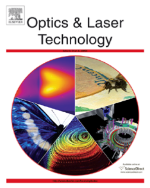
Optics & Laser Technology 54 (2013) 191–198

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec



The influence of different volume ratios of He and Ar in shielding gas mixture on the power waste parameters for Nd:YAG and CO_2 laser welding

N.S. Hosseini Motlagh [a], P. Parvin [a,*], M. Jandaghi [b], M.J. Torkamany [b]

[a] *Physics department, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran*
[b] *Iranian National Centre for Laser Science and Technology (INLC), P.O. Box 14665-576, Tehran, Iran*

ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form
24 April 2013
Accepted 26 April 2013

Keywords:
Laser welding
Shielding gas mixture
Power waste parameters

ABSTRACT

In this paper, we numerically solve the Saha equations to drive the number densities of electrons and ions, the degrees of ionization of the plasma as well as the refractive indices and the inverse Bremsstrahlung absorption coefficients as a function of temperature for a variety of volume ratios of the (He+Ar) mixtures. Furthermore, the heat transfer equation was solved to determine the plasma temperature. The effect of shielding gas volume ratios on the power waste parameters was estimated during long pulse Nd:YAG and CW CO_2 laser welding accompanying the experimental verification.

1. Introduction

During the laser welding, interaction of intense high power laser radiation with a work piece leads to the formation of a long, thin cylindrical cavity in a metal, called a keyhole. In this case, metal vapor ejected from the keyhole absorbs laser power to ionize and forms a plasma plume just above the weld keyhole. The plasma plume causes decrease in the beam energy based on power waste parameters, i.e. the inverse Bremsstrahlung absorption and light defocusing, that are largely dependent upon laser wavelength and plasma plume thermodynamic characteristics such as temperature and electron density.

Laser welding systems mostly rely on Nd:YAG or CO_2 laser sources with wavelengths at 1.064 and 10.64 μm respectively due to different wavelengths they have different loss effects [1].

Also, the plasma plume consists of the metal vapor plasma diluted by a shielding gas, thus the corresponding compositions of shielding gas influence on the plasma characteristics accordingly and as a result varies the loss effects. So an optimum value of the transmitted energy to the weld pool is estimated by determining shielding gas composition ratios at the desired laser wavelength.

Helium+argon mixture is vastly used because helium does not interact with the molten metal (keyhole) and it cannot be ionized due to its high ionization energy. Similarly, argon as an abundant inert gas exhibits tenfold heavier than helium, hence it is sluggish to localize on the welding surface particularly for low flow rates and protects the surface of ionization against oxygen [2]. However, argon is cost-effective and less expensive than helium.

In 1995, Beck and co-worker [3] obtained the effect of plasma formation on beam focusing in the deep penetration welding with CO_2 lasers by solving the paraxial wave equation. They found that, by applying a shielding gas mixture of He:Ar with the ratio 3:1, the variation of the focal diameter with plasma temperature can be significantly reduced. Therefore, they recommended this shielding gas mixture for enhancing the stability during welding with high-power CO_2 lasers. Furthermore, the effects of different shielding gases during CO_2 laser welding were studied by Glowawcki [4]. He solved the Saha equations for the case of several two-component mixtures, namely ($Ar+O_2$), ($Ar+N_2$), ($Ar+H_2$) and (Ar+He).

He found out that the properties of the helium+argon mixture change drastically as the volume ratio of the two gases alters. The mixture is a suitable one for laser welding because it causes slight defocusing of laser beam above the keyhole and decreases inversely Bremsstrahlung absorption coefficient as well. Wang and Chen [5] reported three models of the laser-induced plasma plume characteristics in CW CO_2 laser welding. Due to the cooling effect of the shielding gas, the dimensions of the plasma plume become smaller and thus laser absorption and refraction by the plasma plume can be reduced. Hoffman and Szymanski [6] stated that the laser beam absorption in the plasma plume is ~5% of the incident beam power in the case of argon and 10% for the metal plasma.

The influence of shielding gas and different lasers such as CO_2, Nd:YAG, disk and fiber lasers on the weld penetration and the

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[*] Corresponding author.

E-mail addresses: hosseinimotlagh@gmail.com.(N.S. Hosseini Motlagh) parvin@aut.ac.ir.(P. Parvin)maryamjandaghi@gmail.com.(M. Jandaghi) mjtorkamany@gmail.com.(M.J. Torkamany)

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http://dx.doi.org/10.1016/j.optlastec.2013.04.027

Nomenclature

a_W	inverse Bremsstrahlung absorption coefficient
C_p	heat capacity
c	speed of light
D	penetration depth
Δr	change in beam radius
E_i	ionization energy
h	planck's constant
e	electron charge
ε_0	permittivity of free space
g_0	level degeneracy for atoms
g_e	level degeneracy for electrons
g_i	level degeneracy for ions
h	plank constant
I_a	loss due to inverse Bremsstrahlung absorption
I_d	loss due to defocusing effect
I_{in}	the laser beam intensity when enters into the plasma plume
I_{out}	intensity of the laser beam which departs from the plasma plume
K	Boltzmann's constant
k	conduction heat transfer coefficient
L	distance of laser to work piece
λ_0	beam wavelength
m_e	electron mass
n	refractive index
n_e	electron density
n_0	neutral atom number density
n_1	number density of the single ions
n_2	number density of doubly ionized atoms
n_i	number density of i times ionized atoms
n_H	number density of heavy species
ω	laser frequency
P	mean laser power
p	plasma pressure
Q	thermal power density
r	radial distance
ρ	density of the particles
T_e	plasma temperature (electron temperature)
w	largest interval between adjacent energy levels of the atoms and ions in the plasma (eV)
w_0	initial beam radius
W	weld width
z	axial distance

mechanical properties of weld was investigated [7]. In the case of CO_2 laser, it has been found that, Ar and N_2 gases form plasma, resulted in the apparent decrease in weld penetration. Whilst in the case of YAG, fiber or disk lasers at 1.064 μm, the shielding gas effect is minor, and the laser power density is the dominant factor.

The CO_2 laser beam welding experiments were carried out on the tailored blanks of DP600/TRIP700 sheets to investigate the effect of the shielding gases and flow rates on the weld penetration, tensile strength and formability [8]. They have reported that the higher the helium shielding gas flow rate is, the deeper weld would be that penetrate accompanying the narrower weld width. Moreover, CO_2 laser welding of DP/TRIP steel sheets was strongly influenced by changing shielding gas types and speed.

Although, many studies have been reported on the minimization of the power waste parameters in terms of volume ratios of gases for the CO_2 laser welding; however this investigation was not performed extensively for pulsed Nd:YAG laser welding. The others also worked on the optimization of the parameters of keyhole during laser welding [9,10,11,12].

In this paper, the number densities of each species, the refractive index and the inverse Bremsstrahlung absorption coefficient were calculated as a function of temperature in plasma plume, by solving the set of equations explaining the kinetic theory and the thermodynamic equilibrium laws for different ratios of He and Ar shielding gases. Then, the temperature profile and mean temperature are given by solving the heat transfer equation for the presumed plasma plume in order to drive the corresponding loss parameters i.e. inverse Bremsstrahlung absorption coefficient and defocusing effect. Afterward, the percent of loss was determined and compared to each other for different ratios of He and Ar shielding gases in welding with long pulse Nd:YAG and CW CO_2 lasers as well as compared to experimental results.

2. Theoretical model

As mentioned, loss parameters in plasma plume during laser welding depend on laser wavelength and plasma plume characteristics (plasma temperature and density electron). On the other hand, the plasma temperature is dependent on heating rate at a certain laser line while the electron density mainly depends on ionization energy of particles.

First part of the model discuses dependence of the number density of electrons and ions, inverse Bremsstrahlung absorption coefficient and refractive index (as a main parameter in defocusing effect) on the temperature and how the shielding gas ratios alter these parameters.

The present modeling is based on several assumption as below: (i) Gaussian beam profile, (ii) atmospheric ambient pressure, (iii) no significant nonlinear effects [13] (laser pulse duration ~msec), (iv) negligible reflection of light, (v) optically thin and dilute plasma and (vi) plasma in local thermal equilibrium (LTE).

A plasma is said to be in LTE when the values of mean energies of atoms, ions and electrons are similar, which means that there exists a single plasma temperature common both to ions and to electron. The density of electrons of the plasma under such equilibrium must be sufficiently high so that the three-body collisional de-excitations will dominate over the irradiative de-excitations [1]. The LTE conditions for optically thin plasma is $n_e \geq 1.6 \times 10^{18} T_e^{0.5} w^3$ $[\mathrm{m}^{-3}]$ [4], where w is the largest interval between adjacent energy levels of the atoms and ions in the plasma in electron-volts and T_e is the temperature of the plasma in K.

The temperature and pressure-dependences of the degree of plasma ionization and the number densities are described by the formula called the Saha equation which is given by [14]

$$\frac{n_e n_i}{n_o} = \frac{g_i g_e (2\pi K m_e T_e)^{3/2}}{g_o h^3} \exp\left(\frac{-E_i}{K T_e}\right) \tag{1}$$

where m_e is the electron mass, K is Boltzmann's constant, g_0, g_e, g_i are the level degeneracy for atoms, electrons and ions respectively, E_i denotes ionization energy, h is Planck's constant, n_e is density of electron, n_0 and T_e ascertain the neutral atom number density and plasma temperature respectively. Moreover, n_i is the number density of atoms after i times ionization. For instance, n_1 is the number density of atoms which is single ionized (A^+) and n_2 represents the double ionized atoms (A^{2+}) density. Similarly, n_i denotes the density of multiple ionized atoms (A^{i+}).