Effect of high power CO$_2$ and Yb:YAG laser radiation on the characteristics of TIG arc in atmospherical pressure argon and helium

Shikai Wu *, Rongshi Xiao
Institute of Laser Engineering, Beijing University of Technology, Beijing 100124, China

**A R T I C L E   I N F O**

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**A B S T R A C T**

The effects of laser radiation on the characteristics of the DC tungsten inert gas (TIG) arc were investigated by applying a high power slab CO$_2$ laser and a Yb:YAG disc laser. Experiment results reveal that the arc voltage–current curve shifts downwards, the arc column expands, and the arc temperature rises while the high power CO$_2$ laser beam vertically interacts with the TIG arc in argon. With the increase of the laser power, the voltage–current curve of the arc shifts downwards more significantly, and the closer the laser beam impingement on the arc to the cathode, the more the decrease in arc voltage. Moreover, the arc column expansion and the arc temperature rise occur mainly in the region between the laser beam incident position and the anode. However, the arc characteristics hardly change in the cases of the CO$_2$ laser–helium arc and YAG laser–arc interactions. The reason is that the inverse Bremsstrahlung absorption coefficients are greatly different due to the different electron densities of the argon and helium arcs and the different wave lengths of CO$_2$ and YAG lasers.

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1. Introduction

Due to its high welding speed, deep penetration depth, low distortion, good microstructural and mechanical characteristics, high flexibility, and possibilities of automation and robotization, laser beam welding has become an established process in automobile, shipbuilding and aerospace industries in the last 20 years. However, the engineering application of laser beam welding has its limitations due to the shortages of poor bridge ability, high cost, and process instability in some cases such as welding of aluminum alloys and so on. To overcome these disadvantages, laser–arc hybrid welding is receiving intensive study all over the world and has found practical applications in many industrial fields [1]. By combining two heat sources with different physical characteristics and energy transfer mechanisms, the laser–arc hybrid welding process helps in improving the welding efficiency, reducing the welding cost, increasing the joint fit-up tolerance, enhancing the process stability, and eliminating the weld defects [1–3]. Currently, the most commonly used high-power laser types are still the CO$_2$ laser, the disc and fiber laser for laser–arc hybrid welding application. As secondary heat sources, the MIG/MAG is of primary interest for its high filler metal deposition rate and the joint fit-up tolerance. But the metal transfer increased the process complexity in MIG/MAG. Consequently, the TIG arc with no transfer of metal and no molten droplets of spatter is most suitable to investigate the physical phenomena and the mechanisms concerning laser–arc interaction.

Most studies have addressed the influence of the laser–arc hybrid welding processes to demonstrate the advantages of the hybrid welding, and it seems that the complicated physical phenomena and mechanisms of the interaction between the focused laser beam and the arc plasma are not fully understood. The laser and arc characteristics during laser–arc interaction have not been detected directly during hybrid welding for the additional disturbances, e.g. the laser induced metal evaporation. Steen [4] headed the study in this field and found that the arc is stabilized and the arc voltage decreases during CO$_2$ laser–TIG hybrid welding of steel. Gorny and Redozubov [5] found the similar phenomena in CO$_2$ laser–TIG hybrid welding of corrosion-resistant steel, titanium, copper and aluminium. The study of Chen et al. [6] shows that the arc root is dramatically compressed at a lower arc current ($I=40$ A) and the arc expands when the current is increased to $100$ A in CO$_2$ laser–TIG hybrid welding of steel with a laser power of 1000 W. They also found that laser-supported combustion waves generate at an arc current of 200 A. Naito et al. [7] investigated the arc behavior in YAG laser–TIG hybrid welding. The high speed photographs reveal that a part of the arc column becomes concentrated in the vicinity of the keyhole mouth, but...
the unstable laser induced plume emitted from the keyhole causes the violent fluctuation of the arc. Stute et al. [8] stated in their paper that the arc burns steadily up to a welding speed of 5 m/min in Nd:YAG laser–TIG arc hybrid welding with a laser power of 300 W due to the arc anode stabilization of the laser heated zone. Hu and Ouden [9] discovered that the arc stability and melting efficiency are much improved in the YAG laser–TIG arc hybrid welding process than in the TIG welding process. Seyffarth and Krivtsun [10] proposed that the local character of the plasma heated by a focused laser beam in hybrid welding results in significant redistribution of the current density, which may therefore lead to a fundamental change in the energy balance of the arc.

The characteristic change of the arc in the hybrid welding process is related to its electron density change. Lu et al. [11] evaluated the electron density of the arc plasmas in TIG and laser–TIG hybrid welding by the method of Stark Broadened Linewidth. The results show that the electron density of the arc plasma in laser–TIG hybrid welding is $5.2 \times 10^{17}$ cm$^{-3}$, much greater than that of $0.95 \times 10^{17}$ cm$^{-3}$ in TIG welding. Hu and Ouden [9] measured the electron density and composition of the arc plasma in Nd:YAG laser–TIG arc hybrid welding of steel and found that the number of Fe ions is much higher throughout the arc whereas the intensity of the Ar lines is significantly lower in hybrid welding than that in TIG welding, resulting from the ionization of the metal atoms due to the laser induced evaporation. Liu and Hao [12] studied the arc electron temperature and ionization of the metal atoms due to the laser induced evaporation and ionization of the target metal in laser–arc hybrid welding. In recent years, with the development of high power and high beam quality laser sources, hybrid welding technologies with such lasers have intensively been studied [13-15]. However, the effect of high power laser on the arc properties has not been fully investigated. At the same time, the laser induced evaporation and ionization of the target metal influence the arc characteristics greatly. In order to further explore the essential mechanism of the interaction between laser beam and arc plasma, the effects of high power CO$_2$ and Yb:YAG laser radiation on the arc characteristics in atmospheric pressure argon and helium were investigated in this study.

## 2. Experimental conditions

A Rofin DC035 slab CO$_2$ laser with the maximum power of 3.5 kW, a Rofin DS040 HQ disc Yb:YAG laser with the maximum power of 4 kW and a Fronius TS5000 digital arc welding power source were used. In order to eliminate the influence of the laser induced evaporation and directly measure the laser power absorbed by the arc, the laser beam is horizontally directed through the arc plasma, schematically shown in Fig. 1. A parabolic mirror with a focal length of 300 mm for the CO$_2$ laser beam and a lens with a focal length of 300 mm for the YAG laser beam were used, yielding focal spots of 0.27 mm and 0.3 mm in diameter respectively. The maximum power densities at the focal spots were $6.12 \times 10^6$ W/cm$^2$ for the CO$_2$ laser beam and $5.66 \times 10^6$ W/cm$^2$ for the YAG laser beam. The focal spots were set at the central axis of the TIG arc. The cathode and anode electrodes with diameters of 2.5 mm and 30 mm are tungsten containing 2% Ce$_2$O$_3$. The distance between the cathode and anode electrodes with diameters of 2.5 mm and 30 mm was 6 mm. Argon and helium with a purity of 99.99% were used as the inert arc atmosphere and the flow rates were 15 L min$^{-1}$ and 25 L min$^{-1}$ respectively. During the experiment, a digital voltmeter and a digital current meter were installed to measure the voltage and current of the TIG arc, and a Molelectron 3sigma laser power meter was placed behind the arc to measure the laser power. The arc configuration was taken with a PHOTRON Fastcam 1024R2 high speed camera. The frame rate was fixed at 8000 frames per second. Using a PI Acton Research Spectra Pro 2500i spectrograph with a focus of 500 mm in combination with a lens of 100 mm in focal length and an optical fiber of 200 μm in diameter, the spectrums of the arc plasma were acquired for calculating the arc temperature.

## 3. Experimental results

### 3.1. Voltage–current characteristic

Fig. 2 shows the voltage–current characteristic of the arc in argon and helium when the laser beam interacts with the TIG arc at the middle position between the two electrodes. It can be seen that the voltage–current plot of the arc in argon shifts downwards in the case of CO$_2$ laser–TIG arc interaction, and the shift value increases with the laser power accordingly. However, with the interaction of YAG laser, the voltage–current plot of the arc remains almost
unchanged. At the same time, there is also no obvious influence of the laser radiation on the voltage–current plot of the helium arc.

Moreover, the arc voltage decrease is relative to the laser incident position when the CO2 laser beam interacts with the arc. Fig. 3 shows the relationship of the arc voltage and the laser power with an arc current of 50 A. It can be found that the voltage decreases most when the laser interacts with the arc near to the cathode and least when the laser interacts with the arc close to the anode. In other words, the closer the laser–arc interaction position to the cathode, the more the decrease in voltage.

3.2. Arc configuration

Fig. 4 demonstrates the relationship of the local arc column diameter ratio ($D/D_0$) and the laser power when the laser interacts with the arc in the middle region of the arc column. Here $D_0$ stands for the initial arc column diameter at the laser incident position, and $D$ means the local arc column diameter with laser irradiation. As shown in Fig. 4, the local arc column diameter increases considerably when the CO2 laser beam passes through the argon arc. The arc column expansion becomes more significant at a lower arc current and increases with the laser power. The diameter almost doubles when the laser power is 3500 W. However, the arc expansion is inappreciable in the case of the CO2 laser interaction with the helium arc. The diameter increases only by about 5% with a laser power of 3500 W. Furthermore, the arc column remains unchanged when the YAG laser interacts with the arc.

Fig. 5 shows the configurations of the initial argon arc and those interacted with the CO2 laser with an arc current of 50 A and a laser power of 500 W. As shown in Fig. 5, no matter where the laser interacts with the arc, the arc column expansion happens mainly in the region from the laser beam incident position to the anode. When laser incident position is close to the cathode, the whole arc column expands.

Besides, laser support combustion (LSC) waves were observed when the CO2 laser passes through the argon arc with a laser power of more than 1500 W (the corresponding power density is $2.62 \times 10^6$ W/cm²), as shown in Fig. 6. The LSC waves ignite within the arc plasma, and then propagate against the laser incident direction at subsonic velocity and diminish after reaching a certain height from the arc column. These processes appear periodically. In the experiment, the frequency of LSC waves measured is about 500–1000 Hz, and the propagation velocity is about 15 m/s. However, no LSC waves are generated when the CO2 laser interacts with the helium arc even with a laser power of more than 3500 W. Moreover, the LSC waves do not occur in the case of YAG laser–arc interaction with a laser power of more than 4000 W even in argon.

3.3. Arc temperature and electron density

It is well known that the particles in the plasma have an energy distribution given by the Maxwell equation and the collision processes are dominant relative to the radiation processes on the
condition of the local thermodynamic equilibrium (LTE). So the population \( n_p \) of an excited state \( p \) is determined via the Boltzmann distribution:

\[
n_p = \frac{n_0}{Z}\frac{g_p}{\exp(-E_p/kT_e)}
\]

where \( n_0 \) is the population density of atoms in the ground state, \( Z = \sum g_p \exp(-E_p/kT_e) \) is the partition function, \( g_p \) is the degeneracy of the \( p \) state, \( E_p \) is the energy of the \( p \) state above the ground state, \( k \) is for the Boltzmann constant, and \( T_e \) is for the electron temperature of the plasma.

In the condition of assuming that the plasma is optically thin and the lines are free from self-absorption, the spectral line emission intensity for the transition from level \( p \) to level \( q \) is described by

\[
I_{pq} = \frac{n_e A_{pq} h_p \nu_{pq}}{h_0^3 \exp(-eU_i/kT_e)}
\]

where \( A_{pq} \) is the atomic transition probability between upper state \( p \) and lower level \( q \), \( h_p \) is Planck’s constant and \( \nu_{pq} \) is the frequency of the spectral line from level \( p \) to level \( q \).

Combining Eq. (1) with Eq. (2) and taking into account the relation between the wave lengths, the light speed and the wave frequency, one can obtain the following equation:

\[
\ln \left( \frac{I_{pq} h_p \nu_{pq}}{A_{pq} g_p} \right) = \ln \left( \frac{n_e h_p \nu_{pq}}{Z} \right) - \frac{E_p}{kT_e}
\]

where \( Z \) is the partition function, and \( \ln(n_0hc/Z) \) is a constant. A Boltzmann plot of \( \ln(I_{pq} h_p \nu_{pq}/A_{pq} g_p) \) versus \( E_p \) for transitions originating on several different states \( E_p \) then yields a slope \(-1/kT_e\) [12,16–17]. By this method, the electron temperature \( T_e \) can be estimated. And then the plasma density can be obtained by the Saha equation [18]:

\[
\frac{n_e n_i}{n_0} = \frac{(2\pi m_e kT_e)^{3/2} 2g_i}{h_p^3 g_0} \exp \left( \frac{eU_i}{kT_e} \right)
\]

where \( n_e \), \( n_i \), and \( n_0 \) are the electron, ion and neutral atom number density respectively; \( e \) is for the elementary charge; \( m_e \) is for the electron mass; \( h_p \) is for the Planck’s constant; \( g_0 \) and \( g_i \) are for the total degeneracy of the atom and ionized states; and \( U_i \) is for the atom’s ionization energy from the \((i-1)\)th to the \(i\)th level (\( U_1 \) is for the first ionization energy).

In order to reduce the error in the Boltzmann plot method, spectral lines of the same element with the same ionization state are usually preferred. In the present experiment, the emission lines of Ar I 415.859 nm, Ar I 420.0674 nm, Ar I 696.5431 nm, Ar I 706.7218 nm, Ar I 714.704 nm and Ar I 772.3761 nm were selected to estimate the electron temperature.

Fig. 7 shows the arc temperature distribution along the longitudinal axis. It can be seen that the arc temperature increases when the CO2 laser beam interacts with the arc, and the temperature increase mainly happens in the region between the laser beam incident position and the anode. However, the arc temperature near
the cathode seldom changes unless the laser interacts with the arc in this area.

Table 1 shows the comparisons of the local temperature and electron density of the arc at the laser incident position with and without the CO2 laser beam interaction. It can be seen the local electron density and the temperature increase simultaneously when the CO2 laser beam interacts with the TIG arc.

3.4. Total arc power

Fig. 8(a) shows the effect of the CO2 laser incident position on the electric power (\(P_{el}\)) and the total power of the argon arc, where \(P_{el}\) is the initial electric power. The total power is the sum of the electric power and the absorbed laser power. Fig. 8(b) shows the effect of the laser power on the total power when the laser interacts with the arc at the middle location between the cathode and anode. It can be seen that the electric power decreases when the laser interacts with the arc. The nearer the laser incident position to the cathode, the more the decrease in electric power. However, the total power increases. The closer the laser incident position to the anode, the more the electric arc power and the total power.

4. Discussions

The laser–arc interaction can be attributed to the laser–plasma interaction. When the laser beam propagates in the arc plasma, a part of the laser energy will be absorbed by the electrons in the plasma via the process of inverse Bremsstrahlung, i.e. an electron absorbs a photon in the electric field of an ion. Consequently, the absorbed energy is transformed into kinetic energy by the collisions of high-frequency oscillation of the electrons with the ions [18,19]. As a result, there is an attenuation of the laser power when the laser beam passes through the arc plasma. According to the classical electron–ion collision theory, the inverse Bremsstrahlung absorption coefficient of electromagnetic waves in the plasma is given by the following equation [20,21]:

\[
K_a = \frac{Z^2 n_e n_i e^2 \mathcal{G}}{6\sqrt{3} \pi \epsilon_0 \mu_0 c^3 \omega^3} \frac{m_e}{2\pi kT_e} \exp \left( -\frac{\hbar \omega}{kT_e} \right) \quad (5)
\]

where \(Z\) is the charge number of the atom, and \(n_e\) and \(n_i\) is the electron and ion number density respectively; \(e\) is for the elementary charge; \(m_e\) is for the electron mass; \(k\) is for the Boltzmann constant; \(\hbar\) is for the Planck’s constant; \(h_\nu\) divided by \(2\pi\); \(\epsilon_0\) is for the permittivity of the vacuum space; \(\mu\) is for the refractive index; \(\mathcal{G}\) is for the average quantum-mechanical Gaunt factor; \(\omega\) is for the circular frequency of the electromagnetic wave; and \(T_e\) is for the temperature of the plasma.

For the high-frequency laser beam, \(\hbar \omega \ll kT_e\). Eq. (5) can be approximated as follows:

\[
K_a \approx \frac{Z^2 n_e n_i e^2 \mathcal{G}}{6\sqrt{3} \pi \epsilon_0 \mu_0 c^3 \omega^3} \frac{m_e}{2\pi kT_e} \quad (6)
\]

where \(\lambda\) is for the laser beam wavelength.

Eq. (6) shows that the absorption coefficient is proportional to the square of the electron density of the plasma and the laser wavelength, and inversely proportional to the 3/2 power of the plasma temperature. This implies that the absorption is much more intensive in the case of CO2 laser–arc interaction than in the case of YAG laser–arc interaction for the shorter wavelength of YAG laser. In our experiment, the local arc temperatures at the laser incident position are about 14,000–15,000 K and 16,000–18,000 K for the argon and helium arc plasma respectively. The electron densities, mainly primary ionization electrons, have the value of \(1 \times 10^{23} \text{ m}^{-3}\) for the argon arc plasma and \(1 \times 10^{22} \text{ m}^{-3}\) for the helium arc plasma. That indicates that the absorption of the helium arc plasma is much weaker than that of the argon arc plasma. The analyses are in agreement with the present work. Fig. 9 shows the laser power transmission ratio (\(P/P_0\)) passing through the TIG arc in argon and helium, where \(P\) and \(P_0\) are the attenuated and initial laser power respectively. It can be found that a considerable partition of the laser energy is absorbed by the arc plasma in the case of the CO2 laser–arc interaction, but the laser energy is less absorbed in the case of the CO2 laser–helium arc interaction and no laser energy is absorbed in the case of the YAG laser–arc interaction. That is the reason the arc characteristics change greatly in argon and inappreciably in helium with the CO2 laser interaction, and remain the same with the YAG laser interaction.

When the arc plasma absorbs a partition of the laser power, the electron energy equation [22] can be modified as follows:

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_e kT_e \right) = k_e \nu^2 T_e - \frac{5}{2} kT_e \mathbf{v} \cdot \nabla T_e - S(T_e, n_i) + j_e \mathbf{E} + K_a (n_0 e^{-K_a Z})
\]

where \(n_e\) is the electron number density; \(T_e\) is the electron temperature of the arc plasma; \(k_e\) is the electron thermal conductivity; \(k\) is the Boltzmann constant; \(T_e\) is the electron flux; \(j_e\) is the electron current density and \(j_e \mathbf{E}\) represents the electron Joule heat; \(K_a\) is the inverse Bremsstrahlung absorption coefficient; \(n_0\) is the initial laser beam intensity; \(Z\) is the laser propagating distance in the arc plasma; \(S(T, n_i) = 1.42 \times 10^{-34} n_i^2 T_e^{7/2} / (W \text{ cm}^{-3})\) is the power density of ion Bremsstrahlung radiation; and \(Z\) is the charge number of the atom.
The five terms on the right hand side of Eq. (7) represent the thermal conductivity, convection, radiation, Joule heat of the arc plasma and the absorbed laser power. In the condition of the local thermal equilibrium, the gain and loss of the arc energy must balance, so Eq. (7) can be expressed as follows:

\[ J_e \dot{E} + K_a (I_0 e^{-k_e z}) = -k_v \nabla^2 T + \frac{5}{2} k \Gamma_e \nabla T + S(T, n_e) \]  

(8)

It can be seen from Fig. 8 that the total input power of the arc will increase when the CO\(_2\) laser beam passes through the argon arc plasma. Consequently, deduced from Eq. (8), the arc temperature must rise to maintain the thermal equilibrium. The arc temperature rise induces the generation of LSC waves.

Despite there are electrons and ions in the arc column, the electron flow in the arc column is 1000 times of the ion flow because of the great difference between the electron and ion masses. Consequently, the absorbed laser energy by the arc plasma is mainly transported toward the anode region by the electron flow, which dominantly affects the arc characteristics in the region between the laser interaction location and the anode. This is the reason that the arc column expansion and the electron temperature rise only occur in the range between the laser incident position and the anode. In order to confirm this claim, the arc with reverse polarity (DCRP) was used in additional experiments. The experiment results show that the electrode is rarely burning loss without laser incident, but the electrode melt off immediately when the CO\(_2\) laser acted on the argon arc plasma, in which the laser power is 500 W and the arc current is 50 A. Then the arc column can be divided into two parts and the voltage can be described by \( U = E \times l + E' \times l' \), where \( E \) and \( E' \) stand for the electric field intensities of the arc column from the laser incident position to the cathode and the anode respectively, and the \( l \) and \( l' \) mean the corresponding arc length. The closer the laser beam incident position to the cathode, the greater the arc column region affected by the laser interaction, and then the more the decrease in arc voltage.

Furthermore, under the condition of lower arc amperage, the degree of ionization is lower, and there are lesser electrons in arc column. So with the absorption of laser energy, the degree of ionization is increased greatly. As a result, the voltage and the column diameter are increased significantly. With the arc current increasing, the arc plasma is ionized completely, so the influence of absorbed laser energy on the degree of ionization is decreased. This is the reason for decrease in lower arc voltage and arc column expansion, as shown in Figs. 2 and 3. In these cases, the absorbed laser energy will induce the generation of LSC waves.

As for the phenomenon that the LSC waves generate and propagate against to the incident direction of the laser beam with a laser power beyond 1500 W, it can be explained in the following way. With the interaction of the laser beam, the arc temperature increases and a part of the energy is transferred to the gas layer around the arc plasma through thermal conduction and radiation. Then the arc column will expand. If the laser intensity is strong enough, the ambient gas layer will be overheated and no longer transparent to the laser radiation due to the thermal ionization. As the gas layer begins to absorb a significant fraction of the laser energy, a self-perpetuating absorption process commences that results in the plasma propagating into the surrounding atmosphere. Then the subsequent gas layers experience the same ingestion process, i.e. heating initially by energy transfer from the plasma until laser absorption is initiated in the ambient gas, then rapidly heating by laser absorption to produce a strongly absorbing plasma. The combustion wave propagates against the laser beam until the irradiation is reduced to irradiance level that can no longer support the absorption wave. When the LSC wave front reaches the
maximum propagation distance, the LSC wave extinguishes and then the laser beam acts on the arc plasma again. Consequently, the LSC wave is generated again. The above described process is essentially the same with the process during laser–target interaction [23], but the ignition threshold of LSC waves is decreased due to the existence of large numbers of initial electrons in the arc plasma.

5. Conclusions

This paper discusses the influence of high power CO2 and Yb:YAG laser radiation on the characteristics of the TIG arc in atmospheric pressure argon and helium. The following conclusions can be formed from the experiment results:

1. Effects of the laser–arc interaction on the arc characteristics depend on the laser beam characteristics. The arc characteristics will be affected by CO2 laser radiation, but not by YAG laser radiation at a power density up to 5.66 × 10^6 W/cm².

2. Effects of CO2 laser radiation on the arc characteristics are relative to the arc atmosphere. CO2 laser radiation affects the arc characteristics in atmospheric pressure argon significantly, but negligibly in atmospheric pressure helium at a power density up to 6.12 × 10^6 W/cm².

3. The arc voltage–current curve shifts downwards when CO2 laser interacts with the TIG arc in argon. The arc voltage decreases with the increase of the laser power and depends on the laser interaction position. The closer the laser beam interaction position to the cathode, the more the decrease in voltage.

4. The arc column expands and the arc temperature rises with the interaction of CO2 laser in atmospheric pressure argon, and the arc column expansion and arc temperature rise mainly occur in the range from the laser interaction position to the anode. These phenomena result from the absorption of laser radiation and the absorbed energy transfers toward the anode through the electron flow.

5. The different behaviors of the arc when interacted with CO2 and YAG lasers in atmospheric pressure argon and helium result from the different inverse Bremsstrahlung absorption coefficient due to the different electron densities of the argon and helium arcs and the different wave lengths of CO2 and YAG lasers.

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