DOI: 10.1007/s12541-016-0034-8 ISSN 2234-7593 (Print) / ISSN 2005-4602 (Online)

Laser-Assisted Hybrid Processes: A Review

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KEYWORDS: Hybrid processes, Laser, Machining, Welding, Coating

Today, hybrid processes have a great influence on various material process fields due to factors such as improvements in the machinability and reductions of process forces. Also, the development of hybrid processes represents a new opportunity for the growth of manufacturing technology. Hybrid processes are developed to enhance the advantages of individual processes. The effect of hybrid processes is better than the sum of the advantages of a single process. Many researchers have studied a number of approaches to combine various manufacturing processes. Specifically, since the development of the laser, it has been applied in various engineering fields. Moreover, interest in laser and non-laser hybrid processes is recently increasing in various industries. The laser is a type of non-contact thermal energy technology and is used in material processing. The laser heat source can be used for the heating and preheating of various materials. In this paper, the laser is selected as an energy source and laser-assisted hybrid processes over the past five years are reviewed, including those related to machining, welding and coating processes. The last part of this paper discusses the trends in future research on laser-assisted hybrid processes.

Manuscript received: December 29, 2015 / Revised: January 12, 2016 / Accepted: January 12, 2016 (Invited Paper)

1. Introduction

In today's manufacturing industry, with the continuing development of advanced materials and the high quality requirements of customers, various processing methods have been applied to produce products. These processes generally include machining, additive manufacturing, forming, joining, welding and heat treatments, among others. However, these processes have technological constraints. For example, with machining, it is difficult to machine complex shapes due to tool accessibility issues. Additive manufacturing is still restricted owing to long production times and poor surface quality levels.[1-7]

To overcome the aforementioned problems, many researchers have studied hybrid processes. Hybrid processes refer to a combination of processes which serves to produce products.[4-6] The purpose of a hybrid process is to enhance the advantages and minimize the disadvantages of individual techniques. However, the concept of a 'hybrid' is broadly defined. Schuh et al.[8] defined it using four concepts: (1) a combination of different energy sources at the same time; (2) a combination of process steps; (3) the integration of different processes within a single platform; and (4) as products of a hybrid structure or hybrid function.

In this paper, hybrid processes are defined as processes which combine different energy sources at the same time. Also, the laser, widely used in material processing is selected as an energy source. Therefore, this review discusses laser-assisted hybrid processes which have been developed over the last five years.

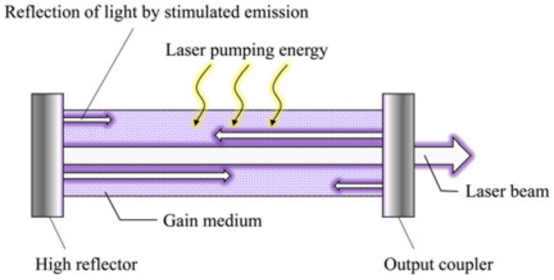

Fig. 1 Basic laser system

2. Laser (Light Amplification by Stimulated Emission of Radiation)

2.1 Basics

A laser is an acronym for light amplification by stimulated emission of radiation. This refers to devices that emit energy through a process of optical amplification based on the stimulated emission of

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Table 1 Characteristics of lasers for material processing[9,12-14]

	CO_2	Excimer	Nd:YAG	High power diode	Fiber laser
Wavelength (μm)	10.6	0.125-0.351	1.06	0.65-0.94	1.07
Overall efficiency (%)	5-10	1-4	1-3	30-50	10-30
Output power in CW mode	Up to 20 kW	300 W	Up to 16 kW	Up to 4 kW	Up to 10 kW
Focused power density (W/cm^2)	10^{6-8}	-	10^{5-7}*, 10^{6-9}**	10^{3-5}	-
Pulse duration (sec)	10^{-4}	10^{-9}	10^{-8}-10^{-3}	10^{-12}	10^{-13}
Fiber coupling	×	○	○	○	○

*Pumping by flash lamp

**Pumping by diode

Table 2 Different types of lasers and applications[9,10,15]

Laser (wavelength)	Applications
CO_2 laser (10.6 μm)	Cutting, welding, and rapid prototyping Surface treatment including cladding, and alloying Laser ablation, and laser glazing
Excimer laser_KrF (0.248 μm)	Optical stereolithography
Excimer laser_XeCl (0.309 μm)	Marking, scribing, precision micromachining related to drilling, machining, etching
Nd:YAG laser (1.06 μm)	Drilling, welding, machining, marking, and rapid prototyping
Semiconductor laser/Diode laser (0.7-1.0 μm)	Optical computers, CD drivers, laser printers, scanners, and photocopiers Optical communication Industrial alignment Holography, spectroscopy, bio-detectors, ozone layer detector, pollution detection, bar code scanners, 3D image scanners Cutting, and laser ablation
Fiber laser (1.07 μm)	Laser cleaning in conservation of artifact, pint stripping
Copper vapor laser (0.51 μm)	High speed photography Detection of finger prints Precision micro-hole drilling and cutting Excitation source for isotope separation

electromagnetic radiation.[9] The laser consists of a gain medium, a mechanism to energize it, and a device to provide optical feedback,[10] as shown in Fig. 1.

2.2 Types of lasers

Laser light has photons of the same frequency, wavelength and phase. Thus, a laser beam has high directionality, a high power density and high focusing characteristics. Due to these unique characteristics, lasers have been applied in the fields of science, medicine, and engineering. Specifically, laser beams are useful for the processing of materials. Moreover, lasers are used widely depending on the type of laser. Nd:YAG lasers and CO_2 lasers are the most widely used types in laser applications. Nd:YAG lasers have a low beam power, but the absorptivity by materials is higher than that of CO_2 lasers. CO_2 lasers have better efficiency and a good beam quality compared to Nd:YAG lasers due to their high beam power. This makes them suitable for high-speed metal cutting. Tables 1 and 2 show the characteristics and applications of different types of lasers.[9-16]

3. Laser-Assisted Hybrid Processes

Fig. 2 shows the laser-assisted hybrid processes discussed in this review. Laser-assisted hybrid processes are classified into the conventional hybrid machining, the non-conventional hybrid machining, the hybrid welding and the hybrid coating processes.[1-4]

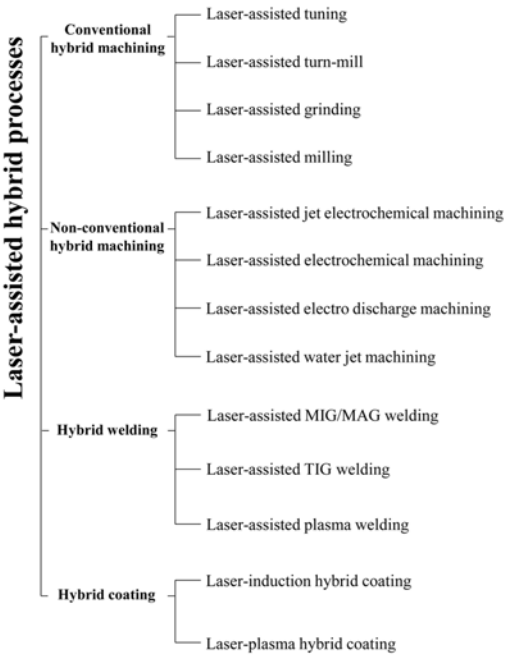


Fig. 2 Laser-assisted hybrid processes

3.1 Conventional hybrid machining (laser and cutting tool)

Laser machining and conventional machining processes such as turning and milling have been used to produce products in various manufacturing

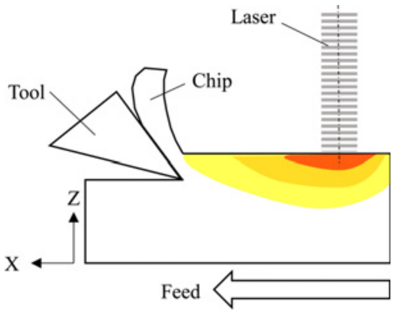


Fig. 3 Schematic diagram of laser-assisted machining

fields.[17-20] The energy source used in laser machining is a laser, and the materials are removed by melting, vaporization and decomposition from the irradiated surface. The important parameters of laser machining are the material properties, such as the reflectivity, thermal conductivity, specific heat and phase transition of the materials.[1]

Lasers for laser machining are widely used to remove materials. However, a laser is partly used to soften materials in combination with conventional machining (cutting tools), as shown in Fig. 3. This hybrid process is known as laser-assisted machining (LAM). In LAM, the material is locally preheated by means of laser power prior to the removal of the material without a phase transition of the material. Currently, laser-assisted turning (LAT) is commercialized in many countries. Moreover, silicon nitride can be successfully machined by this process. However, developments and researches on laser-assisted milling (LAMill) are still ongoing because it is difficult to control the laser heat source and tool path according to the various shapes of the workpiece during this process. To solve these problems, studies of the development of laser devices, system control methods and three-dimensionally shaped workpieces are essential.[21-26]

3.1.1 Laser-assisted turning

Fig. 4 shows a schematic diagram of the LAT process. The workpiece is rotated and is preheated by the laser.[27] Shin et al.[28-30] developed a multi-scale finite element model (FEM) to predict the post machined sub-surface damage in the LAT process. The analysis results were calculated to within 7% to 12% of the experimental results. Also, LAT experiments on titanium alloy and hardened steel were performed. For titanium alloy, the machining cost of LAT was decreased by approximately 30% with an improvement in the machinability. For hardened steel, a good surface finish, R_a, of less than 0.3 μm was obtained.

Mohammadi et al.[31] proposed laser-assisted diamond turning which was coupled with LAT and single point diamond turning, as shown in Fig. 5. Surface roughness was improved about 80% compared to conventional turning.

3.1.2 Laser-assisted turn-mill

Lee et al.[32-37] developed a laser-assisted turn-mill process which was coupled with a turning and milling process, as shown in Fig. 6. Also, laser-assisted turn-mill experiments of various types of clovers, spline and square section members were performed. Consequently, a reduction of the cutting force and an improvement in the surface roughness were confirmed.

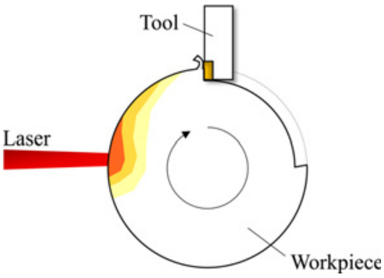


Fig. 4 Laser-assisted turning

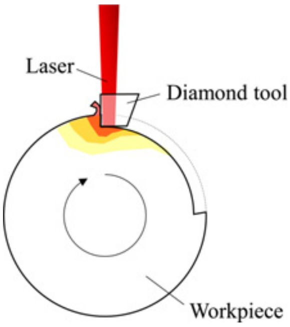


Fig. 5 Concept of laser-assisted diamond turning

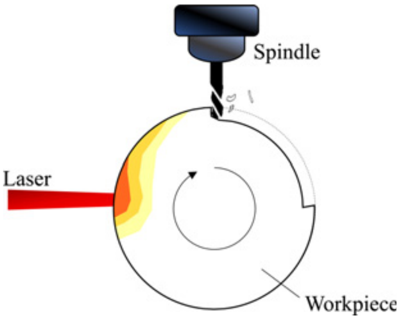


Fig. 6 Laser-assisted turn-mill

3.1.3 Laser-assisted grinding

Fig. 7 shows a schematic diagram of the laser-assisted grinding (LAG) process.[38] Chang et al.[39] studied a LAG process capable of manufacturing micro-features in difficult-to-cut materials such as Si_3N_4 and Al_2O_3 ceramics. The machined surface roughness and subsurface damage were investigated. As a result, subsurface damage was not observed when the LAG process was used, and the machined surface roughness levels were better more consistently than those obtained using the conventional grinding process.

3.1.4 Laser-assisted milling

Fig. 8 shows a schematic diagram of the LAMill process. Hermani et al.[40] studied the LAMill process for advanced materials. The reduction of cutting force, increase of the material removal rate and improvement of tool life without application of cooling lubricants were verified by the experiments.

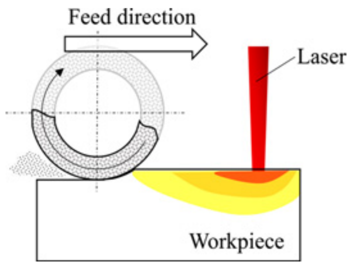


Fig. 7 Laser-assisted grinding

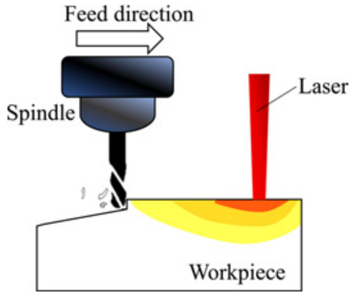


Fig. 8 Laser-assisted milling

Shin et al.[41] performed a numerical modeling analysis of laser-assisted micro-milling (LAMMill) with difficult-to-machine alloys, specifically Ti6Al4V, Inconel 718, and stainless steel AISI 422. Multiple LAMM tests using micro-end-mills with diameters of 100-300 μm were conducted on these materials during the side cutting of bulk and fin workpiece configurations. The flow stress was decreased by approximately 20-25% when the temperature was in the range of 250~450°C.

Dargusch et al.[42] studied tool path strategies in which the laser always preheated the workpiece directly ahead of the cutting tool. Two low-cost methods of rotating the table and the laser module were proposed.

Wiedenmann et al.[43] developed a new processing strategy and a simulation based model of LAMill. A reduction of tool wear and an increase of the material removal rate were confirmed through experiments.

Lee et al.[23,44-50] studied LAMill for three-dimensional shapes such as a workpiece with an inclination angle and a cylindrical shape. The effective depth of cut was proposed by a thermal analysis. Also, a reduction of the cutting force and an improvement of the surface roughness through experiments were confirmed.

3.2 Non-conventional hybrid machining (laser and other energy source)

The energy sources of non-conventional hybrid machining can be an electron beam, a plasma arc, lasers and even water. These non-conventional hybrid machining processes are not affected by chatter or the force of the cutting tool but can be controlled by various parameters of the energy sources such as the input energy and processing speed.[1-7,51-59]

3.2.1 Laser-assisted jet electrochemical machining

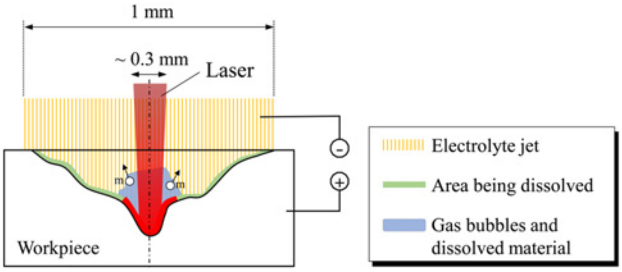


Fig. 9 Laser-assisted jet electrochemical machining

Fig. 9 shows a schematic diagram of the laser-assisted jet electrochemical machining (LAJECM) process. De Silva et al.[60] investigated the thermal effects on several alloys in temperature distribution modeling and by means of an experimental analysis in relation to LAJECM. As a result, LAJECM offered more rapid material removal and better precision than jet electrochemical machining due to the thermal enhancement of the electrochemical action.

Hua et al.[61] developed a hybrid process which incorporated laser drilling with jet electrochemical machining (JECM-LD) to solve several problems related to conventional laser drilling. The proposed hybrid method involved the placement of an electrolyte jet coaxially aligned with the irradiated laser beam onto the workpiece surface. High machining quality with fewer recast layers and reduced spattering was obtained by JECM-LD.

3.2.2 Laser-assisted electrochemical machining

Skoczypiec[62] conducted a detailed analysis of laser-assisted electrochemical machining (LAECM) and proposed a mathematical model of workpiece heating.

Zhong et al.[63] studied LAECM to enhance the etching pit and cavity quality. Etching experiments of stainless steel by LAECM with an excimer laser were carried out. The etching rate and etching depth were greatly improved when the etching time was 8 min.

3.2.3 Laser-assisted electro discharge machining

Clerici et al.[64] studied electric discharge phenomena from different beam shaping configurations, including a Gaussian beam, a Bassel beam and an Airy beam. Different discharge shapes according to the laser beams were tested to control the degree of freedom of the discharges. Fig. 10 shows the principle of this discharge.

Fig. 11 shows a schematic diagram of the combined laser and electro-discharge machining (EDM) process.[65] Al-Ahmari et al.[66] studied a hybrid process which combines a laser and the micro-EDM process for micro-drilling. Optimum machining conditions when combining micro-EDM and laser machining were suggested. As a result, the machining time which does not affect the quality of the microholes was decreased by approximately 50~65%.

3.2.4 Laser-assisted water jet machining

Adelmann et al.[67] conducted a comparison between remote laser cutting with a fiber laser and water-jet guided laser cutting using a 532 nm solid state laser. An advantage of remote laser cutting was the high cutting speed. An advantage of water-jet guided laser cutting was a reduced heat-affected-zone (HAZ), a reduced dross height and the

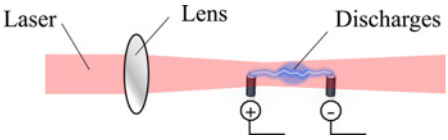


Fig. 10 Principle of laser-guided discharge

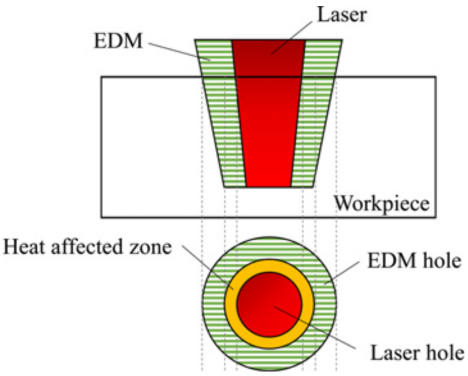


Fig. 11 Laser-assisted electro discharge machining

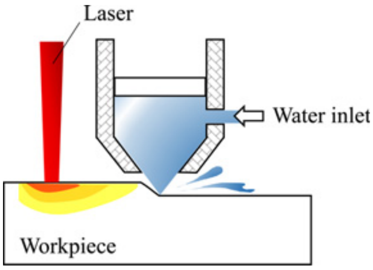


Fig. 12 Concept of laser-assisted water jet machining by Molian et al.

smallest possible bridges.

Molian et al.[68] studied a hybrid manufacturing process that enables synergistic effects of a CO_2 laser and a water jet, as shown in Fig. 12. The proposed process improves the surface quality with an increase in the cutting efficiency.

Nath et al.[69] developed a hybrid laser process which utilizes a water-jet along with a laser beam, as shown in Fig. 13. This process completely removes paint without any trace on the surface.

Romoli et al.[70] studied laser process which involves a moving water-jet, as shown in Fig. 14. The laser beam is guided by the total internal reflection at the water-air interface. The surface roughness was measured to be 450 nm and 150 nm for the EDM and the laser micro-jet process, respectively.

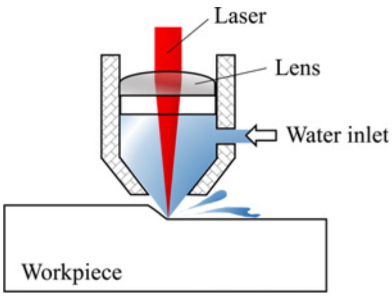


Fig. 13 Concept of laser-assisted water jet machining by Nath et al.

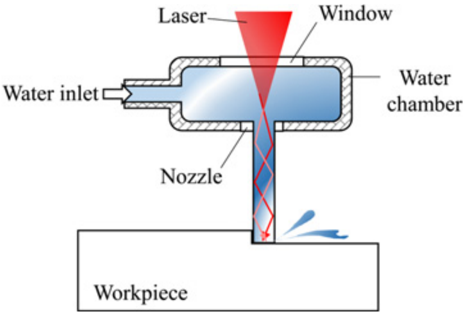
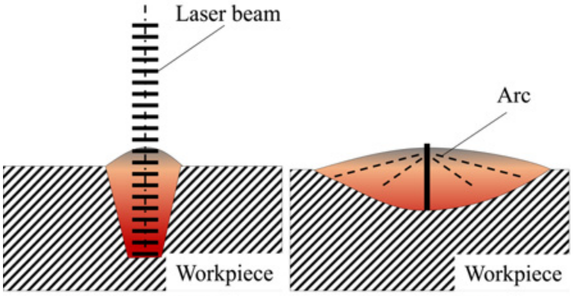
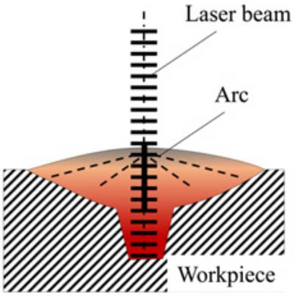


Fig. 14 Concept of laser-assisted water jet machining by Romoli et al.



(a) Laser welding (b) Arc welding



(c) Laser-arc welding

Fig. 15 Comparison of (a) laser welding, (b) arc welding and (c) laser-arc welding

3.3 Hybrid welding

Welding can be largely classified as laser welding and arc welding. Laser welding and arc welding have long been used in various material processing fields. Laser welding leads to a very narrow HAZ with a large depth, as the laser beam has a high energy density and a small heat source diameter, as shown in Fig. 15(a). In addition, a high welding speed can be obtained. However, a high laser power is required due to a low energy efficiency of materials with low specific resistance and excellent thermal conductivity. Also, the cost of the laser welding device increases geometrically according to an increase of the laser power.[71-80]

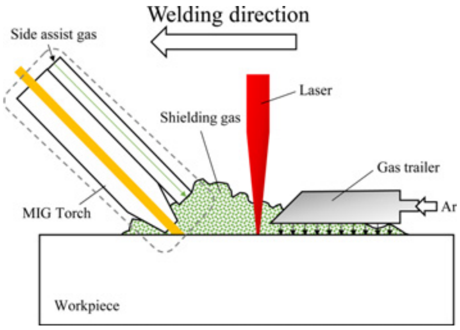


Fig. 16 Laser-assisted MIG welding

Fig. 15(b) shows the arc welding process. Arc welding has a much lower energy density and a slow welding speed, but arc welding causes a bigger heat source, and the cost of an arc welding device is very low compared to the laser welding device. Therefore, by merging these two welding processes, many advantages, such as improved weld quality levels, higher welding speed, less deformation, an excellent gap bridging ability and good process efficiency are achieved.[71-74]

Laser-arc welding which consists of a laser and an arc heat source is capable of offsetting the disadvantages of individual process. Laser-arc welding has been studied by many researchers since the technology of laser-arc welding was initially proposed by Steen.[81] Fig. 15(c) shows the laser-arc welding process. It is formed by the merging of laser welding and arc welding. Furthermore, excellent weldability is confirmed by the efficient synergetic effects between the laser and the arc heat source.

The welding characteristics of laser-arc welding differ according to the order of the two heat sources and the types such as a CO_2 laser, a YAG laser, and TIG, MIG, MAG, and plasma. The determination of parameters such as the distance between the laser and the arc, the relative power levels, the shielding gas arrangement, and the welding speed, among others, are very important because the degree of weldability can differ greatly depending on the materials.[71-74]

3.3.1 Laser-assisted MIG/MAG welding

Fig. 16 shows a schematic diagram of the laser-assisted MIG (LAMIG) welding process. Li et al.[82] conducted a comparison of laser beam welding and the LAMIG method. The weld formation was improved by adding welding wire and with a higher level of heat input. Moreover, compared to laser beam welding, welded joints were improved.

Guen et al.[83] studied the effects of the main operating parameters of laser-assisted MAG (LAMAG) welding. A numerical model of LAMAG welding was proposed through experimental results and simulations.

Gao et al.[84] studied the high power LAMIG welding of AZ31 Mg alloys. Tensile tests were used to evaluate the mechanical properties of welded joints. Stable process and sound joints were obtained using the optimal welding conditions in LAMIG welding. The tensile strength efficiency of the welded joints was also calculated to be 84~98% of the substrate.

3.3.2 Laser-assisted TIG welding

Fig. 17 shows a schematic diagram of the laser-assisted TIG (LATIG) welding process. Zeng et al.[85] investigated the microstructure and mechanical properties of 304 stainless steel joints by LATIG welding. Tensile testing and an analysis of the fracture surfaces were performed. Excellent mechanical properties of the joints were observed by LATIG welding.

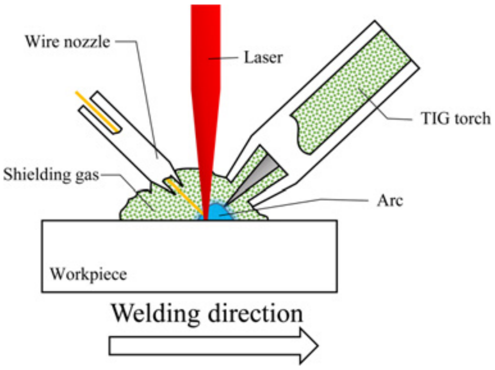


Fig. 17 Laser-assisted TIG welding

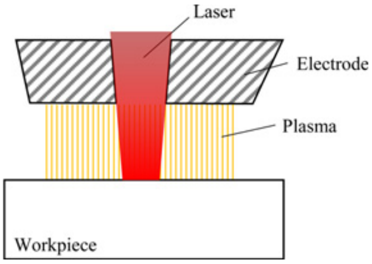


Fig. 18 Laser-assisted plasma welding

Shenghai et al.[86] studied the technologies of the autogenous laser welding and LATIG welding of thick plate of the high strength lower alloy structural steel 10CrNiMnMoV. The unique advantages of LATIG welding were analyzed by comparing the process conditions and welding joints of two processes. In LATIG welding, the assembling clearance and misalignment adaptability of the weldment were significantly improved.

3.3.3 Laser-assisted plasma welding

Fig. 18 shows a schematic diagram of laser-assisted plasma (LAP) welding process. Ribic et al.[87] studied LAP welding using optical emission spectroscopy. The experiments were performed considering the arc currents and heat source separation distances, as these parameters significantly affect the weld quality. The plasma electron temperatures, electrical conductivity and arc stability during hybrid welding were better than those in arc and laser welding.

Moller et al.[88] developed a coaxial LAP welding method for the flux less joining of aluminum. The mechanisms of interaction between the laser and the plasma arc were confirmed by varying certain parameters, including the laser power, plasma current, and plasma polarity.

Schnick et al.[89] investigated the interaction between a laser and a plasma in LAP welding. Experiments were performed with a non-concentric set-up of the laser and the plasma. Improvements in the process stability and penetration depth were confirmed by combining individual processes.

Table 3 Characteristics of laser-assisted hybrid processes

	Scale	Important findings	Problems and challenges	Application[5]
Conventional hybrid machining	μm~mm	Decrease of machining cost[29] Improvement of tool life[40] Reduction of flow stress[41]	High costs Complex control system Application to materials with various shapes[23]	Frequent
Non-conventional hybrid machining	μm	Improvement of electrochemical dissolution[63] Reduction in machining cost[65] Reduction in HAZ[67] Increase of cutting speed[67]	Difficult to machine 3-D structures[63] Thin cutting process[67]	Partly
Hybrid welding	mm	Improvement in tensile strength of welded joints[84] Improvements in process stability and penetration depth[89]	Large number of parameters Complexity of equipment[72] Consumable costs[72] Application to various materials	Very frequent
Hybrid coating	μm~mm	Improvement of microhardness[96] Reduction in residual stress and crack[98]	Determination of parameters in order to enhance hardness	Partly

3.4 Hybrid coating

Coating techniques of materials are applied to induce good mechanical properties and to restore the surface quality levels of materials. Coating techniques such as electro-deposition, thermal spraying and laser cladding are very important for the fabrication of composite coating. Specifically, laser cladding has been steadily used to change microstructure and mechanical properties. Compared to other coating techniques, including deposited welding, laser cladding has a number of useful characteristics, such as minimum dilution, a small HAZ, less distortion and better processing flexibility.[90-92]

However, laser cladding has been not widely used in many industries owing to several disadvantages, such as low cladding efficiency, low coverage rates, and high thermal stress, inducing cracks in the cladding layer. In order to overcome these problems, laser-assisted hybrid coating technologies have been developed.[90-95]

3.4.1 Laser-induction hybrid coating

Fig. 19 shows a schematic diagram of the laser-induction hybrid coating (LIHC) method. Zhou et al.[96] studied the efficiency of the LIHC process. An analytical model of LIHC for Ni-based WC composite coatings was also proposed. Experiments were conducted to verify the calculated results. The maximum error between the measured and the calculated coating heights was 13.6%.

Huang[97] studied LIHC through powder feeding, dilution action and through the elemental composition distribution. A relationship between the dilution and the composition distribution was confirmed in LIHC. Various microstructures and mechanical properties were obtained by adjusting the laser and the induction energy.

Wang et al.[98] studied the residual stress and cracking behaviors of Cr13Ni5Si2 based composite coatings by LIHC. An X-ray based layer-removal method was used to obtain the residual stress, which was found to be remarkably decreased in LIHC, with no cracks observed over a large area and with high thickness, hard facing coatings.

3.4.2 Laser-plasma hybrid coating

Roy et al.[99] reported the fabrication of compositionally graded hydroxyapatite (HA) coatings on Ti by combining laser engineering net shaping (LENS^{TM}) and radio frequency induction plasma spraying processes. The hardness of the base metal of 189±22 Hv was significantly increased to 922±183 Hv.

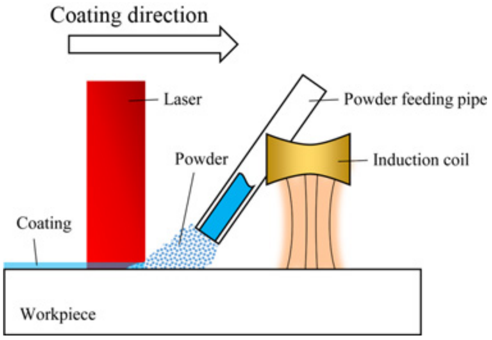


Fig. 19 Laser-induction hybrid coating

Serres et al.[100] studied the properties of NiCrBSi alloy layers obtained by a laser-plasma hybrid coating (LPHC). The effects of a combination of a laser and plasma were verified by improvements of mechanical properties such as the adhesion, hardness and elastic modulus.

4. Conclusions and Future Directions

This paper reviewed laser-assisted hybrid processes over the last five years. Table 3 summarizes the characteristics of the reviewed processes. Lasers have been applied to process the materials in various industries. Lasers and other energy sources have also been combined to enhance the advantages and to minimize the disadvantages found in individual techniques.

As discussed above, the studies of laser-assisted hybrid processes are ongoing by many researchers. These results continue to lead to the development of the manufacturing industry.[101-103]

In the future, the relationships between processes and control systems will be established, leading to the introduction of new methods of process combinations. Also, advances in individual processes can accelerate the development of hybrid processes.[4,5]

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2015021823).

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