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Determination of Maximal Gap for Laser Welding

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Abstract

Nowadays laser welding is widely used in industrial applications. Often, steel sheets are welded without welding material by using this process. The research aims to determine the maximal gap size and the related welding parameters for the laser welding of a 3 mm thick steel sheet of S235J2 steel grade. During welding, a joint gap may occur due to inadequate edge preparation, which must be considered during the design of the technology. The result of the experiments is that using the Trumpf TLF 5000 turbo-type carbon dioxide laser of 4.5 kW power, 3000 mm/min welding speed, with a focus the maximal gap size is 0.10 mm, while at 2000 (mm/min) welding speed, with 5 mm above focus the maximal gap size is 0.27 mm which can be welded with acceptable seam quality.

Keywords: *unalloyed steel, laser welding, welded joint, joint gap.*

1. Introduction

In the 1970s, laser machining systems were introduced to the market, providing advantages across a broader technological spectrum compared to existing manufacturing systems. It also opened up entirely new application possibilities. Development in this field is ongoing. Today, laser technology has also reached the realms of both the economy and private life. Some examples include essential technological elements in automotive manufacturing (cutting, drilling, welding, hardening) [1, 2].

For high-power lasers used in material processing, the raw laser beam diameter is reduced by focusing to create the appropriate power density in the spot and to ensure that the spot size aligns with the processing area. Focusing can be achieved by lenses and mirrors. The spot size linearly changes with the distance between the focus and the optics, allowing the determination of the spot diameter at a given distance from the focal plane [3, 4]. „If the workpiece is located outside the focal distance, we refer to positive focal shift; if it is inside, we talk about negative focal shift" [5].

A portion of the laser beam can be reflected on the surface, another part can penetrate the material. The fraction that enters may be absorbed, converting into heat. The unabsorbed portion that passes through the workpiece exits from it. These three types of interaction together should determine the initial intensity. During absorption, the intensity decreases exponentially in the depth direction. This decrease depends on the material's composition, structure (crystalline or amorphous), and the wavelength of the laser radiation. The penetration depth is determined based on the 1/e ratio decrease in surface intensity. For metals, laser light transmission is zero, so the amount of reflection and absorption equals the initial intensity. Therefore, if we know one parameter, we can calculate the other. **Figure 1** shows emission among the possible interactions, which is responsible for the laser radiation phenomenon and forms the basis of solid-state lasers.

For metals, absorption occurs at depths of micrometres or less. During the absorption of laser radiation in the material, free electrons near the surface become excited, increasing their kinetic energy. The energy is transmitted towards the atomic nuclei, which vibrate with increasing amplitude. As a result, the temperature rises in the surface layers. The absorbed energy further propagates into deeper layers through heat conduction.

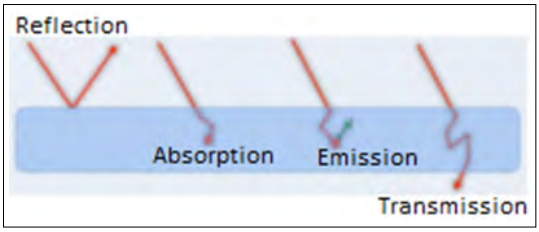

Figure 1. *Possible forms of light-matter interaction.*

With the increase in temperature, absorption also increases A sudden jump in absorption is observed during the phase change at melting, indicating that the material absorbs laser radiation to varying degrees in the solid and liquid phases.

Laser radiation is classified into seven groups based on its application: everyday and entertainment, industrial and material processing, medical, measurement and control technology, energetic, military, scientific and research. In the case of industrial and material processing laser equipment, the power (energy content) of the laser beam is always used for material processing, which is partially absorbed in the material, turns into heat, and produces various effects (heats, melts, vaporizes, transforms into a plasma state, breaks down compounds, creates material transformation) [4–6].

Lasers are typically categorized into four main groups based on the state of their active laser medium: gas, solid-state, semiconductor, and dye lasers.

1.1. Gas Lasers

Gas lasers use gas as the active medium, such as a helium-neon mixture, argon (its ions), excimer (Ar_2, F_2)/ exciplex (a noble gas and a halide element mixture, e.g., XeCl) laser gas mixtures, and carbon dioxide, as applied by us. The advantages of using gas include its homogeneity, relatively low cost, and ease of refilling. However, its drawback, inherent in its physical nature, is that it requires a large quantity of gas due to its low density to achieve population inversion[4, 5].

1.2. He-Ne Laser

The He-Ne laser (1961, Bell Laboratories) was the first type of laser that could produce continuous laser radiation. A very popular and widespread laser type in industrial practice. Both gases are contained in a glass tube, where the pressure (a few hundred pascals) is lower than atmospheric pressure, as this is necessary to induce electrical gas discharge [4, 5].

1.3. Ar-ion Laser

Argon ion lasers (similar to noble gas ion lasers) emit radiation in the visible and near-UV range. In this laser medium, low-pressure argon is used, and a direct current of 30–50 (A) creates population inversion. Argon ion lasers operate in pulsed mode, but ring discharge can also be applied to achieve continuous output radiation. Their maximum output is in the order of 100 (W) [4, 5].

1.4. Excimer / exciplex Laser

The classic meaning of excimer is an excited, homopolar molecule consisting of identical atoms (e.g., Ar_2, F_2). Nowadays, it's more common to use a mixture of a noble gas and a halide element (heteropolar, e.g., XeCl), making the correct term exciplex (excited complex) laser, although this term hasn't widely spread in practice (fortunately, these substances function similarly when used as an active laser medium). Excimer lasers typically involve a two-atom molecule formed by a noble gas or a noble gas and a halogen mixture. Excimer lasers are suitable for the heat-free ablation of organic materials and biological tissues, facilitated by the high photon energy and significant absorption characteristic of the UV range. It is also used for the excitation of dye lasers and material processing; in chip manufacturing, they are applied as a light source for photolithography [4, 5].

1.5. Carbon-dioxide Laser

The CO_2 laser operates between the vibrational levels of carbon dioxide molecules and is the most powerful gas laser, boasting the highest efficiency (15–20%). The active laser medium is a mixture of CO_2, N_2 and He gas or H_2O vapour in roughly a 1:1:8 ratio [4, 5].

1.6. Solid-State Lasers

Solid-state lasers have become worthy competitors to CO_2 lasers in recent times. In this case, the laser medium consists of solid-state materials (Nd: YAG, Nd: glass, alexandrite, Ti: sapphire, etc.). It is worth noting that low-power semiconductor lasers are also grouped with solid-state lasers. The YAG-based version has gained the most popularity, with the essential types being:

- Flashlamp-pumped YAG lasers,
- Diode-pumped YAG lasers,
- YAG disk lasers (hybrids) [1].

Laser welding has seen significant development in the past few decades. Numerous laser machining processes are known and applied in today's

industrial practices. Laser cutting is typically widespread, but laser welding is increasingly applied in various industries. The applications of laser machining are decisively determined by the applied lasers, the achievable power, and the type of laser [7–9].

Several research results are known regarding the laser welding of special materials [8–10].

The aim of the research is to determine the maximum fit-up gap for laser welding, where a suitable weld can still be created using the Trumpf TLF 5000 turbo CO_2 laser.

2. Experiments

2.1. Materials Used

The experiment was conducted on steel plates of quality S235J2, with its chemical composition provided in Table 1. This steel quality is easily-weldable and suitable for laser welding, given its low reflectivity of the base material surface, thermal conductivity of 54 W/(m²·K), and thermal expansion of $1.2 \cdot 10^{-5}$ 1/°C.

The mechanical properties of the used steel are $R_{p0,2} = 235$ MPa, $R_m = 540$ MPa, minimum elongation at fracture $A \geq 24$ %, and a density of $\rho = 7{,}85$ kg/dm³. For the experiments, plates with a thickness of 3 mm were utilized.

2.2. Welding Experiments

The experiments were conducted at Bay Zoltán Non-profit Ltd. for Applied Research using a Trumpf TLF 5000 turbo carbon dioxide laser with a wavelength of 10.6 µm, max power of 5 kW, and five-axis CNC control. The device's working area is 1600×1000×400 mm, suitable for cutting, drilling, welding, and heat treatment. To determine the welding parameters, fillet joint test welds were performed. In fillet welding, no joint is formed with another piece (Figure 2).

The constant parameters are included in Table 2. During the welding process, three different speeds (500 mm/min, 2000 mm/min, 3000 mm/min) and three focal positions (0, +5, +10 mm), were applied, resulting in a total of nine welds.

The results of the fillet welding experiments were evaluated, and the parameters of the further experiments were determined based on visual inspection and fusion depth.

To determine the weldable gap, the two plates were welded in the configuration shown in Figure 3 where one side of the plates was matched, and the other side was separated by 1 mm using a gap plate. The welding parameters are summarized in Table 3.

Table 1. *S235J2 steel chemical composition (m%)*

Components	C	Si	Mn	P	S	Cu	Fe
%	<0.17	–	1.4	0.025	0.025	<0.55	left-overs

Table 2. *Constant welding parameters.*

Filling	Performance (W)	Nozzle distance (mm)
CW (continuous operation)	4500 (90%)	1
Working gas	Gas pressure (bar)	Amount of working gas (l/min)
Helium 4.6	5	6

Table 3. *Experimental parameters.*

Signal of the sample	Focus shift (mm)	Performance (W)	Welding speed (mm/min)
A	0	4500	3000
B	+5	4500	2000

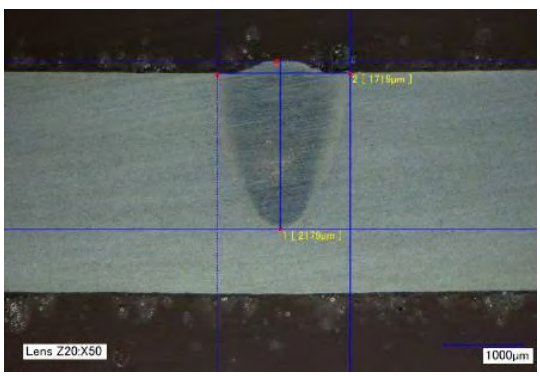

Figure 2. *Section of a fillet joint.*

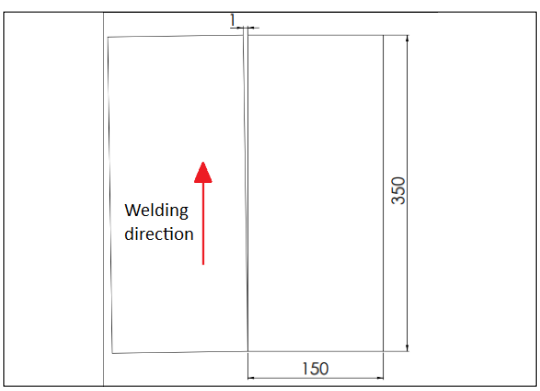

Figure 3. *Experimental arrangement.*

Table 4. *Hardness values*

	Average Hardness HV10		
Signal of the sample	**Base material**	**Heat effect zone**	**Welded joint**
A	130	150	190
B	130	160	200

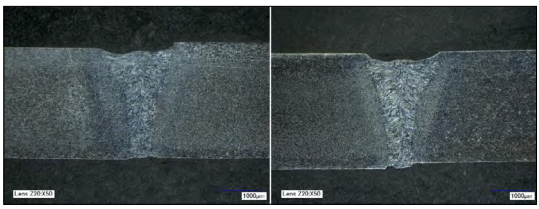

Figure 4. *Acceptable joint cross-section; focus shift: 0 mm.*

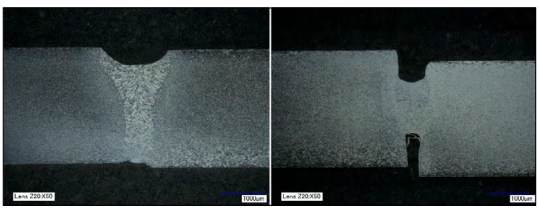

Figure 5. *Appropriate joint with +5 (mm) focal shift.*

Figure 6. *Tensile test specimens.*

3. Results

After the test welding, we observed that when welding in focus (0 mm) with a 0.1 mm gap, a satisfactory weld was achieved. **Figure 4** shows the cross-section of the welded joint with a 0.1 mm gap, welded with a power of 4.5 kW and a welding speed of 3000 mm/min.

The fusion of the two plates occurred, and the joint was successfully formed.

We have found that a +5 mm focal shift with a gap of 0.27 mm was weldable, maintaining satisfactory weld quality. **Figure 5** displays the cross-section of the welded joint with a 0.27 mm gap, welded with a power of 4.5 kW and a welding speed of 2000 mm/min.

To verify the adequacy of the weld, a tensile test was conducted. We found that in all cases, the fracture occurred in the base material, confirming the integrity of the welded joint (**Figure 6**).

We also wanted to verify the test results with hardness measurements and found that the hardness in the weld, heat-affected zone, and base material was below the permissible 380 HV10 (**Table 4**).

4. Conclusions

During sheet metal cutting, precise alignment is not always achieved, resulting in gaps at the joints of the two plates that are not uniform. Therefore, it is crucial to determine the permissible gap size to allow for the creation of a weld using laser welding without the addition of welding material. Based on the results of the conducted laser welding experiments, it can be stated that using the Trumpf TLF 5000 turbo carbon dioxide laser with a power of 4.5 kW, with welding speed of 3000 mm/min, focal shift of 0 mm, and a gap of 0.1 mm, as well as with the same power, welding speed of 2000 mm/min and a focal shift of +5 mm, a gap of 0.27 mm can be welded with acceptable weld quality.

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