**Rare Metal Materials and Engineering**
Volume 49, Issue 6, June 2020
Available online at www.rmme.ac.cn

Science Press

**Cite this article as:** Rare Metal Materials and Engineering, 2020, 49(6): 1894-1900.

ARTICLE

# Relationship Between Molten Pool Behavior and Keyhole-Induced Porosity in Pulsed Laser-arc Hybrid Welding of Magnesium Alloy

**Xin Lijun[1], Lin Sanbao[2], Liu Xuping[3], Piao Zhigang[3], Wu Fufa[1], Chen Minghua[1]**

*[1] Liaoning University of Technology, Jinzhou 121001, China; [2] State Key Laboratory of Advanced Welding and Jointing, Harbin Institute of Technology, Harbin 150001, China; [3] Petro China Jinzhou Petrochemical Company, Jinzhou 121001, China*

**Abstract:** The porosity is an important kind of weld defects in deep-penetration laser-arc welds. This work gives an experimental study on relationship between molten pool behavior and keyhole-induced porosity in pulsed laser-arc hybrid welding. In this research, the impact effect of laser pulse on the weld pool, and live behavior of the laser keyhole and the porosities in the weld were investigated. Results show that the impact effects from the laser pulse depend on the laser pulse parameters and stronger impact effect helps restrain the porosity formation. The laser keyhole state dominants the welding pool behavior. The keyhole dimension and open-close state directly influences the porosity formation. Extremely high laser pulse power always brings about porosities after welding. Lengthening the laser keyhole opening time and giving the gas enough time to escape will be an effective way to restrain the porosity.

**Key words:** magnesium alloy; molten pool; laser-arc welding; porosity; laser keyhole

Recently, the laser-arc hybrid welding technology was rapidly developed to overcome those shortcomings coming from single laser welding and single arc welding[1,2]. Although laser-arc welding has been proven to be a robust process for producing satisfactory welds in steels, it can be less straightforward to achieve acceptable weld quality due to the porosity, especially in welding of light metals, such as magnesium, aluminum and titanium alloys[3,4].

Porosity is an important kind of weld defects in deep-penetration laser-arc welds, which can have great bad effects on the mechanical properties of welded joints[5]. Due to the large welding speed of hybrid laser-arc welding, the solidification process of liquid metal is much shortened. The pores in the liquid metal have no enough time to escape, especially in welding of metals with small density, resulting in the generation of residual porosities in the weld seam. The porosity is closely related to the behavior of laser keyhole structure during liquid metal solidification. So, these porosities in laser or laser-based welds are quite different from other fusion welds[6], especially in the shapes and locations.

Researcher dedicated their energy on the relationship between liquid metal flow and porosity formation during laser or laser-based welding[7, 8]. Much research work has been done based on computer simulation, and many valuable and encouraging results were obtained. Pang et al[9] developed a three-dimensional sharp interface model for self-consistent keyhole in laser deep penetration welding. Both keyhole collapsing and bubble formation processes were simulated. They found that the humps in the keyhole strongly influence the keyhole behaviors. In their other reports, the bubble formation in laser keyhole welding was also analyzed through computer simulation method. In those researches, it can be found that the quick decrease of gas pressure in keyhole will result in the involvement of ambient gas into the keyhole. At the same time, the high speed metallic vapor ejection generates a low pressure area near the keyhole opening, which can also increase the

Received date: June 26, 2019
Foundation item: Opening Program of State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology; National Natural Science Foundation of China (51571006, 51805236); Natural Science Foundations of Liaoning Province (JQL201715402, 20180510.40); Program for Liaoning Distinguished Professor
Corresponding authors: Chen Minghua, Ph. D., School of Material Science and Technology, Liaoning University of Technology, Jinzhou 121001, P. R. China, Tel: 0086-416-4199650, E-mail: chenmh@lnut.edu.cn

chance for the shield gas to enter the keyhole[10,11]. In the research from M. Courtois et al[12], a three-dimension simulation of a laser welding process was performed to discover the keyhole oscillations and porosity formation. Zhou et al[13] proposed a study toward the porosity formation and prevention in pulsed laser welding by computer simulation. They claimed that the formation of porosity in pulsed laser welding is caused by two competing factors: one is the solidification rate of the molten metal and the other is the backfilling speed of the molten metal during the keyhole collapse process. The above-mentioned researches are extremely valuable. They contributed much to the laser keyhole search area. In fact, the actual situations in laser-arc hybrid welding process are much more complicated with respect to the single laser welding situation, which restrains the flexibility in direct use of these simulation results, and decreases the accuracy of final results. Cho et al[14] carried out a three-dimensional analysis of molten pool in gas metal arc (GMA)-laser hybrid welding. They found that the molten flow at the bottom of the keyhole rises up slowly, and therefore a vortex can be observed throughout the molten pool. This research helps to understand the liquid metal behaviors in the laser-arc hybrid welding. But, the interactions between the laser and arc plasma were neglected. Lu et al [15] proposed a 3D model, in which liquid metal flow, bubble movement and solidification were coupled. In their computer simulations, they found that the bubble number was determined by the frequency of keyhole collapse.

From the above results, it can be seen that as the most important unstable structure in the molten pool of laser-referred welding process, the keyhole plays an dominant role in weld formation and porosity generation. The keyhole behavior during welding needs to be researched. Meanwhile, it is noted that most of the present researches refer to the welding process using a continuous laser. Seldom literature can be seen to aim at the pulsed laser-arc welding. The keyhole behaviors in the continuous laser and pulsed laser are totally different, resulting in the difference in porosity formation mechanism. Therefore, the exact relations between the porosity formation and keyhole behaviors are still unclear, and need to be disposed.

In this study, experiments were conducted to specially investigate the influence of pulsed keyhole on porosity formation during pulsed laser-arc welding. Based on direct observation of keyhole outlet state on the weld pool surface, the weld state after solidification, and the keyhole behaviors and porosity formations were analyzed. During analysis, the impact effect from the laser pulse was fully considered. It is thought that the experimental phenomenon provided and the analysis in this study will be helpful in further understanding of keyhole behavior-porosity formation and laser-arc interactions.

## 1 Experiment

The welding heat source is a laser-arc hybrid heat source, a combination of a pulsed Nd:YAG laser and a gas tungsten arc (GTA), as is sketched in Fig.1. During welding, the laser beam vertically radiates the surface of the welding material. A convex lens was used to focus the laser beam into a spot with minimum 0.6 mm in diameter. The electric arc acted ahead of the laser beam in welding direction with the angle of 45°. Bead-on-plate welding was performed on two kinds of plates. 5 mm thick magnesium alloy plates were used in laser-arc hybrid welding process to observe the keyhole outlet; 3 mm thick TA15 titanium alloy plates were used to record solidification of the liquid metal after laser pulse action in single laser welding experiments.

In order to synchronously observe the detailed behavior of the laser keyhole and the welding arc behavior during laser-arc welding, a high-speed camera with the acquisition speed of 2000 frame/s was sideway placed towards the welding arc. Due to the existence of the burning arc plasma with extremely high radiation intensity, a low power laser with the central waveform of about 808 nm was specially used as the illuminating light source. The detailed device and method referred can be found in the reports from Chen et al.[16]. After welding, the welding seems were cross-sectioned and polished. The cross sections were observed by an optical microscopy after being etched by the acid solution (5% HCl + 95% alcohol).

## 2 Results and Discussion

### 2.1 Impact effect of laser pulse on molten pool

In pulsed laser-arc welding, the arc heats the metal continuously while the laser beam radiates the liquid metal discontinuously. Due to the extremely short acting time, the laser beam has an impact effect on the molten pool, which will influence the hybrid welding process and weld formation. In this part, special experiments were conducted to investigate the laser pulse impact effect in single laser welding. TA15

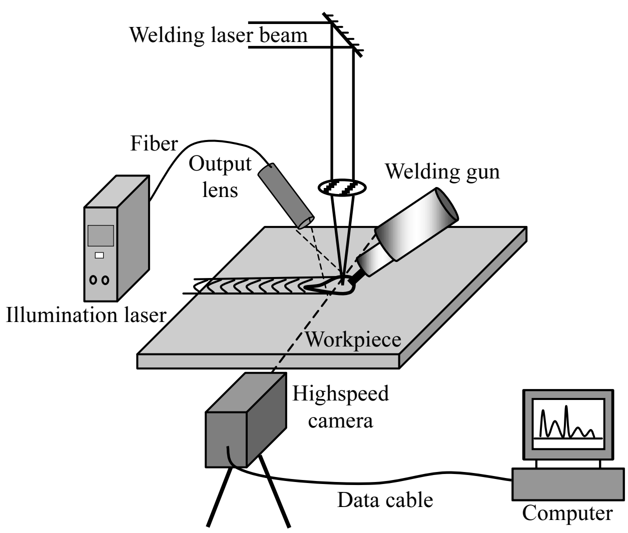


Fig.1 Sketch of the experimental devices

titanium alloy plates were selected as the target, and three main laser pulse parameters were tested. The top appearances of the laser pulse radiated area are given in Fig.2. From Fig.2, it can be seen that with the 0.6 mm diameter laser pulse action, a subcircular melting area on the base material appears. Many concentric ripples can be found in the area. The ripples become larger and deeper near the margin of the area, while near the area center, there are few ripples. These ripples expose that when the laser pulse acts, a strong shock to the liquid metal exists. The shock generates waves on the molten pool surface. However, the impact effect can not last for a long time, and will disappear before all the liquid metal finishing the solidification, because the ripples can not be seen in the center of the pulse acted area.

With the help of optical microscopy, the crystallization state of liquid metal of this area can be roughly obtained. As the typical welding microstructure of Ti alloy, martensite needles within the parent $\beta$-Ti grains can be observed in the regions 1, 2 and 3 indicated in Fig.2. It can be found that the crystal grains in region 3 are the finest, while the grains in region 1 are much coarser. The difference of the grain size in different areas may come from the breaking effect of the laser pulse to the grains during solidification.

In the experiments, it is observed that the ripples on the laser pulse acted area are different when different laser pulse parameters were used. As shown in Fig.3a, the ripples are smaller with the laser pulse energy of 8 J. When the laser pulse energy is improved to 14 J, the ripples are larger and deeper as presented in Fig.3b, indicating a stronger impact effect of laser pulse to the liquid metal.

In order to examine the influence of laser pulse parameters on the impact effect, some experiments were conducted. In the experiments, the laser pulse energy and duration were changed,

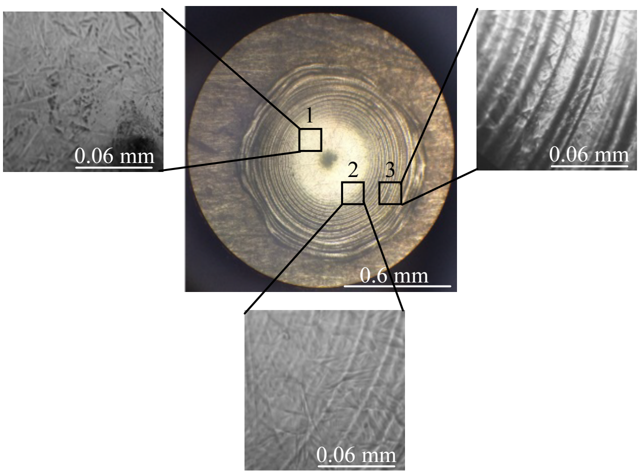


Fig.2 Morphology of laser pulse acted area (parameters: laser pulse energy 12 J, laser spot diameter 0.6 mm, laser pulse duration 1.5 ms, Ar gas shielded)

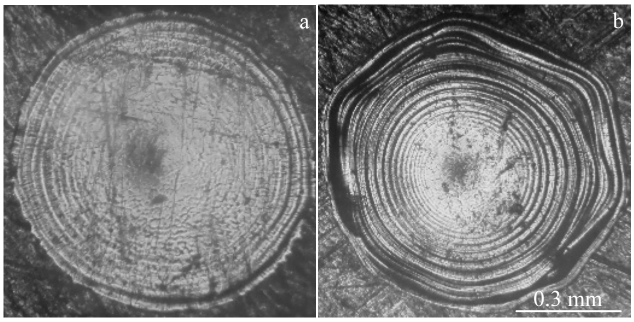


Fig.3 Effect of laser pulse energy on ripples: (a) laser pulse energy 8 J and (b) laser pulse energy 14 J (other parameters: laser spot diameter 0.6 mm, laser pulse duration 1.5 ms, Ar gas shielded)

and the wave roughness was recorded. The waves of the area radiated by laser pulses with different parameters were scored in levels 1~5, in which the level 5 represents the wave with the largest roughness on the surface. The results are given in Table 1. From these results it can be found that both the laser pulse energy and duration have influences on the wave characteristics of the laser radiated area. Bigger laser pulse energy always generates stronger waves, while larger laser pulse duration will depress the waves. The results indicate that if the larger energy transfers to the materials within a shorter time, the impact effect will be strong.

## 2.2 Keyhole behaviors in laser-arc welding of magnesium alloy

A keyhole observation was conducted to obtain the keyhole outlet state during the laser-arc welding process, as presented in our previous reports[16,17]. The behaviors of the keyhole outlet at different welding conditions were observed directly. In the experiments, it is found that a single laser pulse action will bring about an open-close process of the keyhole outlet, which means every laser pulse can generate an isolated keyhole, as presented in Fig.4. From Fig.4, it can be clearly seen that during laser pulse action (in the first two milliseconds), a hole is generated on the surface of the molten pool created by the electric arc. After laser pulse action, the keyhole exists for a period of time. The opening state of the keyhole outlet lasts for nearly 13 ms in this welding condition, and then the keyhole outlet finally closes.

Obviously, the keyhole outlet size and the keyhole outlet

**Table 1 Effect of laser pulse parameters on ripple features**

| Laser pulse energy/J | Laser pulse duration/ms | Ripple levels |
|---|---|---|
| 8 | 1.0 | 2 |
| 8 | 2.0 | 1 |
| 12 | 1.0 | 4 |
| 12 | 2.0 | 3 |
| 16 | 1.0 | 5 |
| 16 | 2.0 | 4 |

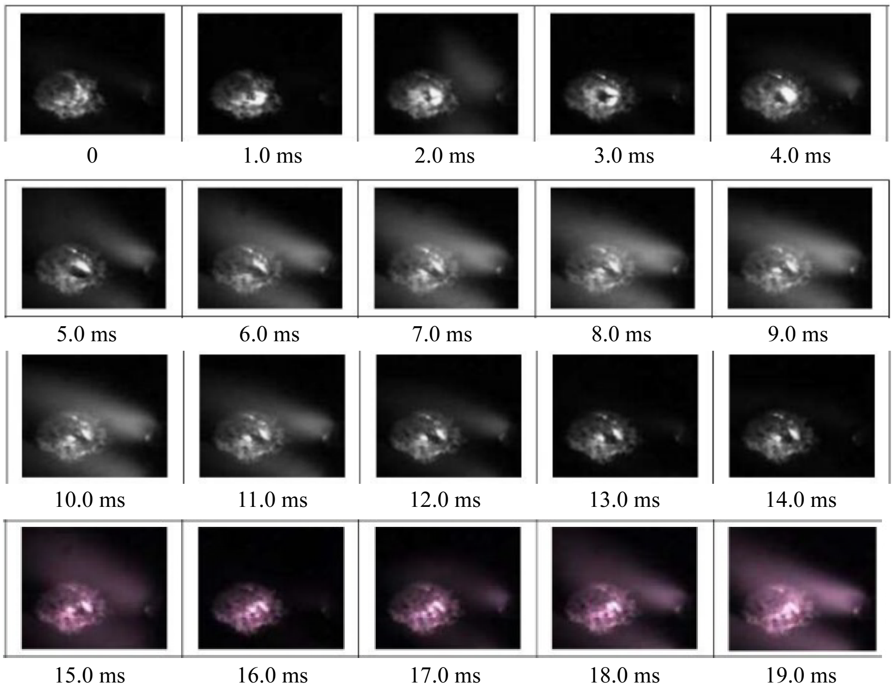


Fig.4 Keyhole behavior during a laser pulse action cycle (parameters: laser pulse energy 16 J, laser pulse duration 2.0 ms, laser pulse frequency 30 Hz, electric arc current 80 A, welding speed 600 mm/min. The laser pulse action period was marked with darker background)

opening time are the two main characteristics of the keyhole behavior, which have great influences on the liquid metal solidification and welding quality. So, in this part of experiments, the effects of welding parameters on those two characteristics were investigated.

Fig.5 presents the influence of laser pulse frequency on keyhole outlet diameter and the keyhole opening time. From Fig.5, it is found that when the laser pulse frequency increases from 10 Hz to 35 Hz, the keyhole average diameter is around 1.2 mm, and the keyhole opening time varies around 3.0 ms. This indicates that during laser-arc welding process, the laser

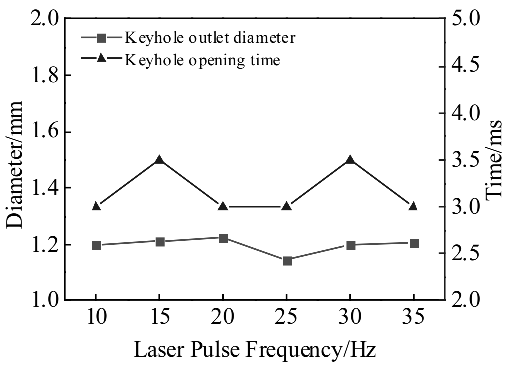


Fig.5 Effect of laser pulse frequency on keyhole characteristics (parameters: laser pulse energy 16 J, laser pulse duration 2.0 ms, electric arc current 120 A, and welding speed 600 mm/min)

pulse frequency hardly influences the keyhole state. The reason may be that every single laser pulse generates a keyhole, and the evolution of the laser keyhole finishes before the next laser pulse comes. So, the adjacent laser keyhole seems to bring no influence to each other.

The influence of laser pulse duration on laser keyhole state is given in Fig.6. From Fig.6, it can be seen that the laser pulse duration has effects on the keyhole opening time, but hardly influences the keyhole outlet diameter. With the laser pulse duration increasing from 1.5 ms to 4.0 ms, the laser keyhole opening time increases firstly and then decreases gradually. The keyhole opening time reaches its peak of almost 4 ms at 2.5 ms laser pulse duration. The laser pulse duration represents the time for the laser energy to input to the material. When the laser pulse energy is constrained to a value, a small pulse duration means to deliver the constrained energy to the material in a short time. This represents an extremely high laser pulse power. In this situation, the heat penetration of the laser to the material may be large; however, the stability of the keyhole will be poor. So, the keyhole outlet will close within a short period after laser pulse action. When the pulse duration is improved from 1.5 ms to 2.5 ms in this welding condition, the laser pulse power is depressed. However, the value is still large enough for achieving a relatively stable keyhole and an acceptable heat penetration depth on the workpiece. But, when the pulse duration is improved up to 4.0 ms, the heat penetration ability of the laser beam becomes weak, resulting in an unstable keyhole with a small penetration depth.

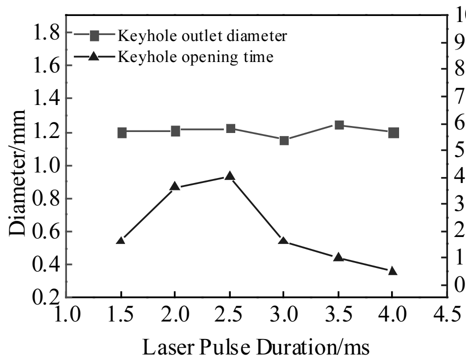


Fig.6 Effect of laser pulse duration on keyhole characteristics (parameters: laser pulse energy 16 J, laser pulse frequency 25 Hz, electric arc current 120 A, and welding speed 600 mm/min)

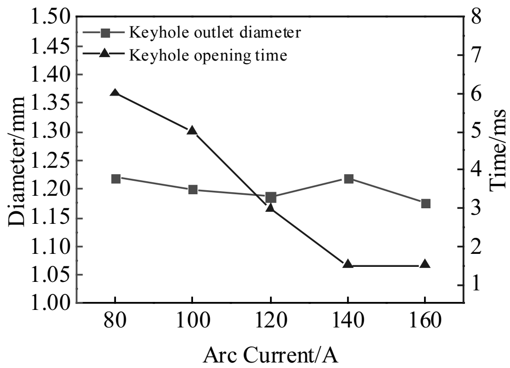


Fig.8 Effect of electric arc current on keyhole characteristics (parameters: laser pulse energy 16 J, laser pulse duration 2.0 ms, laser pulse frequency 25 Hz, and welding speed 600 mm/min)

The influence of laser pulse energy on the laser keyhole property was experimentally investigated, and the results are presented in Fig.7. Results exhibit that the laser pulse energy has influences on both laser keyhole outlet diameter and keyhole opening time. With the increase of laser pulse energy from 8 J to 18 J, the laser keyhole outlet diameter increases gradually. When other laser pulse parameters are confirmed, the increased laser pulse energy directly leads to the enhanced laser pulse power and the improved heat input to the material. So, the laser keyhole dimension will be enlarged, with larger keyhole outlet diameter and deeper keyhole depth. As to the keyhole opening time, with the increase of laser pulse energy, it increases first and then decreases. The keyhole opening time reaches its peak value at about 14 J laser pulse energy, indicating that in this situation the laser keyhole is more stable, and the keyhole outlet can last for a longer time.

As shown in Fig.8, the welding arc current has little influence on the laser keyhole outlet diameter. However, with the increase of arc current, the keyhole opening time decreases. When the electric arc current is improved, the temperature of the liquid metal in the welding pool will be higher, resulting in the decrease of the surface tension of the liquid metal. Small surface tension of the liquid metal will directly lead to the unstable state of the keyhole outlet, and collapse will happen easily. So, in the experiments, it is noticed that the keyhole outlet can not stay long when the arc current is improved.

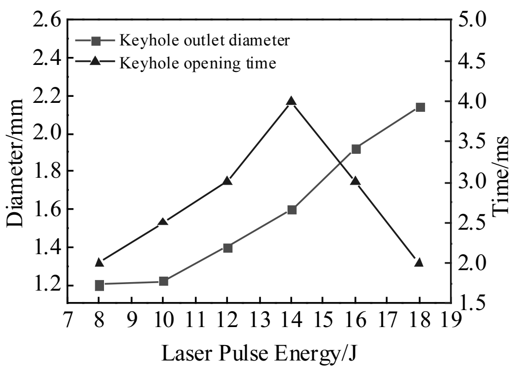


Fig.7 Effect of laser pulse energy on keyhole characteristics (parameters: laser pulse frequency 25 Hz, laser pulse duration 2.0 ms, electric arc current 120 A, and welding speed 600 mm/min)

### 2.3 Keyhole-induced porosity

Porosity are always generated in laser-referred welding processes. The porosity generation is closely related to the keyhole behavior. During pulsed laser-arc welding, every single laser pulse forms a keyhole. Therefore, the laser pulse directly influences the porosity generation. In this part, the relationship among the laser pulse parameter, keyhole behavior and porosity generation were experimentally studied.

Fig.9 exhibits the typical porosities in the weld seam. From Fig.9, it can be found that the porosities trend to form at the keyhole bottom, and depending on the laser pulse parameters,

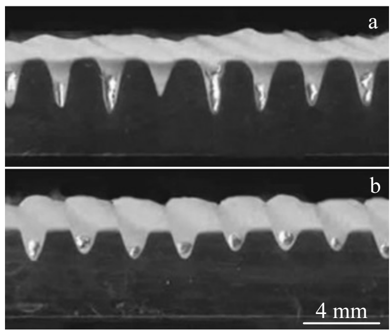


Fig.9 Porosities observed in the longitude section of the weld seam: (a) laser pulse energy 16 J, laser pulse duration 1.5 ms; (b) laser pulse energy 14 J, laser pulse duration 2.0 ms (parameters: laser pulse frequency 5 Hz, welding speed 600 mm/min)

the porosities are in different profiles. With the parameters given in Fig.9, almost every laser pulse forms a porosity.

In our previous research, it has been proved clearly that a large depth to wide ratio of the laser keyhole always leads to the increase of porosity generation chance. Keeping the keyhole outlet open for a longer time benefits the porosity restriction[18]. As shown in Fig.10, when 4.0 ms laser pulse duration is used, the laser pulse penetration ability is weakened, and the porosity is almost eliminated after welding.

Therefore, in order to restrict the porosity formation, the keyhole state must be controlled. Within all the laser parameters, the laser pulse energy and laser pulse duration together dominate the keyhole profile. In the experiments, it is found that a proper laser pulse energy-duration match can effectively depress the porosity. Results are given in Fig.11. If higher laser pulse energy is used, the laser pulse duration must be increased to achieve a lower porosity percentage. This reflects a fact that the porosity of the weld has a strong relationship with the laser pulse power. In pulsed laser welding, the laser pulse power $P$ can be expressed as:

$$P = \frac{E}{t_d} \tag{1}$$

in which $E$ is the laser pulse energy, and $t_d$ is the laser pulse duration. A small laser pulse power represents a gentle energy input to the material, and the welding pool tend to stay in a stable mode. Therefore, there is more time left for the gas escaping from the keyhole bottom, resulting in a small chance to form a porosity after the keyhole outlet is closed.


Fig.10 Longitude section of the weld seam (parameters: laser pulse frequency 5 Hz, welding speed 600 mm/min, laser pulse energy 14 J, laser pulse duration 4.0 ms)

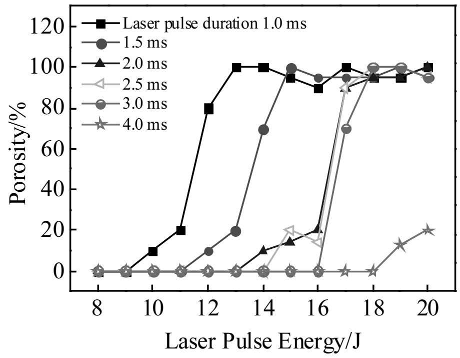


Fig.11 Effect of laser pulse energy on porosity formation (parameters: laser pulse frequency 25 Hz, welding speed 600 mm/min)

## 2.4 Analysis

In pulsed laser-arc hybrid welding, the welding pool is always in the relatively unstable state. Different to the continuous welding process, every laser pulse generates a laser keyhole, and the welding pool has a periodical evolution. Meanwhile, the impact of laser pulses to the liquid welding pool brings extra influence to the metal solidification. To investigate the liquid metal flow state in the melting pool, pulsed laser welding experiments were carried out on $Ti_{43}Zr_{27}Mo_5Cu_{10}Be_{15}$ alloy. As one of typical Ti-based amorphous, the $Ti_{43}Zr_{27}Mo_5Cu_{10}Be_{15}$ alloy possesses special solidification characteristics. During the fast solidification, the whole alloy tends to freeze the interaction state of atoms and phases in the liquid state. So, the liquid metal flow during laser pulse action can be directly reflected by the patterns on the weld top surface after solidification, as shown in Fig.12. From Fig.12, it can be found that, there are several vertexes existing in each molten pool generated by laser pulse during welding process. In the welding direction, the liquid metal flows from front to rear of the molten pool, and two large vertexes occur. At the same time, small vertexes can be found near the rear of the welding pool. The vertex pattern tells us the intensive liquid metal fluent during laser pulse action. Furthermore, the ripples on the molten pool margin indicate a strong shock effect of the laser pulse on liquid metal in the molten pool.

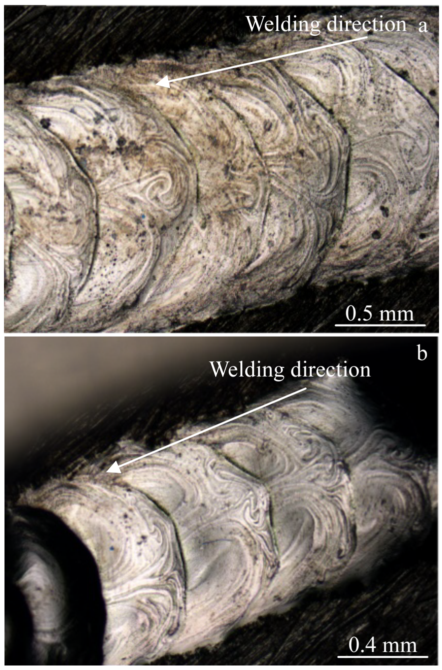


Fig.12 Top surface patterns of the pulsed laser welded seams: (a) welding speed 600 mm/min; (b) welding speed 800 mm/min (parameters: laser pulse energy 12 J, pulse duration 2.0 ms, pulse frequency 25 Hz)

In the experiment, the welding speed was adjusted while other welding parameters were kept constant. As shown in Fig.12b, the increase of welding speed only lowers the laser pulse overlap rate, but brings little influence to the liquid metal flow. Before the next laser pulse acts, the liquid metal finishes the solidification process. In other words, there is nearly no relationship in the keyhole formation between the adjacent two laser pulses.

## 3 Conclusions

1) During pulsed laser-arc welding, there are strong impact effects from the laser pulse on the welding pool. The impact effects depend on the laser pulse parameters. Stronger impact effect helps restrain the porosity formation.

2) The laser keyhole's state dominates the welding pool behavior. The keyhole dimension and open-close state directly influences the porosity formation. Extremely high laser pulse power always brings about porosities after welding. A proper laser pulse power value should balance the welding efficiency and porosity formation.

3) Lengthening the laser keyhole opening time and giving the gas enough time to escape will be an effective way to restrain the porosity.

## References


1 Bappa Acherjee. *Optics & Laser Technology*[J], 2018, 99: 60

2 Giuseppe Casalino, Andrea Angelastro, Patrizia Perulli *et al*. *Journal of Manufacturing Processes*[J], 2018, 35:216

3 Zhang Yin, Song Xiping, Chang Liyan *et al*. *Rare Metal Materials and Engineering*[J], 2017, 46(9): 2411

4 Guo Yuquan, Wu Dongjiang, Ma Guangyi *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(11): 2663

5 Wang Zhimin, Oliveira J P , Zeng Zhi *et al*. *Optics & Laser Technology*[J], 2019, 111: 58

6 Liu Liming, Shi Jipeng, Xu Xinkun. *International Journal of Advanced Manufacturing Technology*[J], 2018, 96: 401

7 Mu Z, Chen X, Zheng Z *et al*. *International Journal of Heat and Mass Transfer*[J], 2019, 132: 861

8 Song Gang, Yu Jingwei, Li Taoao *et al*. *Journal of Manufacturing Processes*[J], 2018, 31: 131

9 Pang S, Chen L, Zhou J *et al*. *Journal of Physics D: Applied Physics*[J], 2011, 44(2): 25 301

10 Pang S, Chen X, Shao X *et al*. *Metallurgical and Materials Transactions A*[J], 2016, 82: 28

11 Pang S, Chen W, Wang W. *Metallurgical and Materials Transactions A*[J], 2014, 45(6): 2808

12 Courtois M, Carin M, Le Masson P *et al. Journal of Laser Applications*[J], 2014, 26(4): 42 001

13 Zhou J, Tsai H. *Journal of Heat Transfer*[J], 2007, 129: 1014

14 Cho J, Na S. *Welding Journal*[J], 2009, 88: 35

15 Lu Fenggui, Li Xibin, Li Zhuguo *et al*. *International Journal of Heat and Mass Transfer*[J], 2015, 90: 1143

16 Liu Liming, Chen Minghua, Li Chenbin. *Optics and Lasers in Engineering*[J], 2013, 51(10): 1153

17 Liu Liming, Chen Minghua. *Optics and Lasers in Engineering*[J], 2013, 51(2): 96

18 Chen Minghua, Xu Jiannan, Xin Lijun *et al. Optics and Lasers in Engineering*[J], 2017, 93: 137


# 激光-电弧复合焊接镁合金过程中匙孔行为与气孔形成的关系


辛立军[1]，林三宝[2]，刘旭平[3]，朴志刚[3]，伍复发[1]，陈明华[1]

(1. 辽宁工业大学，辽宁 锦州 121001)

(2. 哈尔滨工业大学 先进焊接与连接国家重点实验室，黑龙江 哈尔滨 151001)

(3. 中国石油天然气股份有限公司 锦州石化分公司，辽宁 锦州 121001)



**摘 要**：在激光-电弧复合深熔焊接接头中，气孔是一种对焊接质量影响极大的焊接缺陷。本工作通过实验研究了激光-电弧复合焊接镁合金板过程中匙孔行为与气孔形成的关系。详细研究了激光脉冲对熔池的冲击作用，激光匙孔的动态行为以及焊接接头中的气孔形成规律。结果表明：激光脉冲对熔池的冲击作用有利于抑制气孔的形成，冲击作用的大小取决于给定的激光脉冲参数。激光匙孔的状态决定焊接熔池的行为，匙孔的几何尺寸和开/闭行为直接影响气孔的形成。较高的激光脉冲峰值功率会导致焊后气孔的出现。延长匙孔开口的闭合时间，可以给匙孔中的气体足够的时间逃逸，进而可以抑制残留性气孔的生成。


**关键词**：镁合金；熔池；激光-电弧复合焊接；气孔；激光匙孔

作者简介：辛立军，女，1982 年生，博士，副教授，辽宁工业大学材料科学与工程学院，辽宁 锦州 121001，电话：0416-4199650，E-mail: eva3456@163.com