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S. H. Guo, a) J. L. Zou, a) and R. S. Xiao

AFFILIATIONS
High-power and Ultrafast Laser Manufacturing Lab, Institute of Laser Engineering, Beijing University of Technology, Beijing 100124, China

a)zoujianglin1@163.com

ABSTRACT
To reveal the enhancing energy coupling effect of plasma, a comparison of the welding mode transformation process during 1-μm and 10-μm laser welding of aluminum alloys is carried out through experimental observation and theoretical analysis. The heat conduction welding stage hardly exists in 10-μm laser welding and obviously exists in 1-μm laser welding. Alloy composition and surface roughness of the welded plate hardly influence the deep penetration welding threshold (DPWT) of the 10-μm laser, whereas they have a significant impact on that of the 1-μm laser. In addition, 1-μm laser welding and 10-μm laser welding have similar DPWTs. These phenomena are attributed to the formation of plasma near the workpiece surface during 10-μm laser welding owing to metal vapor breakdown by 10-μm laser irradiation. The plasma remarkably enhances the energy coupling between the 10-μm laser and workpiece by thermal conduction, and the DPWT of the 10-μm laser is thus reduced to approximately equal to that of the 1-μm laser.

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I. INTRODUCTION
Laser welding has been considered as one of the most prospective welding technologies in the 21st century due to its overwhelming advantages such as inherent flexibility, weld beads with a high depth-to-width ratio, low heat input, and high welding efficiency. According to the laser wavelength, lasers can be divided into 1-μm and 10-μm lasers in the field of laser welding. In recent years, a lot of research studies suggest that many welding defects existing in 1-μm laser (i.e., fiber laser, Nd:YAG laser, or disk laser) welding, such as plenty of spatters, poor weld surface formation, and penetration fluctuations, are significantly different from those in 10-μm laser welding (i.e., CO2 laser). Moreover, 1-μm laser cutting or welding of thick plates is inferior to that with a 10-μm laser. Therefore, study of the differences between 1-μm and 10-μm laser welding is expected to further optimize 1-μm and 10-μm laser welding technology.

The laser-induced plasma/plume is an intuitional phenomenon to distinguish the welding process with a 10-μm laser or 1-μm laser. Since the inverse bremsstrahlung absorption of the incident laser by metal vapor is proportional to the square of the wavelength, the metal vapor above the laser-induced keyhole is more easily broken down by the 10-μm laser (CO2 laser) to form the blue plasma. In 1-μm laser welding, the yellow-orange unionized cluster above the molten pool is referred to as plume. The weld penetration and process stability are significantly improved by means of auxiliary plasma (arc) during fiber laser (1-μm laser) welding. This indicates that the welding defects may be related to the fact that plasma is not produced during 1-μm laser welding, which plays an essential role in improving the welding process stability.

About the effect of plasma, some researchers indicate that laser induced plasma has a significant effect on energy coupling to the target during the interaction between the laser and materials. In 10-μm laser welding, many studies have suggested that the plasma has a negative effect on the welding process owing to the refraction and absorption of the plasma for the 10 μm-laser, and a few research studies also insist that the plasma can improve...
energy coupling. The difference of these conclusions indicates that the plasma may have two characteristics: negative effect and positive effect. However, more evidence is needed for supporting the viewpoint about the positive effects of plasma during welding.

In laser welding, there are two types of welding modes: heat conduction mode and deep penetration mode. With the characteristic of 1-μm laser welding without plasma production, this paper utilized a high-speed camera and a spectrograph to observe the physical phenomenon of the transition process from the heat conduction mode to the deep penetration mode during 1-μm and 10-μm laser welding of an aluminum alloy. A comparative study of the effects of laser induced plasma on the deep penetration welding thresholds (DPWTs) is conducted in this paper. In addition, whether the 10-μm laser welding plasma plays a positive role in coupling the energy to the workpiece is discussed as well as plasma characteristics and energy coupling mechanism.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

Experiments were performed by using a DC035 CO₂ laser with a wavelength of 10.6 μm and a CW025 Nd:YAG laser with a wavelength of 1.06 μm, made by Rofin of Germany. The focal spot diameter of the CO₂ laser is 0.27 mm which is obtained by focusing a rotating parabolic copper mirror with a focal length of 300 mm. The Nd:YAG laser beam is transmitted through a quartz fiber with a core diameter of 600 μm and focused by a quartz convex lens with a focal length of 120 mm and the focal spot diameter is 0.36 mm. A high-speed camera (PHOTRON Fastcam 1024R2, America) was used to record the dynamic behavior of the plume or plasma with a frequency of 2000 fps. The spectrum was detected by using a transient spectrometer (PI Acton Research Spectra Pro 2500i, USA). The signal acquisition mode and parameter setting of the spectrometer were shown in our previous study.

The schematic diagram of the experimental setup is shown in Fig. 1. The experiments were conducted with two types of targets: 2024 and 5083 aluminum with the same size of 100 mm × 50 mm × 7 mm, and the chemical composition of these two kinds of aluminum is 92.25Al+ 0.5Si+ 0.5Fe+ 4Cu+ 0.5Mn+ 1.5Mg+ 0.1Cr + 0.25Zn + 0.15Ti, wt. %, respectively. The surface of 2024 aluminum was polished to a roughness of 0.04 μm and sanded to 4.63 μm, respectively. The surface of 5083 aluminum was sanded to a roughness of 4.12 μm. A laser power meter (Molelectron 3 Sigma, America) was utilized to measure the actual output power of the laser before experiments. The laser spot diameter and the focal position corresponding to different laser powers were measured by using a beam spot quality diagnostic instrument (Prometer UFF100, Germany).

Bead-on-plate welds were performed with a focused laser spot on the surface at a constant feed rate of 1 m/min. The weld seam was protected by using helium with the flow rate of 15 l/min during welding. The gas nozzle with an inner diameter of 3 mm was located at an angle of 45° to the axis of the laser beam. The direction of gas flow is the same as the welding direction. The P/d value (the ratio of the laser power to spot diameter) is a more suitable description of the DPWT than P/S (the ratio of the laser power to spot area). Hence, P/d is also adopted to characterize the welding mode transition in this paper.

III. EXPERIMENTAL RESULTS

A. The morphology of weld surface

The weld surface in Nd:YAG laser welding of 2024 aluminum with a polished surface is shown in Fig. 2. The P/d corresponding to the welds from top to bottom in Fig. 2 is between 3.11–3.95 kW/mm. The upper weld surface is relatively smooth and homogeneous, which indicated a typical thermal conduction welding mode. The last two welds in Fig. 2 were recognized as in the deep penetration welding mode due to apparently wider beads and rough appearances. Although the weld width increases gradually as the P/d value increases, the width of the same weld is approximately equal.

The typical weld morphologies of CO₂ laser welding of polishing 2024 aluminum are shown in Fig. 3. The P/d values of the weld from top to bottom are 3.84 kW/mm, 4.14 kW/mm, 4.29 kW/mm, 4.44 kW/mm, and 4.74 kW/mm, respectively. The welded plate surface begins to show signs of melting with a P/d value of 3.84 kW/mm.
When the P/d is 4.14 kW/mm, it is already in the deep penetration welding mode; this means that the interval of the P/d value from the start of melting to the deep penetration mode in CO₂ laser welding of 2024 aluminum is so small that there is almost no thermal conduction stage. In addition, when the P/d is 4.14 kW/mm during CO₂ laser welding, the weld shows an uneven surface that including an unmelting stage, a slight melting stage, and a deep penetration stage in the end. It is obvious that the morphology of the welds of CO₂ laser welding of aluminum is completely different from that of Nd:YAG laser welding.

### B. Characteristic comparison between plume and plasma

The typical plumes and the corresponding weld cross sections in Nd:YAG laser welding of polished 2024 aluminum are shown in Fig. 4. In the thermal conduction welding stage, the increase in weld penetration is slight with increasing P/d value. When the P/d value comes up to 3.84 kW/mm, the deep penetration welding mode has been achieved because the penetration depth suddenly increases. In addition, there is a bright white plume above the workpiece during the thermal conduction stage, indicating that significant evaporation already exists in the molten pool during thermal conduction welding.

As shown in Fig. 3, a whole weld at P/d = 4.14 kW/mm in CO₂ laser welding of aluminum alloy simultaneously includes an unmelting stage, a slight melting stage, and a deep penetration stage in the end. The resultant cross sections in the slight-melting stage and deep penetration stage obtained from the weld at P/d = 4.14 kW/mm and the corresponding plasma morphology are shown in Fig. 5. It can be seen that the plasma is small when the workpiece surface begins melting slightly. There is only a small illuminant in the area where the laser spot acts on, and there is barely melting trace in the cross section. When the deep penetration welding mode begins, a large bright blue plasma appears above the welded plate in the meantime.
When the P/d value is 3.78 kW/mm, the spectrum emitted by the plume during Nd:YAG laser welding is shown in Fig. 6(a). The spectral lines of the plume are mainly continuous with few line spectra, which indicates that the temperature of the plume is relatively low. Figure 6(b) shows the typical spectrum emitted by plasma during CO\textsubscript{2} laser welding of 2024 alloy (P/d = 4.14 kW/mm). The line spectra are mainly distributed in the visible spectrum and the intensity is relatively salient, which indicates that the temperature of plasma induced by the CO\textsubscript{2} laser is higher than that of plume induced by the Nd:YAG laser.

C. Comparison of deep penetration welding threshold

The variation of weld penetration with P/d values separately in Nd:YAG laser and CO\textsubscript{2} laser welding of 5083 alloy and 2024 alloy with two kinds of surface roughnesses is shown in Fig. 7. As shown in Fig. 7(a), the DPWTs of Nd:YAG laser welding of milled 5083 alloy and 2024 alloy are about 3.25 kW/mm and 3.65 kW/mm, respectively. The DPWT of welding of polished 2024 alloy is about 3.84 kW/mm. Under the abovementioned three conditions, the DPWTs of Nd:YAG laser welding of Al alloy have some difference, indicating that alloy composition and surface roughness have a significant influence on the DPWT of the Nd:YAG laser.

In Fig. 7(b), the DPWTs of CO\textsubscript{2} laser welding with different alloy compositions and surface roughnesses are approximately the same and the value is about 4.14 kW/mm. The DPWT is hardly influenced by alloy composition and surface roughness. Two remarkable characteristics can be summarized from Figs. 7(a) and 7(b): (1) the DPWTs of these two kinds of laser welding are similar despite a large discrepancy in aluminum alloy absorption of the Nd:YAG laser and CO\textsubscript{2} laser and (2) the DPWT of CO\textsubscript{2} laser welding of aluminum alloy is much less affected by alloy composition and surface roughness in contrast to Nd:YAG laser welding.

The first weld bead in Fig. 3 consisting of unmelting and slight melting states is simultaneously recognized as a critical state of fusion. The melting thresholds and DPWTs of the welded material in these two kinds of lasers are listed in Table I. In fact, the melting threshold of Nd:YAG laser welding is smaller than 3.11 kW/mm.
### IV. THEORETICAL ANALYSIS AND NUMERICAL CALCULATION

#### A. Melting and evaporation thresholds for laser welding

The DPWTs and melting thresholds of two wavelengths of laser welding can be calculated. For the modeling of a tiny molten pool in laser thermal conduction welding, the effect of fluid behavior and metal vapor behavior can be reasonably neglected. Therefore, a surface heat source is introduced in the calculation. It is assumed that the laser heat source obeys the Gaussian distribution given by the following equation:

\[
I(r) = \frac{2AP}{\pi R_l^2} \exp \left( -\frac{2r(t)^2}{R_l^2} \right),
\]

where \( P \) and \( R_l \) are the laser power and effect radius of the laser spot and \( r(t) \) represents the instantaneous distance to the center of the heat source, which consists of the welding velocity. \( A \) denotes the absorption of laser energy dependent on temperature. Except for the heating of the surface Gaussian distributed source, heat loss by convection and radiation of the target materials is included in the calculation with an integration convection coefficient \( h_i \). The heat loss at the boundary of the model can be expressed as

\[
q_a = h_i(T - T_0).
\]

The initial temperature of the workpiece and the ambient temperature are 300 K. Based on the conservation law of energy, the governing equation in the three-dimensional laser welding temperature field in the conduction mode is

\[
\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T + I(r) - q_a,
\]

where \( \rho \), \( c_p \), and \( \lambda \) are the density, specific heat, and thermal conductivity of welding materials, respectively. \( \rho \), \( c_p \), and \( \lambda \) are dependent on the temperature and are obtained from the commercial thermal parameter calculation software, JMatPro. Equations (1) and (2) are as the source terms in Eq. (3). When the temperature of the molten pool surface in the laser spot edge reaches evaporation temperature, a deep penetration welding condition has been reached. In addition, the DPWT of the welded material can be written as

\[
P_d = \frac{\sigma L_v}{A} \sqrt{\frac{m_v}{k_B T_v}} + \frac{2\sqrt{2\pi(T_v - T_0)\lambda}}{A(T) \exp\left( -\frac{\rho c_p T_0}{4T} \right)}.
\]

where \( \sigma \) is the molten pool surface tension coefficient, \( L_v \) is the latent heat of evaporation of the liquid metal, \( k_B = 1.38 \times 10^{-23} \text{ J/K} \) is the Boltzmann constant, \( m_v \) is the mass of the vapor molecule. Pure aluminum absorption of the incident laser dependent on temperature is calculated by referring to the work of Huttner. The resulting dependence on the material temperature is shown in Fig. 8. It is noted that in the ideal surface state, absorption values at room and boiling temperature with an incident YAG laser are approximately 3 times those of the CO\(_2\) laser.

In this calculation, the transient temperature field of laser conduction mode welding is obtained by the finite element method. Figure 9 shows a longitudinal-sectional temperature distribution of the weld bead obtained by Nd:YAG laser welding of 2024 alloy. In this paper, the melting threshold is defined as the laser spot irradiating edge temperature reaching the melting point temperature of the welded material. Similarly, the evaporation threshold is also defined as the temperature at which the acting laser spot edge reaches the evaporating point.

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### TABLE I. Melting threshold and DPWT in laser welding of 2024 alloy with a polished surface.

| Condition of surface (YAG) (CO\(_2\)) | Melting | Penetration |
|---------------------------------------|---------|-------------|
| (YAG)                                 | <3.11   | 3.84        |
| (CO\(_2\))                            | 3.84    | 4.14        |

The melting threshold and DPWT of CO\(_2\) laser welding of 2024 alloy are 3.84 kW/mm and 4.14 kW/mm, respectively, and these two values have almost no difference. In addition, the DPWTs of these two kinds of laser welding are similar.
TABLE II. Theoretical melting threshold and DPWT (kW/mm).

|          | YAG laser | CO₂ laser |
|----------|-----------|-----------|
| Melting  | 2.69      | 8.81      |
| DPWT     | 3.86      | 9.15      |

The calculated values of the melting threshold and DPWT with YAG laser and CO₂ laser action are concluded in Table II. The DPWT of Nd:YAG laser welding of 2024 aluminum with a polished surface is about 3.84 kW/mm in Fig. 7, which is consistent with the calculated DPWT in Table II. A more polished surface can result in lesser absorption. According to Eq. (4), a greater deep penetration welding threshold will be achieved. This is the reason why the DPWT of Nd:YAG laser laser welding of 2024 aluminum with a polished surface is bigger than that of a milled surface, as shown in Fig. 7. In addition, the alloy composition also has an apparent impact on the thermal physical parameters of the welded material and absorption, which also explains the difference in DPWTs between Nd:YAG laser welding of 5083 alloy and 2024 alloy.

The calculated melting threshold and DPWT of CO₂ laser welding of 2024 aluminum in Table II are much bigger than their experimental value in Table I. Theoretically, only if a P/d value is higher than 9.15 kW/mm, there will be a deep penetration welding mode during CO₂ laser welding of 2024 aluminum. However, the deep penetration welding has already existed with a P/d value of 4.14 kW/mm in experiment. The value set of aluminum thermal physical parameters is also used in Nd:YAG laser welding of aluminum, and the results in Table II are consistent with the experimental value in Nd:YAG laser welding. Hence, the thermal physical parameters chosen are reasonable.

Another influencing factor is the actual absorption coefficient. As shown in Fig. 7(b), the actual absorption coefficient is independent of the alloy composition of the welded material and the surface roughness of the welded material during CO₂ laser welding. The most apparent difference between Nd:YAG laser and CO₂ laser welding is whether plasma is generated during welding. Theoretical calculation of Fresnel absorption based on Fig. 8 with the two-wavelength laser has a uniform criterion. Thus, a steep increase in plate surface absorption of the CO₂ laser can only be attributed to plasma appearance.

Walters et al.¹¹ compared the interaction between the laser and aluminum alloy in vacuum and atmospheric environments and confirmed that plasma could increase the energy coupling remarkably between the laser and aluminum alloy. In consequence, the abrupt appearance of plasma is the dominating reason for absorption increase. In addition, the absorption increases closer to the absorption of the Nd:YAG laser, which accounts for the experimental results; the DPWT of CO₂ laser welding quite closer to that of the Nd:YAG laser is under its calculated melting threshold value.

B. Plasma formation in CO₂ laser welding

If melting of the target bulk has not occurred and plasma is required to enhance energy coupling to reduce the melting threshold or DPWT, then the prerequisite is that the metal vapor on the surface is broken down by the CO₂ laser and becomes plasma. Walters et al.¹¹ observed the surface of the Al alloy before and after laser irradiation with a scanning electron microscope and revealed that numerous defects were found to be present on the plate surface. In addition, the bulk at the defect location is the first to evaporate after irradiation. The defects are considered to be isolated from the bulk material. The laser power for evaporating defects at the center of the laser spot can be estimated by

\[ cm(T_v - T_0) + mL_v = Alst, \]

where \( c \) is the specific heat of the material, \( m \) is the mass of the defect layer, \( I_0 \) is the intensity of the incident Gaussian laser spot, \( s \) is the surface area of a defect, \( t \) is the characteristic action time of the laser spot, and \( A \) is the absorptivity of the CO₂ laser incident alloy. For example, a defect has a length and width of 1 μm and a thickness of 0.5 μm. The absorptivity of the CO₂ laser is a constant value of 2% in the calculation. The P/d value of the CO₂ laser required to completely evaporate the defect is 2.85 kW/mm. However, the melting threshold in the CO₂ laser welding experiment is 3.84 kW/mm (see Table I). According to the above discussion, there must be a small amount of metal vapor generated from the defect before bulk melting, and the metal vapor appears to be uncorrelated with the surface condition and alloy composition.

When the P/d of the CO₂ laser is 4.14 kW/mm (that is, the power is 1.12 kW and the spot diameter is 0.27 mm), the target surface experiences three stages of unmelting, slight melting, and deep penetration (see Fig. 3). There exists a mass of bright blue plasma on the weld surface in the third stage, which indicates that the power of 1.12 kW of the CO₂ laser used in the experiments is sufficient to break up the defect vapor to form plasma. The reflectivity of the CO₂ laser irradiated alloy reaches up to 98% at the unmelting and slight melting stages. The equivalent laser power can reach up to 2.24 kW due to a coincident coupling (duplication) between the incident and reflected laser beams. Therefore, metal vapor evaporating from surface-defects will break down into plasma. The plasma-luminosity site over the acting region in the thermal conduction stage is shown in Fig. 5. The deep penetration welding mode will be realized once the plasma ignited from the defect vapor is enough to enhance the energy coupling between the laser and target surface.

C. The mechanism of plasma enhancing energy coupling

There are three factors affecting the energy coupling between the laser and target: Fresnel absorption, thermal conduction, and thermal radiation promoted by the plasma from surface defects. The plasma will change the gas environment outside the target surface from air to plasma, which causes a change in the refractive index for laser irradiated materials. Hence, the plasma atmosphere will influence the Fresnel absorption of laser irradiated targets. As for air to the metal target surface, the refractive index of the atmosphere is about 1 and the metal absorptivity of laser can be calculated using the following equation:

\[ A = \frac{n_2}{(n_2 + 1)^2 + \kappa_2^2}, \]

where \( n_2 \) and \( \kappa_2 \) are the real and imaginary part of the refractive index of the CO₂ laser in interaction with the Al alloy, respectively.
When the boundary condition becomes plasma-metal, the modified absorption becomes
\[
A' = \frac{4n_1n_2 + 4\kappa_1\kappa_2}{(n_1 + n_2)^2 + (\kappa_1 + \kappa_2)^2},
\]  
where \(n_1\) and \(\kappa_1\) are the real and imaginary part of the refractive index of the CO\(_2\) laser in interaction with plasma, and these two parts can be expressed by the following equations:
\[
n_1 = \sqrt{1 - \frac{n_0e^2}{\varepsilon_0m_e\omega^2}},
\]
\[
\kappa_1 = \frac{e}{v}K_v.
\]

The inverse bremsstrahlung absorption of laser irradiating plasma \(K_v\) is
\[
K_v = \frac{2\pi Z^2 e^4 n_e n_i}{6\sqrt{3} \varepsilon_0 m_e \omega^3} \left[ 1 - \exp\left( -\frac{\hbar \omega}{n_0e^2}\right) \right] \tilde{g}.
\]

Here, degeneracy \(\tilde{g} = 1.5\)\(^{22}\), and \(n_e\) and \(n_i\) are the number density of electrons and ions in plasma, respectively. Considering that the plasma in laser welding is regarded as primary ionization, then \(n_i = n_e\) and \(Z = 1\); \(\varepsilon\), \(\varepsilon_0\), and \(m_e\) are the elementary charge, vacuum permittivity, and electron mass, respectively. \(\omega\) is the circle frequency of the laser beam, \(T\) is the temperature of plasma, and \(c\) is the speed of light in vacuum. The frequency of plasma is calculated as \(\omega_p^2 = \frac{e^2}{\varepsilon_0 m_e}\). Saha equation,
\[
n_e^2 = \frac{(2\pi k n T)^{3/2} 2g' e}{g''} \exp\left( -\frac{\varepsilon_T}{k_B T}\right)
\]
where \(n_0\) is the atom number density. For aluminum plasma, partition functions \(g' = 1\) and \(g'' = 6\),\(^{29}\) and \(\varepsilon_T = 5.98\) eV is the excited level energy. The pressure of plasma is given by\(^{1,24}\)
\[
P_0 = (2n_e + n_i)k_B T_e.
\]

The temperature of aluminum plasma is assumed to be 8000 K according to previous studies. Since the plasma near the target surface is first formed by evaporation and then ignited by the laser, the partial pressure of aluminum vapor can be assumed to be 1 atm. The refractive index of plasma consisting of \(n_i\) and \(\kappa_1\) can be directly calculated by combining Eqs. (8)–(12). The aluminum bulk refractive index of the CO\(_2\) laser \((n_2 + i\kappa_2)\) with different temperatures can be obtained according to the literature.\(^{21}\) Therefore, using Eq. (7), the Fresnel absorptions of CO\(_2\) laser incident aluminum under the influence of plasma with different surfaces temperatures are shown in Table III.

| Temperature (K) | \(A\) (%) | \(A'\) (%) |
|-----------------|----------|----------|
| 300             | 1.08     | 1.06     |
| 2500            | 7.56     | 7.51     |

V. CONCLUSION

Based on these differences in the welding mode transformation process during 1-\(\mu\)m and 10-\(\mu\)m laser welding of aluminum,
the effect of plasma on the energy coupling between the laser and metal is comparatively studied. The following conclusions can be drawn:

1. In 1-μm laser welding, the range of the P/d value is relatively large in the heat-conduction mode, and alloy composition and surface roughness have an apparent effect on the DPWT.
2. The melting threshold is quite close to the DPWT, and alloy composition and surface roughness of the welded plate hardly influence the DPWT during 10-μm laser welding.
3. 1-μm laser welding and 10-μm laser welding of polished Al alloy have similar DPWTs. When P/d is equal to the DPWT, the weld bead consists of unmelting first, then slight melting appearance, and the last deep penetration appearance during 10-μm laser welding.
4. Theoretically analysis shows that plasma obviously increases the energy coupling of the 10-μm laser to the workpiece in the welding mode transformation process. The general absorption is greatly enhanced by heat conduction, and both melting and deep penetration welding threshold values are thus decreased to approximately equal that of the 1-μm laser.

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