment of the beam after they are reinstalled. In better systems and with some experience, the cleaning takes approximately 1 hour. Realignment can take several hours if required.

The fast-flow laser resonator consists of a series of mirrors and has turbines circulating the gas mixture. The output coupler requires periodic cleaning and replacement once the cleanings become ineffective. The frequency of replacement depends on the material of the output coupler and the cleanliness of the purge gas. The minimum life of the output couple is a year. The cost of replacement can be several thousands of dollars and take several hours. Over time, internal deflection mirrors also need to be refurbished depending on the cleanliness of the gases. The typical life of these mirrors is more than 10 years. There are also a number of high-voltage electrodes and quartz tubes in the resonator. The quartz tubes will age and deteriorate over time. The electrodes are subject to random failures, and monthly inspections for arcing are typically part of a comprehensive maintenance program. A complex matrix of fittings and tubing is found in the resonator. This plastic tubing is used extensively on the resonator to deliver coolant to mirrors and heat exchangers and is also used to deliver the gas mixture to the resonator. The tubing and fittings deteriorate over time, leading to the development of leaks. Proper maintenance is required to prevent the potentially disastrous consequences of a leak. A complete refurbishment of the resonator approximately every 10 years to replace the tubing, internal mirrors and quartz tubes is part of a good maintenance program. Refurbishments take months to execute, so the complete replacement of the resonator is often required at costs that can be in the hundreds of thousands of dollars. The generators also have electronic components similar to old vacuum tube televisions. A Tetrode tube is commonly used in the final amplification stage of some generators. This tube degrades over time, requiring periodic checking and monitoring to predict when it should be replaced. These tubes, which cost more than US$10,000, have life expectancies of less than 2 years. All these components have a life and need to be checked or replaced, usually by a highly skilled factory technician.

The DC lasers have no moving parts and will deploy long-life diamond output couplers, thus reducing the maintenance requirements for this type system.

In an SSL system, the beam guiding and resonator are completely enclosed. There are no movable parts for circulating gases as in the fast-flow CO_2 resonator. There no parts that have to be checked. The only part that has to be changed periodically is the protective window at the end of the optics, which is directly in contact with the process zone. The glass is shielded by an air knife to protect it from vaporous material. Depending on the application and the operating conditions, the window may need to be changed every week. This work can be done quite easily in less than 10 minutes.

The SSL diodes used to pump energy into the resonator will degrade over time. The laser manufacturers build in added capacity to the systems to allow for compensations to be made for the degradation. Life spans for the pumping diodes allow for time between replacement periods of more than a decade. When replacements are required, modular designs allow for simplified procedures that can be executed in as little as 10 minutes. The cost of pumping modules is in the order of US$25,000.

The above costs are not the most significant when comparing the differences of these two laser types; consumables are the highest cost. Differences in energy and gas consumption account for the largest portion of the running costs of these systems. The wavelength and absorption behavior require the use of helium as a shielding gas in high-power CO_2 laser welding applications. Approximately 20–70 l/minute is used during the laser welding process to deflect the plasma away from the work zone. Helium is an expensive gas currently in short supply and is difficult to procure in some areas. The SSL technology uses argon, which is less costly and more widely available than helium.

Energy cost is another key factor in considering the differences in laser technologies. Power consumption is a function of efficiency. The CO_2 laser has a wall plug efficiency of approximately 6% as compared to 40% for an SSL. For example, to achieve an output power of 15 kW, an input power of approximately 250 kW is required for CO_2 versus about 40 kW for the SSL. It is understood that the laser in a coil-joining welder only requires these levels of power during the welding cycle, so the energy cost differences are seen only for less than 5% of operating time. Further, the carbon footprint of the SSL is less than that of the CO_2 laser. Companies purchasing new equipment must show efforts to reduce their carbon footprint and the purchase of SSL welders supports those initiatives.

The third component of consumption is the cooling system. Both laser types have to be cooled precisely to ensure a stable and high-quality laser beam. CO_2 systems typically require a large industrial chiller with two different cooling circuits that need periodic maintenance. The SSL systems can often use the low-cost industrial water typically available in the plant. The CO_2 laser system must have separate circuits to isolate the copper components from the aluminum components to avoid galvanic corrosion effects. The coolant in these circuits is low-conductivity demineralized water that is chemically treated with specially formulated additives for protection against corrosion, microbial growth and freezing. The coolant must be changed annually. The environmentally responsible disposal of the spent coolant further adds to the operating cost for this type of system.

Laser Welding Performance

In this section, welding performance is assessed in regards to the robustness of weld parameters and process quality (e.g., spatter, sparks or joint imperfections).

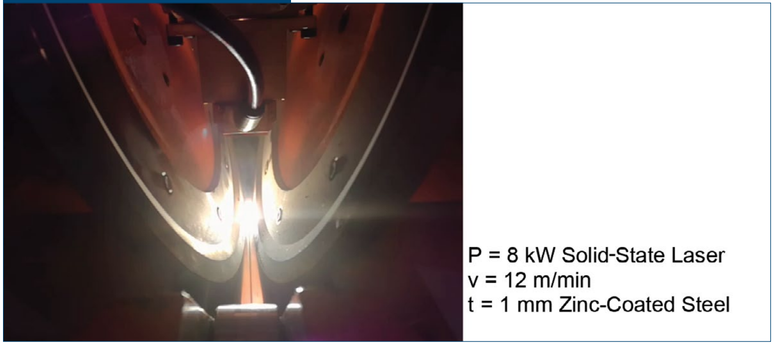
To determine the weld quality, the appearance and strength of the weld seam are evaluated as well as the resultant spatter bonded to surfaces. The quality of a weld seam is defined today in international standards such as DIN EN ISO 5817: 2014-6. In this case, evaluation criteria, defined in terms of pores, cracks or inclusions, classify the seam into quality rating groups. These can then be objectively used for the subsequent application as a rating system. These criteria cannot be used to evaluate the welds in coil joints.

The weld strength for a given set of parameters is qualified by destructive testing procedures. Tests like the Erichsen bulge test, tensile testing and reverse bending are typically used as they simulate bending and tensile stresses a weld would be subjected to in a process line.

When changing from CO_2 to solid-state laser welding, the spatter tendency of the solid-state laser is noticeable. Due to the shorter wavelength and thus the direct transfer of energy into the workpiece without the transmission medium plasma, the process becomes significantly more dynamic. Due to the Brewster angle, the vapor capillary lays about 3° flatter into the workpiece compared to the CO_2 laser. As a result, the formation of gas jets on the keyhole front wall pressure builds up toward the rear keyhole back wall. This can lead to ejected melted material, which may adhere to the surfaces as spatter.

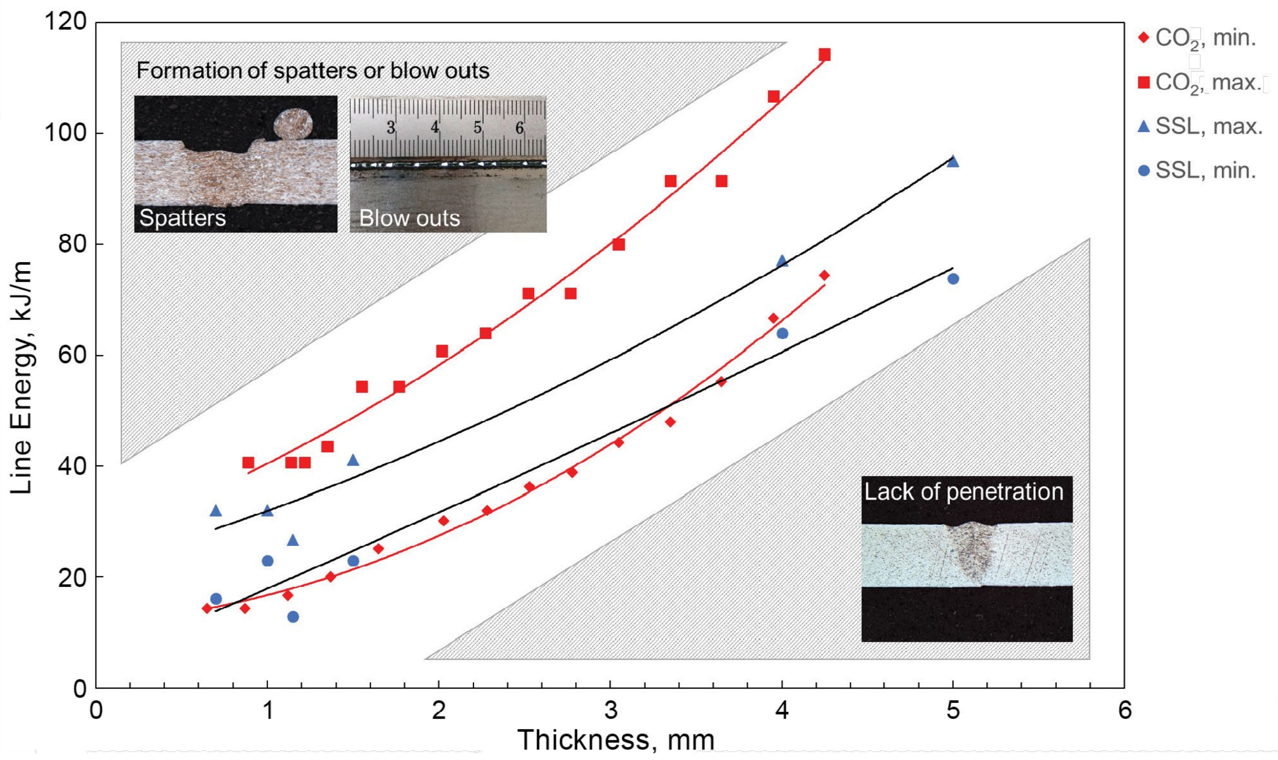
To reduce this tendency, it is necessary to find suitable methods to calm the process to avoid spatter. Alterations in the working gas (flow, alignment and type), laser intensity and geometry (intensity distribution) make it possible to reduce spatter to acceptable levels, thus making the SSL weld process applicable to

Figure 4



Spatter-free SSL welding of steel (weld point view between Miebach pilot head).

Figure 5



Parameter window for CO_2 and SSL of different sheet thicknesses and grades.

coil joining. Fig. 4 shows the spatter-free behavior of an SSL weld that can be achieved with the appropriate parameter set.

The challenge in adjusting the parameters to avoid spattering is that the parameter window is significantly reduced when welding with SSL. Fig. 5 shows parameter ranges for different sheet thicknesses.

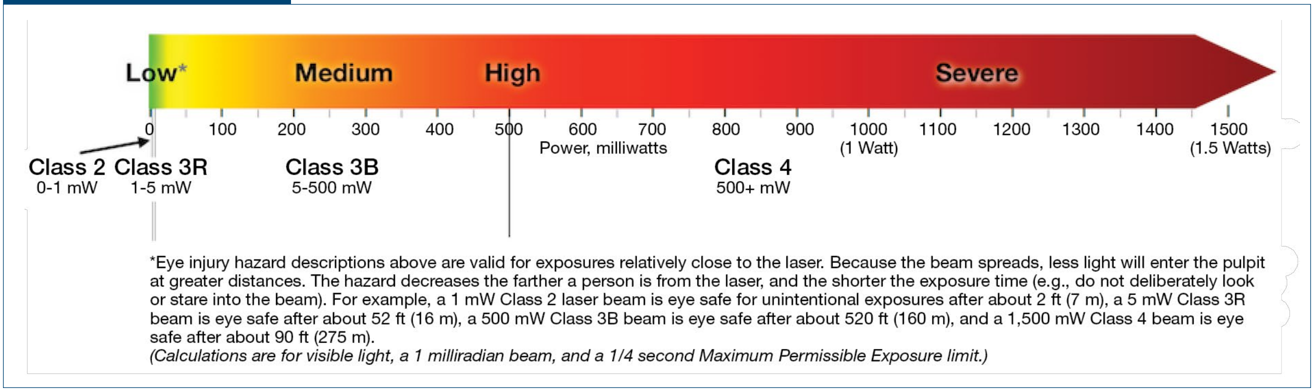
When considering the maximum values of the respectively verified parameter ranges, it can be seen that the range between the maximum and the minimum of the solid-state laser is 30% lower compared to the range between the values of the CO_2 laser. In particular, it is clear that the CO_2 laser process can cope with more energy density changes without rendering the seam unusable. In the case of solid-state lasers, an increased energy input leads to an increased spattering tendency. This restricts the working envelope when welding with the SSL. Outside the two working areas, there is a lack of penetration accompanied with spatter and ejection of material (blowholes and similar inconsistencies). This indicates that for a given sheet thickness, the parameter tolerances with the SSL are tighter.

Laser Safety Aspects

Lasers are separated into different safety classes based on the potential of causing damage to the human eye or skin. The classification is based on power levels.

Class 4 (power ratings greater than 500 mW) is typical for the high-power lasers used in welding. Lasers of this class pose a greater risk for permanent damage to eye or skin without being magnified by optics of eye or instrumentation. Further, diffuse reflections of the laser beam can also be hazardous to skin or eye within the nominal hazard zone. The nominal hazard zone is the area around a laser in which the applicable maximum permissible exposure (MPE) is exceeded. The MPE is the highest power or energy density (in W/cm^2 or J/cm^2) of a light source that is considered safe. It is usually about 10% of the dose that has a 50% chance of creating damage[7] under worst-case conditions. The MPE is measured for a given wavelength and exposure time. A calculation of the MPE for ocular exposure takes into account the various ways light can act upon the eye. For example, infrared light with a wavelength longer than about 1,400 nm is absorbed by the transparent parts of the eye before it could reach the retina, which means that the MPE for these wavelengths is higher than for visible light. The MPE is specified as power or energy per unit surface, it is based on the

Figure 6



Eye injury hazard.

power or energy that can pass through a fully open pupil (0.39 cm^2) for visible and near-infrared wavelengths. This is relevant for laser beams that have a cross-section smaller than 0.39 cm^2.

Therefore, in areas where laser radiation can occur, safety methods or engineering controls need to be implemented on the machine to shield the environment. The regulations differ based on the laser's wavelength but in all cases include the need for:

- Protective eyewear.
- Interlocks and automatic shutdown.
- Laser safety officer.

Both laser types mandate equipment designs to prevent direct exposure to the laser beam. The main difference comes when considering the reflected or diffuse exposure to the laser radiation. The longer wavelengths of CO_2 lasers allow for greater exposure limits than the SSL, which impacts the equipment design requirements. The SSL machines require much more extensive protection. This adds to the cost of the equipment and accessibility for maintenance.

Conclusion

The trend toward SSLs in steel manufacturing applications is clear. More users of CO_2 lasers are challenged by the high cost of helium consumption and equipment maintenance. SSL technology provides distinct advantages in these areas. CO_2 lasers can still produce better-quality joints with much higher process robustness than SSL. The CO_2 laser welding system still has its place where the priority is on high-throughput production is realized through processing heavier thickness materials with short cycle times. The continuous improvement of the process tolerance and the seam properties is a current subject of development at Miebach. In this way, Miebach ensures its customers the same robustness of CO_2 laser welding with the SSL joining processes of the future.

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AISTech This paper was presented at AISTech 2019 — The Iron & Steel Technology Conference and Exposition, Pittsburgh, Pa., USA, and published in the Conference Proceedings.