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Application and Development Prospect of Laser-Arc Hybrid Welding

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Abstract

This paper presents a systematic study on laser-arc hybrid welding technology, which was developed to meet the needs of high-end manufacturing transformation. Coupling laser and arc welding to achieve complementary advantages, it originated in the late 1970s and has gone through three development stages, now entering a critical period of dual advancement in technology and industrial application. The paper analyzes its core principle of forming a hybrid heat source via spatiotemporal coupling, explores relevant mechanisms, and sorts out mainstream research directions such as laser-MIG/MAG, each with unique scenario-specific advantages. Boasting high efficiency, stable quality and low cost, this technology has been applied in shipbuilding, engineering machinery and other fields, yielding remarkable results for enterprises worldwide. Currently, it faces challenges like a low localization rate of high-end equipment. Going forward, it will develop toward higher efficiency and intelligence. Efforts are needed to break technical bottlenecks, advance equipment localization, integrate cutting-edge technologies, expand its application fields and support the high-quality development of modern manufacturing.

Keywords

Dissimilar Aluminum Alloys; Laser-CMT Hybrid Welding; Oscillating Laser; Laser Induced Arc.

1. Introduction

Against the background of the global transformation of high-end manufacturing towards high efficiency, precision and greenization, welding, as a core joining process in equipment manufacturing, directly determines the reliability and competitiveness of products. Traditional single welding technologies have limitations: laser welding has high energy density and fast welding speed, but requires high assembly precision and has poor gap adaptability; arc welding has high gap tolerance and low cost, but has slow welding speed, large heat input and uneven weld formation quality. Laser-arc hybrid welding technology emerged as the times require. By coupling the two heat sources to achieve complementary advantages, it breaks through the bottlenecks of single welding technologies and becomes a highly potential advanced welding method in the global high-end manufacturing field.

This technology originated in the late 1970s, when Professor W. Steen from Imperial College London first proposed the concept of "arc-enhanced laser welding", initiating global research on dual-heat-source synergy. Over the past 40 years of development, the technology has evolved from laboratory research to global industrial application, going through three stages: the 1980s was the theoretical exploration stage, where research institutions around the world focused on core mechanisms and laid a theoretical foundation; the 1990s was the process transition stage, where the commercialization of industrial lasers promoted the development of integrated hybrid welding torches, enabling initial industrial application; since the 21st century, it has entered a rapid development stage, where breakthroughs in core components have driven technological upgrading, and the technology has been widely applied in global strategic fields such as aerospace and new energy vehicles[1].

At present, this technology has entered a critical stage of dual improvement in global technology and industrial application, and major industrial countries in the world have focused on its layout. In terms of technology, the global market for 10,000-watt fiber lasers is highly competitive, with the mainstream photoelectric conversion efficiency reaching 55%, but there is still import dependence on high-end components, which has become a common global bottleneck; in terms of process, intelligent control and multi-source sensor fusion technologies are widely applied, and technologies such as microsecond-level time sequence management and digital twins have solved the problems of variable cross-section and dissimilar metal joining, with the gap tolerance reaching 1.5 millimeters.

2. Principle of Laser-Arc Hybrid Welding

The essence of laser-arc hybrid welding lies in the spatially and temporally synchronized coupling of laser and arc heat sources to form a synergistically enhanced hybrid welding heat source. Its working principle is not a simple superposition of the two heat sources, but an interaction that achieves a "1+1>2" welding effect. During the welding process, the high-energy-density laser beam first acts on the surface of the metal material, rapidly heating and melting the local region to form a keyhole effect. Relying on the deep-penetration characteristic of the laser, the aspect ratio of the weld is effectively improved. Meanwhile, the arc is ignited and stably sustained under laser induction[2]. The arc heat source significantly enlarges the molten pool volume and enhances adaptability to assembly gaps, compensating for the high requirement of laser welding on workpiece assembly precision.

Significant mutual promotion exists between the laser and the arc. The laser can constrict the arc column, increase arc energy density, suppress arc wandering, and greatly improve the stability of the welding process. The arc provides preheating and post-heating effects on the base metal, reduces the laser reflectivity of the material, improves laser energy utilization efficiency, and optimizes the flow behavior of the molten pool, thereby reducing defects such as porosity and cracks. The two heat sources work synergistically in the same molten pool, retaining the advantages of laser welding including concentrated heat input, small thermal deformation, high welding speed and high joint accuracy, while also possessing the merits of arc welding such as high deposition efficiency, good gap adaptability and relatively low cost[3].

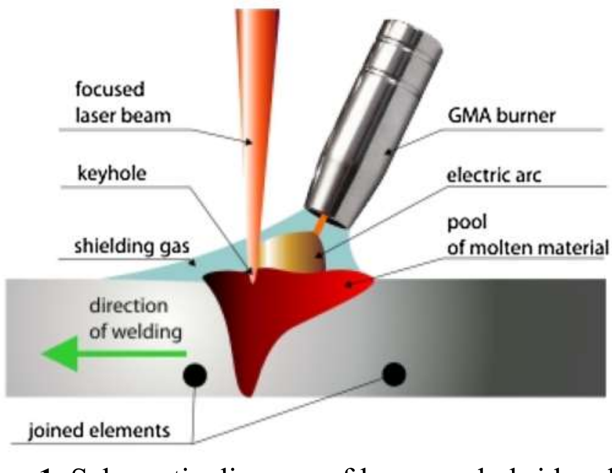

Figure 1. Schematic diagram of laser-arc hybrid welding

Through reasonable regulation of key parameters including laser power, arc current, defocusing amount, welding speed and heat source spacing, precise control of molten pool geometry, weld

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formation and joint performance can be realized. Benefiting from its unique hybrid mechanism, laser-arc hybrid welding can efficiently join medium-thick plates, dissimilar materials, lightweight alloys and complex structural components[4]. It exhibits irreplaceable technical advantages in high-end manufacturing fields such as aerospace, new energy vehicles and rail transit, and has become an important development direction of modern advanced joining technology. The principle of laser-arc hybrid welding is shown in Figure 1.

3. Research on the Mechanism of Laser-Arc Hybrid Welding

3.1 Coupling Behavior between Laser and Arc

3.1.1 Effect of Laser on Arc

At present, researchers have reached relatively consistent conclusions regarding the hybrid welding process with low current and low laser power[5]. It is generally believed that during hybrid welding, the laser attracts the arc, increases arc conductivity, and exerts a compressing and stabilizing effect on the arc. On the one hand, a small portion of laser energy is absorbed by the arc plasma, leading to further ionization of the arc plasma. On the other hand, metal vaporized above the workpiece by the incident laser enters the plasma. Since metal atoms have lower ionization potential than shielding gas, more metal particles are ionized, which increases the local electrical conductivity of the arc and forms a stable conductive channel. As the arc conductive channel follows the principle of minimum voltage, the arc eventually deflects toward the laser keyhole, which is the main mechanism for increasing welding penetration. In addition, the preheating effect of the arc on the workpiece surface during welding greatly enhances the absorption efficiency of laser energy by the workpiece. Therefore, the laser can improve the combustion stability of the arc plasma during high-speed welding, which has been verified by researchers through comparing the morphology of arc plasma and the variation of output electrical signals before and after hybridization.

3.1.2 Effect of Arc Plasma on Laser Propagation

Existing studies suggest that after the laser interacts with the arc, the arc has two kinds of effects on laser propagation. On the one hand, under low current conditions, the ionization degree of particles inside the arc plasma increases, accompanied by a rise in electron density. The arc plasma dilutes the laser plasma, which reduces the absorption and reflection of laser energy by the laser plasma and improves the penetration ability of the laser beam to the workpiece. On the other hand, arc plasma and laser plasma coexist during hybrid welding, and the arc plasma can absorb, refract and scatter the laser beam[6]. In addition, the existence of arc plasma will enhance the inverse bremsstrahlung absorption and photoabsorption when the laser passes through the plasma, reducing the absorption rate of laser energy by the workpiece.

3.1.3 Interaction between Laser and Arc

After the combination of laser and arc, the laser enhances arc stability, and the arc improves the material's absorption of laser energy. The increase in total welding heat input and the interaction between laser and arc enable higher welding speed and better welding quality compared with single laser welding at the same power[7].

Through experiments, Wang Wei et al. found that laser-MIG hybrid welding can be performed at a welding speed 0.6 to 6.5 times higher than that of MIG welding, while significantly increasing the weld width and penetration of MIG welds.

3.2 Research on Droplet Transfer in Laser-Arc Hybrid Welding

Droplet size and transfer mode are directly related to weld quality and the stability of the welding process. In laser-arc hybrid welding, the introduction of the laser changes the arc shape and spatial energy distribution, which ultimately affects the heating and force conditions of the droplets, resulting in a change in the droplet transfer mode[8].

Compared with conventional arc welding, the force state in hybrid welding is more complex. In traditional arc welding, only four forces are usually considered: gravity, electromagnetic force,

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plasma drag force, and surface tension. However, in hybrid welding, affected by the metal vapor jet ejected from the laser keyhole, the types, magnitude, and direction of the forces acting on the droplets all change[9].The forces acting on droplet transfer are shown in Figure 2.

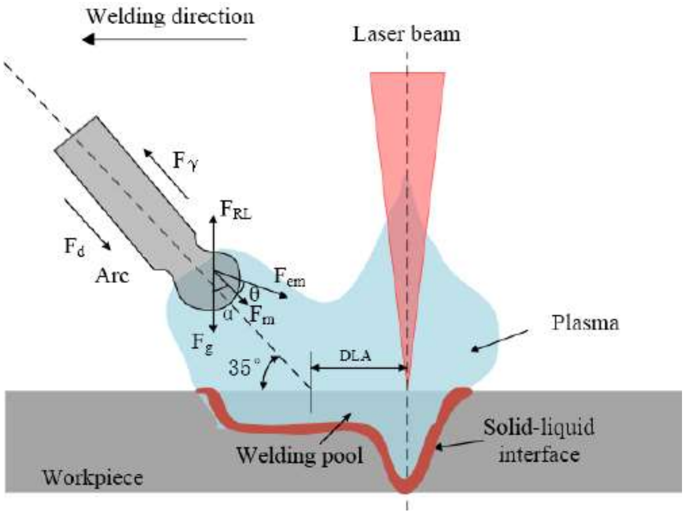

Figure 2. Force diagram of droplet transfer

4. Research Progress at Home and Abroad

Laser-MIG arc hybrid welding technology shows excellent application prospects in the welding of medium-thick steel plates or aluminum alloys. Compared with single laser or arc welding of aluminum alloys, laser-arc hybrid heat source welding can not only increase welding penetration, but also improve weld formation and reduce the formation of welding defects such as porosity and undercut. Especially for the welding of medium-thick aluminum alloy plates, the hybrid heat source demonstrates significant advantages.

However, due to the droplet transfer behavior in laser-arc hybrid welding, which is relatively complex to control, scholars at home and abroad have carried out extensive research on the laser-arc hybrid heat source welding process and droplet transfer behavior.

4.1 Laser-MIG/MAG Hybrid Welding

Laser-MIG arc hybrid welding technology shows excellent application prospects in the welding of medium-thick steel plates or aluminum alloys. Compared with single laser or arc welding of aluminum alloys, laser-arc hybrid heat source welding can not only increase welding penetration, but also improve weld formation and reduce the formation of welding defects such as porosity and undercut. Especially for the welding of medium-thick aluminum alloy plates, the hybrid heat source demonstrates significant advantages.

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4.2 Laser-CMT Hybrid Welding

CMT technology was developed by FRONIUS, Austria. It directly links wire feeding to welding process control. The digital process control detects the short-circuit signal and feeds it back to the wire feeder in real time. The wire feeder responds by retracting the wire, promoting separation between the wire and the droplet. This fully digitalized droplet transfer mode is completely different from conventional transfer modes. The welding process is shown in the figure below.

Volume 12 Issue 3, 2026
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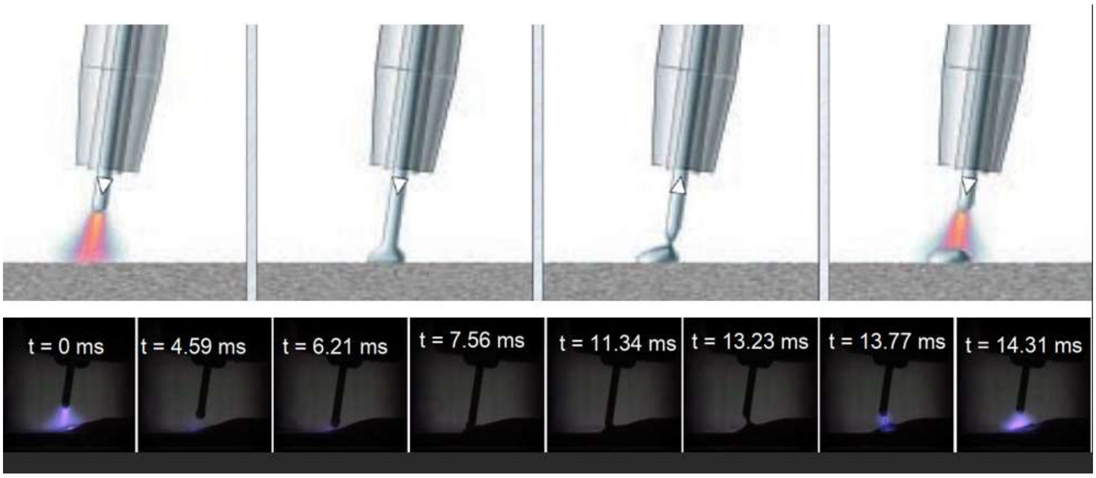

Figure 3. Schematic diagram of CMT welding

The hybrid principle of laser-CMT hybrid heat source welding is based on the spatial coupling of CMT arc energy and laser energy.At the same laser power, a relatively larger weld penetration can be achieved, while the adaptability to errors such as assembly gap and misalignment of workpieces is improved, enabling high-quality welding.

Introducing laser energy into the CMT arc not only retains the advantages of CMT welding, such as high stability and low heat input, but also greatly increases penetration, which is of great significance for the welding of thin-walled components.

4.3 Oscillating Laser-Arc Hybrid Welding

During laser beam oscillation, the oscillating behavior of the laser beam can effectively reduce the temperature gradient of the molten pool and strengthen the stirring effect on molten pool flow. It possesses the capabilities of suppressing weld porosity, promoting heterogeneous nucleation in the molten pool, altering the preferred growth direction of columnar grains, refining grains, and ultimately improving the strength and toughness of welded joints.

Compared with conventional laser-arc hybrid welding, oscillating laser-arc hybrid welding features a wider process window and is more conducive to industrial application. In contrast to single laser oscillating welding, it ensures more reliable weld formation and can significantly reduce laser energy loss during the welding process.

5. Applications of Laser-Arc Hybrid Welding

In recent years, laser-arc hybrid welding, as a high-quality and high-efficiency welding method, has become the focus of attention for research institutions at home and abroad in the welding community due to its broad application prospects and market competitiveness. Relying on its technical advantages such as high efficiency, stable joint quality and low comprehensive cost, laser-arc hybrid welding technology has been successfully applied in shipbuilding, engineering machinery, rail transit, automotive industry and other fields.

5.1 Shipbuilding Industry

Laser-arc hybrid welding plays a key role in the manufacturing of large-scale equipment in important fields such as marine vessels. These components are usually characterized by large thickness, complex joint forms and severe service environments. Welding quality has a direct impact on the performance and service life of the equipment. Traditional gas-shielded welding methods suffer from low welding speed and serious spatter, leading to challenges including low welding efficiency, high energy consumption and large residual stress, which can hardly meet the increasingly demanding manufacturing requirements. However, different from traditional welding technologies, laser-arc hybrid welding successfully integrates the advantages of laser welding and arc welding, featuring deep penetration, high welding speed, high efficiency and superior weld quality. Therefore, this technology has attracted extensive attention and begun to be applied in some key fields.

Meyer Werft in Germany established a 12 kW CO_2 laser-arc hybrid welding production line for the welding of hull flat plates and stiffeners, realizing one-pass forming of 20-meter-long fillet welds and reducing deformation by two-thirds. GE developed a fiber laser-arc hybrid welding system with a maximum output power of 20 kW, which was used in the welding of the USS Saratoga aircraft carrier, saving 800 tons of weld metal and reducing man-hours by 80%. The 725th Research Institute of China State Shipbuilding Corporation adopted a 20 kW high-power fiber laser-arc hybrid welding system, which can reduce welding deformation by 60% and improve welding efficiency by 300%. Shanghai Waigaoqiao Shipbuilding used a 16 kW high-power fiber laser-arc hybrid welding system. The production line adopted a new hybrid process of laser hybrid welding + MAG welding, realizing single-sided single-pass welding and double-sided forming for 4–25 mm thick steel plate butt joints.

5.2 Engineering Machinery

Low-alloy high-strength steel has good mechanical properties, favorable machinability, high corrosion resistance and excellent low-temperature performance, and is widely used in the engineering machinery industry. The boom is the main load-bearing and operating component of crawler cranes, supporting the crane and assisting in luffing. It plays a vital role in the safety and operating capacity of the whole machine, and is generally made of low-alloy steel. The telescopic boom of truck cranes is also a key component, usually made of low-alloy ultra-high-strength steel. At present, laser-arc hybrid welding is adopted for boom welding in XCMG, Sany Heavy Industry and other enterprises.

This process can stably and efficiently achieve single-sided welding and double-sided forming of the main welds of crane booms. The tensile and impact properties of the welded joints meet the relevant engineering application standards. Moreover, the process has strong adaptability to actual working conditions such as gap and misalignment of boom weld joints. In practical engineering applications, groove-free welding can be realized, with a welding speed up to 1.2 m/min.

5.3 Automotive Industry

In the automotive industry, Volkswagen of Germany took the lead in extensively applying laser-MIG hybrid welding technology to the aluminum alloy doors of the Phaeton at an early stage. Among the 66 welds with a total length of 4980 mm on the front door of the Phaeton, 48 welds adopted the laser-MIG hybrid welding process, with a welding length of 3570 mm, accounting for 72% of the total weld length.

There is a 4.5 m long laser-arc hybrid weld in the Audi A8 body, as shown in Figure 1-9, which is mainly distributed on the transverse roof frame of the body structure. The laser output power is 3.6 kW, the welding speed is 3.6 m/min, and the wire feeding rate is 4.5 m/min.

The rear sub-arm of Mercedes-Benz C/E-class models is assembled by two plates, and the joining process adopts laser-arc hybrid welding, as shown in Figure 1-10.

6. Future Outlook

This paper systematically reviews the development history, core mechanism, process optimization and industrial application status of laser-arc hybrid welding technology, sorts out the key achievements and existing challenges of this technology in theoretical research and engineering practice, and looks forward to its development trend combined with multi-field application cases. Overall, by organically integrating the high energy density of laser and the high gap adaptability of arc, laser-arc hybrid welding technology effectively makes up for the inherent defects of single laser welding or arc welding, showing significant advantages in reducing welding defects, improving joint strength and toughness, increasing welding efficiency, expanding process window and other aspects, and has become one of the core technologies to solve engineering problems such as thick plate welding, dissimilar material connection and high-precision component welding.

At the theoretical research level, scholars at home and abroad have clarified the synergistic mechanism between laser and arc, including core laws such as energy complementarity, plasma interaction and molten pool flow regulation, which provides a solid theoretical support for process parameter optimization, equipment upgrading and defect control; in terms of process optimization, through the regulation of key parameters such as laser power, arc parameters, welding speed and beam offset, as well as the application of improved technologies such as oscillating laser and pulsed arc, the stability of the welding process and the consistency of weld quality are further improved, and the requirements for assembly accuracy are reduced.

In the field of industrial application, this technology has successfully penetrated into many core industries such as shipbuilding, engineering machinery, rail transit and automotive industry, realizing large-scale application from high-end equipment to civil products. For example, ship thick plate butt welding, crane boom welding, automotive body structure connection, etc. It not only significantly improves the manufacturing efficiency and quality reliability of products, but also reduces the comprehensive production cost, showing broad market application prospects and industrial value.

At the same time, laser-arc hybrid welding technology still has some urgent problems to be solved: the localization rate of high-end core equipment (such as high-power fiber lasers and special hybrid welding torches) needs to be improved, the joint performance of some dissimilar materials (such as high-strength steel and aluminum alloy) connection still needs to be optimized, the online monitoring and intelligent control technology of the welding process is not mature enough, and the research on welding reliability under extreme service environment still needs to be deepened.

In the future, laser-arc hybrid welding technology will develop towards high efficiency, intelligence, lightweight and greenization. On the one hand, it is necessary to strengthen basic theoretical research, break through key technical bottlenecks such as dissimilar material connection and precise defect control, and promote the localization replacement of core equipment; on the other hand, it is necessary to combine cutting-edge technologies such as intelligent manufacturing, big data and artificial intelligence to develop an online monitoring and intelligent control system for the welding process, so as to realize adaptive optimization of the welding process. In addition, expanding the application of this technology in emerging fields such as new energy, aerospace and marine engineering, and further tapping its potential in energy conservation and consumption reduction will become an important direction to promote the sustainable development of laser-arc hybrid welding technology, providing strong support for the high-quality development of modern manufacturing industry.

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