The development of laser drilling: A review

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Abstract. Laser drilling is of great significance for metal parts production, aerospace parts processing, precision chip manufacturing, etc. In recent years, drilling technology based on new laser devices has become an international research hotspot for its advantages of high speed, high accuracy and low thermal damage. In this paper, the laser drilling is compared with other drilling methods, and the influencing factors and application trends are introduced. At the same time paper introduced the main research on the model and theory of laser drilling at home and abroad. The important effects of thermal effect and molten material on drilling and the latest research progress are introduced.

1. Introduction
Since the birth of laser, it has become a powerful tool in industrial, scientific and military fields because of its controllable and stable energy density as well as superior transmission property. The research and upgrade of laser has never stopped for decades. As drilling on metal materials is an important application of laser, the research on its action mechanism and reaction process is helpful to improve the accuracy and benefit of processing and manufacturing, and also can expand the application of laser to a wider field.

2. Laser drilling
Although all kinds of lasers device have different operation modes and conversion efficiency, as energy generation and transmission machines, the role of the medium, especially the metal, has been the main direction of research and practical application. The use of laser processing of metal devices, for only light beam contact, can effectively avoid friction and noise, and because of the concentration of energy, processing will be more accurate and less impact on the surrounding components. Taking advantage of these characteristics, laser drilling, laser cutting, laser heat treatment, enhanced treatment and melting treatment gradually replaced the traditional mechanical processing methods [1, 2], and developed into the field of energy-containing materials processing and detonation, used in cutting explosives and propellant [3], or used to eliminate unexploded ordnance [4].

Laser drilling, widely adopted in precision machining, chip manufacturing, aviation parts, as one of the most basic application, the theory research and technology improvement never stop. With other methods such as electrochemical machining (EDM), stamping, electrolytic chemical machining (ECM)
compared to laser drilling, stamping and mechanical drilling will not be able to process the high strength alloy; EDM and ECM have high cost and long processing time. Although EDM has better machining quality, it is slower than laser machining and has disadvantages in production efficiency [5, 6]. At present, in addition to the laser drilling method of adjusting the focal length with the change of depth at the established location, it has also developed a variety of methods such as auger drilling and hourglass type drilling [7].

During drilling, processing quality can be assessed by whole taper, whole roundness, material removal rate (MRR), HAZ, recasting layer, aspect ratio, and spatter. In order to achieve the required machining quality, a series of parameters need to be controlled. Figure 1 shows the quality control diagram [5].

![Figure 1. Quality control diagram in Laser drilling](image)

The research on the best drilling performance of lasers has been throughout the development of lasers. For example, J.S. Lash and R. M. Gilgenbach in 1993 studied the processing time of copper, iron and titanium by copper vapor lasers under atmospheric pressure and argon and the reasons for the difference [8]. At the beginning of the 20th century, the Nd: YAG laser developed rapidly. Compared with the traditional CO₂ laser, the metal absorption rate was 3.16 times [9] of the latter, so it gradually became the focus of research and application. For example, In Experimental Investigation Of Quality Characteristics In Nd: YAG [10], the effects of laser energy, pulse repetition rate, pulse width, gas pressure and other process parameters on the performance indexes of laser sputtering area and heat affected area (HAZ) were studied. In Pulsed Nd: YAG laser beam drilling-a review [11], 35 Experimental papers on Nd: YAG laser from 1995 to 2016 were summarized. Article describes the effects of various parameters on whole quality in detail. In recent years, fiber lasers have become the forefront of development. With their special ability of flat-topped beam and square wave output, they have established an advantage over Nd: YAG lasers in the field of aerospace device processing [12].

On the other hand, the emission frequency of lasers is also developing. Nanoseconds, picoseconds, femtoseconds and shorter pulsed lasers are coming into being. Femtosecond, picosecond and nanosecond laser ablation of solids [13] reveals the basic principle of laser and material, and the huge potential of Femtosecond laser in precision machining. Because of the very short (10 -15 s) time, which is far less than the time required to heat conduction and diffusion, HAZ is effectively controlled [6]. Compared with picosecond and nanosecond laser, although the Femtosecond laser’s ablation rate is weaker, in the low energy through electronic microscope, the thermal effect of femtosecond laser is negligible, and the resulting borehole mass is higher than that of picosecond laser [14], and the spatter generated by femtosecond laser is also smaller when analyzed by laser-ablative inductively coupled plasma mass spectrometry (LA-ICP-MS) [15].
3. Theoretical and model research of drilling process
The process of laser drilling on metal is mainly the reaction not only between laser and metal, but also between metal vapor, plasma and a series of other substances, leading to the metal removed in the gaseous or liquid. The reaction from the microcosmic point of view, is free electrons absorb the energy of photons, and transfer to the lattice. However, from the macro point of view, the reaction is the metal absorb laser energy. When the laser energy is higher than the ablation threshold of metal, metal melt and evaporate, molten mass splash of force, even leading to the phase explosion [16]. In this process, thermal effect, molten material state and plasma generation are the most important and worthy of attention.

3.1. Thermal effects
Thermal effect is the main effect of laser application. In application, it is used to disable or ablate targets by heating them, which can be used in medical and industrial fields as well as weapons [17]. Since the temperature field produced by laser, especially the short-pulse laser, changes rapidly in time and space after acting on metal materials, it is very difficult to describe the development of the temperature field by measuring experimental data. Therefore, theoretical derivation and modeling are most often used in research. The most basic model, using the Fourier heat transfer mode (ns time scale) and double temperature equation model (ps time scale), considering the material coefficient of specific heat and thermal conductivity changing with temperature, from the macroscopic scale simplifying the drilling to heat transfer process that a point or small area in infinite plate embedded a concentrated heat source [18, 19]. When the finite element model is adopted, some model kill the material element after it reaches the gasification temperature and reset the loading boundary until the calculation is completed [20]; others simply study the development of the temperature field and ignore the influence of molten material [21]. There are also some special methods, for example, Huang jiang et al. studied the relationship between metal reaction time, liquid flow rate, melting point of the material and the formation of molten spots after pulsed laser action through experiments, and proposed a method to rapidly calculate the temperature of the center by measuring the diameter of molten spots [22]. These methods are consistent with the experimental data to describe the real-time data and developing evolution of the temperature field at the macro level, but are difficult to describe the development and formation of holes in the drilling process because the state and influence of molten material are not considered. However, under a special condition, the molten material will be removed immediately after the formation due to tangential airflow. After taking into account the influence of environmental convection, the model is more accurate [23] and can also make a better prediction of the whole depth [24].

3.2. The state of a molten substance
If the drilling process is to be described in more detail, the metal melt must be taken into account. Recasting layer formed by the re-solidification of molten material and the sealing phenomenon of whole mouth have a great influence on the efficiency and quality. The study on the dynamic characteristics and conduction characteristics of molten material can effectively grasp the key to improve the processing quality. Researchers have adopted a variety of experiment method. Through high-speed video recording drilling process near the specimen edge [25] or observing deformation and thermal radiation near μm-scale boundary of the hole, the development of the drilling process can be clearly observed. While the schlieren diagnostic instrument can observe impaction of steam jet on molten. Shock wave and plasma dynamics high-speed imaging technology not only can record the process of the melt injection and state [26], but also can be used in the prefab holes, record the melt in a certain depth of drilling-hole and plasma development situation [27]. In terms of theory and model research, the research content is no longer a simple heat conduction in the solid surface, but a more complex model, which contains steam-melt interface, relation between evaporation and temperature, mutual influence of fluid velocity and thermal conductivity, change of solid-liquid interface, and so on. A different approach in the study will make a different model, such as two-dimensional transient model
[28] considering the Knudsen melt-steam front layer, without considering the effect of melt flow, Stefan conditions in melt-steam interface model [29], treating boiling point as liquid-phase transitions model [30]. And the model [31] established by using Clausius-Clapeyron equation to constrain temperature and vapor pressure and considering the distribution of flow velocity. These models have been verified by experiments under their own conditions, and the predicted material removal rate and whole development are in good agreement with the experimental results. Some studies also focused on the molding quality of the drilling whole surface, taking into account the reaction force of evaporation, gravity, fluid tension and other factors, and predicted the shape of the meteorite-shaped uplift on the whole surface on COMSOL™, which was generally consistent with the observation during the experiment [32]. There are also studies that bypass the methods of fluid mechanics and molecular dynamics, calculate the separation temperature with the critical temperature and density of the material, define the point separation point that achieves the separation temperature, and thus achieve the purpose of predicting the depth. Through experimental verification, the drilling depth of the length pulse below 10ps is well predicted [33].

3.3. Plasma
When the laser energy reaches the surface of the metal, in a tiny metal thickness, material absorb energy leading to the phase change, ejecting steam contains a large number of electrons, atoms and ions. When the laser energy density is stronger and reaches a threshold, the metal surface temperature increasing makes ejection more acute. Electrons from thermionic emission collide with the nitrogen atom [34] in the air and the metal atom, resulted in a rapid development of plasma steam. In industry, its precipitation on the substrate produce the metal film, which is the pulsed laser deposition (PLD) method. But it can be seen in the simulation of drilling, plasma from beam energy can rapidly reduce the energy of the arriving metal [35], seriously affecting the drilling efficiency. Therefore, gas-assisted method is often used in practical processing and research to weaken the shielding effect.

4. Conclusion
Drilling as the most basic application of laser. The current research results have been able to guide well above the millimeter accuracy of processing production, in this field, the most concerned element is processing efficiency and energy conversion rate directly related to the economy. Therefore, it is still of positive significance and value to conduct energy coupling and response test between various types of laser devices and various processing materials to find the best combination of working wavelength, frequency, waveform and other parameters. On the smaller scale, such as nanoscale, improving the ability to control thermal damage zone, surface flatness and borehole shape through model and theoretical research is of great significance for precision machining including chip manufacturing. In this field, the current study reveals that the individual or part of a gas liquid solid interface under the condition of a particular influence on drilling, a microscopic role includes the whole process of model remains to be seen. On the other hand, looking for characteristic indexes which is easy to be accurate acquired to quick describe processing state such as temperature, energy coupling or material removal rate, still plays an important role in guiding the practical production.

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