Chapter 5

Advanced Laser Material Processing Techniques

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Abstract

The growing importance of laser material processing technologies in various industries, expanding application areas, and decreasing costs of laser systems make this technology critically important. This paper provides a comprehensive review of the advances, applications and impacts of laser technology in manufacturing, with a particular focus on laser surface treatment, welding, cutting, drilling and cladding. Academic research in this area is leading to the development of innovative manufacturing techniques aimed at improving product quality, designing multi-material components and supporting economic benefits. Numerous studies have been conducted to investigate and optimize the effects of lasers on materials, leading to significant advances in laser materials processing. Key findings highlight the importance of laser surface treatment in enhancing material properties, the versatility and precision provided by laser welding, the advantages of non-contact machining, the high speed and flexibility of laser cutting, and the capacity of laser drilling to effectively process hard and high-strength materials. Furthermore, it is critical to carefully determine the appropriate laser parameters to achieve the desired mechanical properties in laser-processed materials. Ongoing research is directed toward further understanding laser-material interactions and improving laser processing techniques. In brief, laser material processing technologies continue to play an important role in improving manufacturing processes and enhancing product quality.

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1. Introduction

Laser material processing technologies are highly important for various industries, due to the rapid expansion of laser applications and the decreasing costs of laser systems (Grigoriev, Volosova, & Okunkova, 2022; Rahman, Haider, & Hashmi, 2014). In industrial contexts, different applications such as drilling, welding and laser cutting (Deepak, R.P, & Saran Sundar, 2023) have developed and achieved common acceptance. However, new developments in laser technology, particularly in the areas of additive manufacturing and micro/nanofabrication, have increased the potential applications of lasers in manufacturing industries (Murzin & Stiglbrunner, 2023). The availability of ultrafast lasers such as femtosecond and picosecond lasers, as well as high-brightness lasers such as disk and fiber lasers, are significant advancements in laser technology (Sugioka & Cheng, 2014). Processing is now possible more precisely and effectively because of the novel beam material interaction phenomena that these types of lasers have revealed (Brown & Arnold, 2010). Thus, advancements in the science and technology of laser material processing will increase the accessibility of laser use (L. Li, 2010).

The main characteristics of lasers that make them ideal for material processing are their repeatability, directivity, and adjustability of the energy that reaches the target (Ion, 2005). The material processing process can be controlled by setting the correct laser parameters and selecting the appropriate physical properties. The high-intensity laser beam can remove atoms from the target by creating effects such as heating, melting, boiling and ionization in the material. These interactions can lead to entrapment in the electronic state of the material, changes in bonds, and the formation of defects. Figure 1 summarizes the specific physical interactions of the material with the laser (Bäuerle, 2011; William M. Steen & Mazumder, 2010).

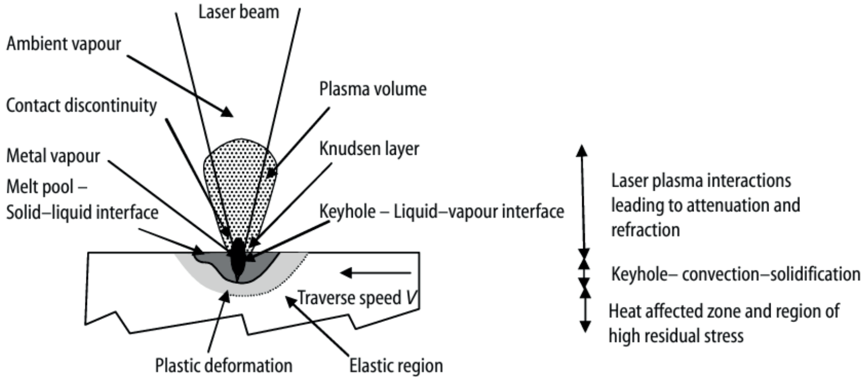

Figure 1. Laser material processing and physical interactions (William M. Steen & Mazumder, 2010).

Lasers are not only established and essential tools for current manufacturing technologies but also can provide solutions to upcoming complex challenges in industrial materials processing. Laser-related research is actively focused on developing innovative manufacturing techniques to improve product quality, explore the engineering of integrated multi-material and multi-functional components, and improve economic and executive benefits (Kukreja, Kaul, Paul, Ganesh, & Rao, 2013). Due to the diversity of laser types and usage areas, many studies have investigated, analyzed, and optimized the various changes that lasers cause on materials (Alhajhamoud, Candan, et al., 2022; Alhajhamoud, Ozbey, et al., 2022; Joe et al., 2017; Solheid et al., 2022)

Laser material processing techniques can be classified as drilling, cutting, welding, surface treatment and cladding. Subclasses within this classification can be created based on material qualities (conductors, semiconductors, insulators), energy, wavelength, pulse duration, and response rate of the laser employed, and the size of the work performed (centimeters, micrometers, and nanometers) (Demir, 2010). The following chapters include general information regarding the laser beam and lasers. Thereafter, the primary laser material processing techniques, laser surface treatment, laser welding, laser cutting, laser drilling, and laser cadding were discussed in detail.

2. Laser Beam and Lasers

The laser derived from "Light Amplification by Stimulated Emission of Radiation," is a device that amplifies electromagnetic radiation through stimulated emission (Zohuri, 2016). The laser can produce a broad spectrum of radiation from ultraviolet to infrared. To obtain a laser beam, three essential components are required: the gain medium for light amplification, a pumping source for stimulation, and feedback systems for saturation (Silfvast, 1996). The basic principle of laser beam generation is shown in Figure 2.

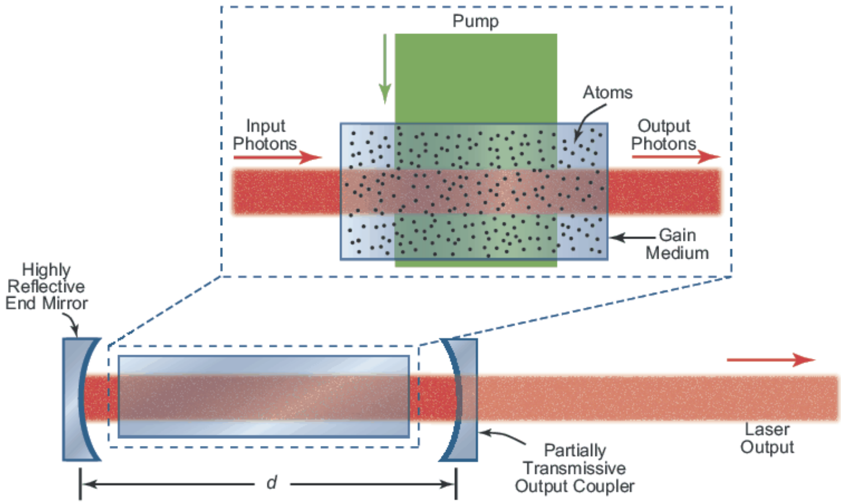

Figure 2. Basic principles of laser beam generation (Justander, 2022).

Lasers are light oscillators that amplify light by excited emission from atoms within an optical resonator. Laser light is very spatially compatible and has a restricted spectral width. Laser beams can focus on a small spot and are highly directional. Because they produce incredibly short light pulses, pulsed lasers have extremely high peak power (Agrawal, 2016). Since its creation in 1960, the laser has played an essential role in several scientific developments and the development of numerous light-based technologies (Affan Ahmed, Mohsin, & Zubair Ali, 2021).

Lasers have quickly expanded in several industries because of their superior and remarkable qualities. Currently, practically every industry, including national defence, agriculture, and manufacturing, uses lasers extensively (Ion, 2005; Tong et al., 2022; Zhou et al., 2023). High-power laser sources offer new opportunities for material processing with different wavelengths. As laser power increases, the power consumption of the system decreases. The laser focal point with increased mobility has improved many manufacturing processes (laser welding, cutting, drilling etc.). Therefore, manufacturers across the world recognize lasers for their success and adaptability (Casalino, 2018).

Laser systems have various types based on the active medium in which they are produced (Singh, Zeng, Guo, & Cai, 2012). They can be classified into fundamental categories such as gas lasers, liquid lasers and solid-state lasers (Fujimoto, Nakanishi, Yamada, Ishii, & Yamazaki, 2013) . Each category has multiple laser types depending on the diversity of the active medium. In gas lasers, laser mediums are created using atoms, molecules, ions, or metal vapor. One notable example of an atomic laser in this category is the helium-neon (He-Ne) laser. Similarly, in solid-state lasers, there are various laser types depending on the medium. Yb (Ytterbium) -doped lasers serve as another example within the solid-state laser category (Yalızay, 2011).

3. Laser Surface Treatment

Laser surface treatment is a significant technology for enhancing a range of material qualities, encompassing improvements in surface strength, hardness, roughness, coefficient of friction, chemical resistance, and corrosion resistance (Shukla & Lawrence, 2015). Material surface qualities are often improved by using laser surface treatment, which modifies a substrate's microstructure, phase composition, and topography. Conduction electrons in the surface area of a material absorb light when it is incident on it. Heat is produced quickly when these excited electrons hit the lattice ions. A layer larger than the typical beam absorption depth rapidly heats up because of the heat in this thin layer being transmitted to the bulk substrate. Heat transfer causes the material to cool when the laser beam is removed. Figure 3 shows the laser interaction with the material. This procedure provides an adaptable method to enhance the material surface characteristics in a controllable manner (W.M Steen & Powell, 1981).

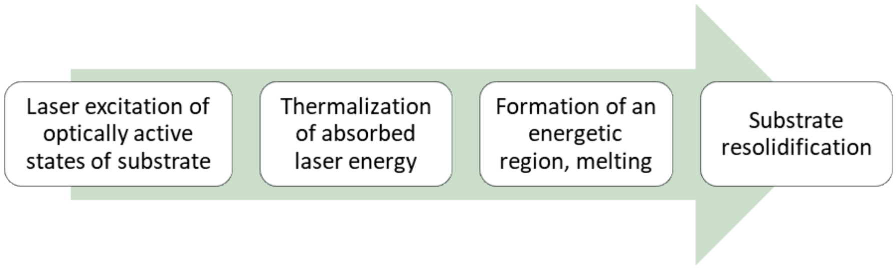

Figure 3. Laser material interaction.

Laser surface processing allows precise control of the final material properties by choosing appropriate laser parameters. This enables the design and optimization of processing procedures to achieve the best material functionality for the intended application. This technique includes various applications of laser surface heat treatment, such as non-melt laser annealing, laser surface melting, cladding, laser cleaning, hardening and laser surface texturing. These applications has various purposes, such as improving material surface properties, incorporating new materials, providing cleanliness, and enhancing tribological characteristics. Laser surface processing offers advantages such as precise control, cost-effectiveness, and flexibility compared with other methods (Etsion, 2004; Sugioka, Michael, & Pique, 2010).

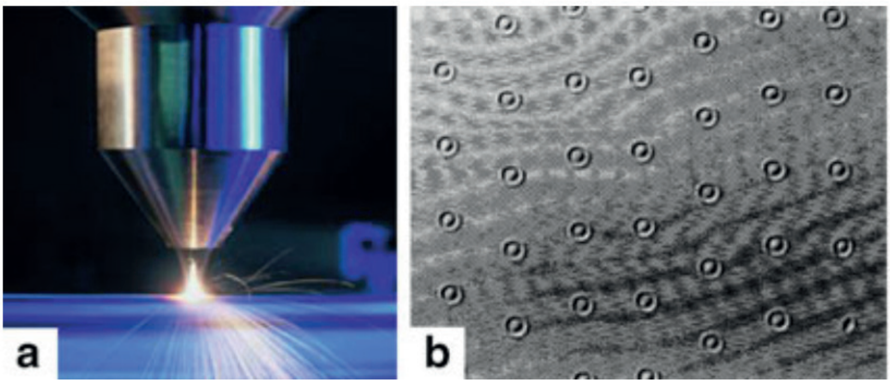

Figure 4. Example of (a) laser surface cladding and (b) laser surface texturing (Sugioka et al., 2010)

4. Laser Welding

Laser beam welding was first used in the 1970s, when lasers began to be used industrially (Wise, 2001). Laser welding is a high-power density fusion welding process and produces high aspect ratio welds with a lower heat input, compared to conventional arc welding techniques. It is a type of fusion welding. Furthermore, near-infrared solid-state laser beam transmission by fiber optics offers higher flexibility than other welding methods, and laser welding can be performed out of vacuum (Blackburn, 2012).

Laser welding is characterized by two different modes of operation: conduction and keyhole, as shown in Figure 5. The applied power density is the principal difference between the two modes. Conduction welding is associated with lower intensity and leads to melting of the material without causing boiling. In contrast, keyhole welding involves higher intensity, leading to vaporization of the material and formation of a keyhole in the molten pool. The conduction mode is suitable for scenarios characterized by lower material density, exhibiting a more superficial penetration depth. In contrast, the keyhole mode is well suited for applications involving higher material density and facilitates deeper penetration. The transition between these modes depends on factors such as laser power, welding speed and material properties. Precise control of these modes is essential for the optimization of laser welding and is compatible with the specific requirements of the materials and joints involved in the process (Assuncao, Williams, & Yapp, 2012; L Quintino & Assunção, 2013).

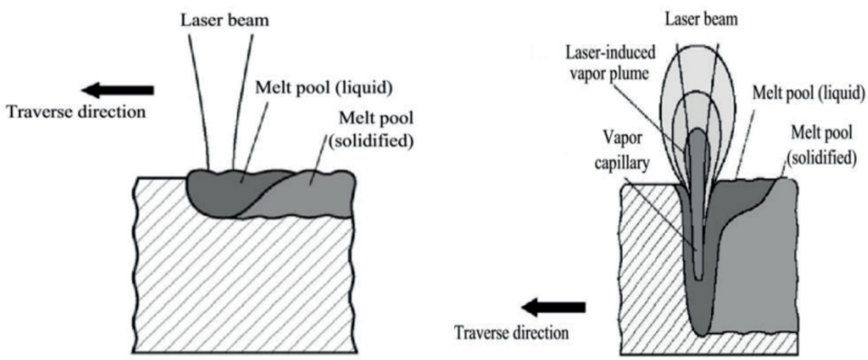

Figure 5. Laser welding modes: a) conduction welding and b) keyhole formation (Petring, Polzin, & Becker, 2007)

5. Laser Cutting

Laser cutting is an established and reliable technique for cutting various materials (Mahrle & Beyer, 2009). Laser cutting is one of the non-contact cutting technique based on thermal power processes. It is generally used for metals such as titanium, stainless steel, aluminium and aluminium alloys. Laser cutting is also applied to non-metallic materials such as wood, glass, plastic, ceramics and composites in various manufacturing industries (Naresh & Khatak, 2022). Three variations of laser cutting technology are currently recognized: inert-gas fusion cutting, reactive-gas fusion cutting, and vaporization cutting (W. Steen, 1998).

Industrial laser cutting performs the cutting process by focusing large amounts of energy on specific areas. This method generally uses laser cutting beams with diameters between 0.003 and 0.006 inches. During the cutting process, the high amount of heat produced by the laser melts or vaporizes the material in the work area. To remove the evaporated material resulting from the interaction of the laser beam with the workpiece protective gasses such as oxygen, CO_2, nitrogen or helium are used (Nedic, Milan, & Aleksijevic, 2016; Tahir & Rahim, 2016; Wardhana, Anam, Ogana, & Kurniawan, 2019).

Laser cutting offers numerous advantages, including its non-contact nature, high speed, and flexibility and ability to cut various materials with minimal waste (Sharma & Yadava, 2018). The process is computer-controlled, ensuring precision and reducing human intervention, while its low running costs and short setup times enhance efficiency. However, laser cutting has limitations such as restrictions on cutting reflective metals, heat exposure leading to a narrow heat-affected zone, and a relatively high initial capital cost (Anghel, Gupta, Mashamba, & Jen, 2018; Eltawahni, Benyounis, & Olabi, 2016; Gupta & Jain, 2013).

In machining, it is essential to determine the ideal cutting parameters based on the interaction of the insert, workpiece material and cutting parameters (Iynen, Sahinoğlu, Özdemir, & Yılmaz, 2020). Laser cutting is a complicated process that is controlled by many variables whose interactions are unpredictable. The parameters of the laser cutting process can be divided into three categories: used laser system, workpiece, and process parameters as shown in Figure 6 (Anghel, Gupta, & Jen, 2020).

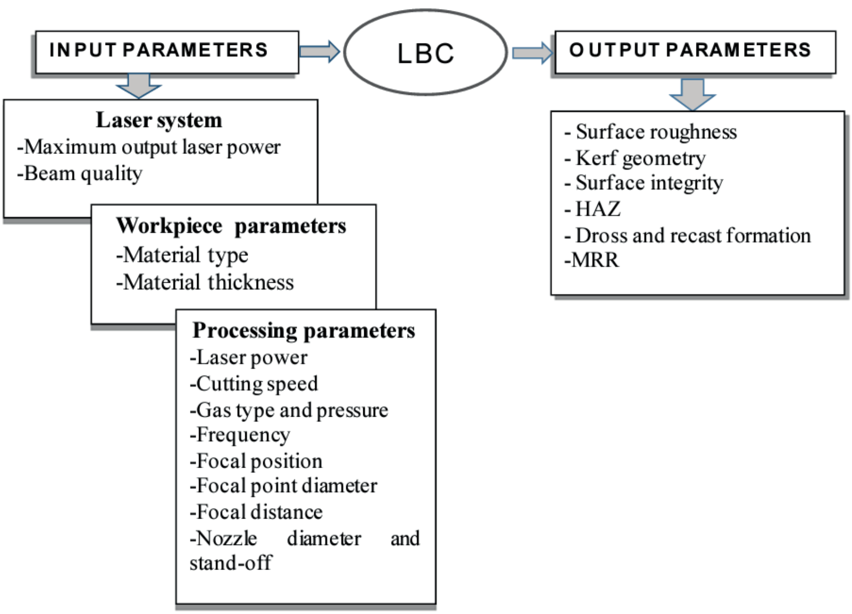

Figure 6. Laser cutting input and output parameters (Anghel et al., 2020).

6. Laser Drilling

Laser drilling is a non-contact unconventional machining process specifically designed for the precision machining of stiff and high-strength materials, including metal alloys, ceramics, composites, and superalloys. Conventional machining methods often struggle with the difficulty of working on these materials. Laser drilling addresses this challenge by offering the capability to create complex and precise holes that might be unattainable through traditional machining processes. Therefore, laser drilling has considered as a crucial technique for effectively machining such materials (Gautam & Pandey, 2018; Sarfraz, Shehab, Salonitis, & Suder, 2021)

Laser drilling is capable of drilling holes of any shape, regardless of the hardness of the material. Highlights of the advantages of laser drilling include the ability to drill holes in difficult-to-machine engineering materials, such as diamond, highly refractive metals, superalloy, ceramics and composites, without tool wear. In addition, this technique has the advantages of being able to produce high-quality holes with minimal spatter and splatter, drill holes of any size and shape, drill holes at different angles and have high drilling speeds. The combination of all these features makes laser drilling a cost-effective process (Dahotre & Harimkar, 2008; Nath, 2014; William M. Steen & Mazumder, 2010)

Laser drilling involves the process of melting or vaporizing material from the workpiece using a fixed high-power-density laser beam. Laser drilling is based on the energy balance between the energy of the laser beam delivered to the workpiece and the conductive heat to be delivered to the workpiece, as shown in Figure 7. Energy losses occur when the melting temperature of the material is reached, because of factors such as plasma formation and low material absorption. While the advantages of laser drilling include its thermal nature, high precision and fast processing speeds, its main limitations include the inability to produce step diameter holes and the lack of accurate depth control (Chryssolouris & Salonitis, 2012).

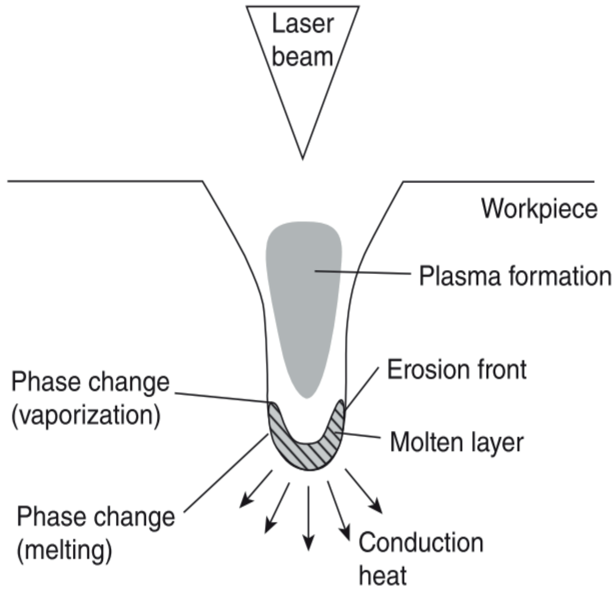

Figure 7. Basic principles of laser drilling (Chryssolouris, 1991).

There are several methods to perform laser drilling, including helical, percussion, single pulse, and trepanning drilling, as shown in Figure 8. Higher quality holes are often produced by helical and trenching drilling, although the drilling time is increased. Although percussion drilling has the benefit of faster drilling, the holes produced by this method are often of lower quality than those produced by trepanning (L. Li, 2010).

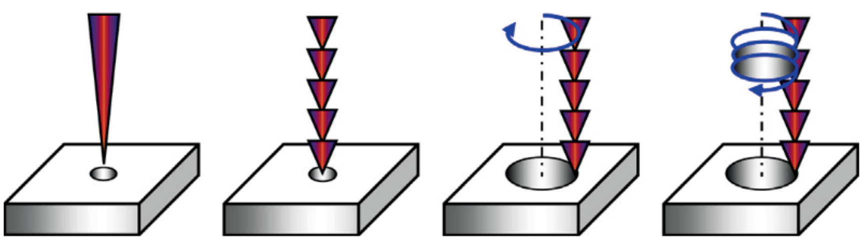

Figure 8. Laser drilling methods (Dausingera, Hügel, & Konov, 2003).

7. Laser Cladding

Laser coating is a leading production technology, finding applications in prototype development, repair, and manufacturing in diverse industries such as aerospace, automotive, defense, and medicine. Its widespread usage demonstrates its versatility and effectiveness in various fields (Dindar, Altay, & Aydın, 2021). This technology is a highly effective method for modifying material surfaces (Chen, Wu, Li, & Liu, 2019). The fundamental principle of this technology involves the direct penetration of metallic powder into the base material through melting. Metallic powder is transferred to the base material via a nozzle and material feeding system, with the simultaneous application of a laser beam to melt the metallic powders (X. Li et al., 2020).

Laser cladding is gaining increasing popularity in applications related to the repair and protection of material surfaces (Hemmati, Ocelík, & De Hosson, 2015). By applying laser cladding, a variety of surface alloys and composites with the necessary qualities can be produced (Shivamurthy, Kamaraj, Nagarajan, Shariff, & Padmanabham, 2012). This technique produces minimal heat input into the part, eliminates a large amount of distortion and reduces the need for post-machining. It also prevents the loss or hardening of the alloying elements of the base material (Luisa Quintino, 2014). In the laser coating process, the powder and substrate materials are heated, evaporated and chemically transformed by the laser beam, as shown in Figure 9.

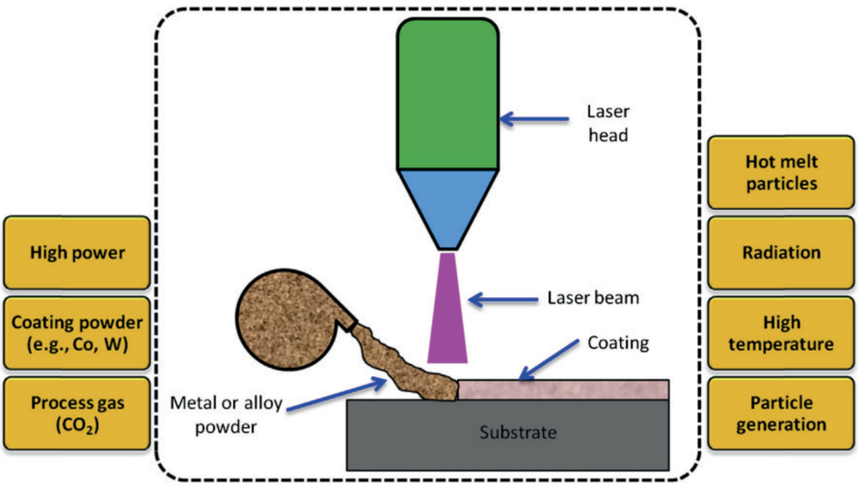

Figure 9. Laser Cladding (Rahman et al., 2014).

8. Conclusion

In conclusion, laser material processing technologies have become important in various industries because of the rapid expansion of laser applications and the decreasing cost of laser systems. With the wide acceptance of applications such as laser surface treatment, welding, cutting and drilling, new developments in laser technology have increased the potential applications of lasers in manufacturing industries, especially in the fields of additive manufacturing and micro/nanofabrication. Technological advances, such as ultrafast lasers, have enabled more precise and efficient processing and introduced new phenomena of beam-material interaction. The potential of the laser to direct energy in a repeatable, direct and tuneable manner makes it ideal for materials processing and enables processes that can be controlled by specific laser parameters.

Laser-related research is actively contributing to innovative manufacturing techniques aimed at improving product quality, designing multi-material components and improving economic and procedural benefits. The diversity of laser types and applications has led to various research efforts to investigate and optimize the effects of lasers on materials. The following conclusions can be drawn from this study:

- Laser surface treatment improves material properties such as strength, hardness and chemical resistance and offers a controllable method for improving surface characteristics.

- Laser welding provides flexibility and precision in joining materials with conduction and keyhole modes.

- Laser cutting, offers the advantages of non-contact processing, high speed and flexibility, while laser drilling addresses the challenges of effectively processing hard and high-strength materials.

- Laser cladding finds versatile applications in prototype development, repair and manufacturing, demonstrating its effectiveness in various industries.

- It is essential to set the appropriate laser parameters to achieve the expected mechanical properties of the laser-processed material.

- There are several studies in the literature that aim to investigate laser material interactions and will continue to do so as there are various parameters that affect laser material input.

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