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PLENARY REPORT

MODERN LASERS AND THEIR APPLICATIONS IN INDUSTRY

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Abstract

The laser is a universal tool for material processing in engineering. It can be used for cutting, welding, applying metal layers, locally hardening the surface of steel parts, and there are many other applications. A laser is a source of high energy density. Thanks to this, when the laser beam interacts with the material, different structural changes occur than we are used to from conventional technologies, for example, the phase composition or the distribution of residual stresses are different. The common advantages of laser treatment are minimal invasiveness and influence of the material around the treated area. It results in lower deformation, lower decrease of local mechanical properties, etc. In the article, conventional technologies are compared with laser technologies and the benefit is indicated in examples from engineering practice.

Keywords: laser, welding, cladding, hardening, surface, properties, microstructure.

INTRODUCTION

Laser technology is one of the fastest growing fields, especially thanks to new types of fiber, disc and diode lasers. At least 32 Nobel Prizes are associated with lasers. There is no doubt about dramatic growth of laser applications, as follow the literature. The prestigious magazine Fortune compiled a list of the fastest growing companies in 2013 [1]. On 9th place, right behind Apple, was IPG Photonics, the most important producer of fiber lasers on the world. Similarly, the number of professional publications is growing. New lasers have electrical efficiency several times higher compared to previous gas CO2 or solid-state Nd:YAG lasers. The quality of the beam is also improving, a few years ago it was not possible neither weld nor cut with diode lasers. Both are common today. The power of lasers is also growing practically exponentially – in 2005, diode lasers were around 1 kW (which is the lower limit for their application in industry). Today, they have outputs in the tens of kW, the most powerful fiber lasers are at 120kW. Such enormous power is enough to weld several tens of millimeters of steel or weld with speeds of over 40 m/min. The laser is therefore a high-quality and affordable tool, with a lot of benefits in applications.

The most frequently cited advantages of lasers are minimal deformation, little heat input, easy and precise power control, localization of the processing position, temperature control, and many others. Much less is said about universality. Regardless of which laser we have, the beam from the source is guided by an optical fiber (with the exception of CO2 lasers) whose diameter normally varies from 50 micrometers for cutting to 1 mm for welding. At the end of optical fiber transmitting beam is an optical head that allows the beam to be further modulated. In this contribution, we want to introduce the laser as an universal tool for a number of technologies. A beam with the smallest diameter of around 0.1mm is used for cutting. All the energy is focused into a small point, which allows melting and vaporization of the material [2]. The extension to a larger diameter (standard between 0.5 to 1 mm) is adjusted for welding. The areal energy density is in the order of tens of kilowatts per square millimeter. A further increase in the cross-section of the beam spot to a few millimeters square is intended for cladding, when the part of energy must be sufficient to melt the supplied powder and part remelt the coated surface to make metallic bond. A further increase in the area of the beam spot is used for surface hardening, when a surface temperature of above 1000°C is sufficient for austenitizing and subsequent phase hardening of the steels.

Fig. 1. *Laser material processing workplace on University of West Bohemia (UWB)*

For the above-mentioned reasons, laser technologies are an interesting topic for mechanical engineering. The interaction of the laser beam with the material brings new knowledge about metallurgy and phase transformations associated with high heating and cooling rates to create non-equilibrium structures and giving to materials new properties. That is why the Department of Materials and Engineering Metallurgy at UWB is dedicated to the development of new technologies and laser material processes (see Fig. 1) as a part both of study programs and research projects.

LASER HARDENING

Laser hardening offers short processing times and appreciable cost savings, as well as capabilities to accommodate almost any geometry, and control the depths and widths of the treated surfaces. In addition, laser processed surfaces exhibit additional beneficial properties when compared to conventionally hardened surfaces. These include improvement in tribological, fatigue, and corrosion behavior, specifically an improved wear life, fatigue and corrosion resistance [3, 4].

Sheet forming dies for automotive industry (Fig. 2) may serve as a good example in this context. The car body consists of about 300 components, which represent a demand for about 750 pairs of press dies (progressive dies, punching and trimming dies). Car manufacturers launch about 120 new car models every year. Based on that number, the cost estimate for die making is 12 billion euro every year. Laser hardening of rounded and shearing edges may double the number of parts formed.

Differences in surface hardening technologies

In ***flame hardening***, the depth of heating is given by the relative speed of the flame movement across the surface. The efficiency of heat transfer to the material is poor and the surrounding surfaces become heated as well. As a result, the dwell time required for austenitizing increases, the grains in the material coarsen, and their boundaries may become burnt. The surface also develops a layer of oxides. In this process, the uniformity and control of temperature are limited and inaccurate. In **induction hardening**, the heat generated depends on electric resistance and current. The depth of austenitizing is given by the frequency of the power source. The lower the frequency, the shallower is the hardening depth. Even with high-frequency induction heating, however, heating takes several seconds.

In **flame hardening**, as well as in **induction hardening**, the heating stage must be followed by sufficiently rapid cooling (using a water spray or polymer solution). There is an ever-present risk that steam and a vapor blanket may form during cooling, which would retard the heat removal rate and prevent the surface from hardening. Similar to the heat-affected zone in weld joints, there is a deep transition zone beneath the hardened layer. This is the zone in which the elevated temperature, though insufficient for hardening, has caused some changes in the matrix of the parent metal. Unfortunately, these changes are typically for the worse.

In ***laser treatment***, the austenitizing temperature must be achieved in the surface, as with the other techniques. However, thanks to rapid heating rates of thousands of degrees per second, the resulting transitional heat-affected zone is very thin. The advantage of laser hardening lies in its ability to alter the microstructure, properties and residual stresses in a workpiece within a localized area. The nature of the laser beam allows even difficult-to-reach locations to be locally hardened within relatively short process times [3, 4]. Thanks to a rather small size of the spot being hardened at any given moment, the surrounding material acts as a cooler, thus eliminating the need for external cooling media. Laser hardening is characterized by high cooling rates reaching up to 1000 K/s [5]. Some researchers [6] report cooling rates as high as 10^4 to 10^8 K/s and thermal gradients between 10^5 and 10^8 K/m. At such values, metastable microstructures with novel properties are obtained. If cooling rates reach the above-mentioned high levels, almost all austenite in steel transforms to martensite. In addition, the growth of crystallites within polycrystalline materials is severely limited during laser hardening [7].

The maximum laser hardened depth is approximately 2 mm, depending on the heat conductivity of the material. The hardening depth can be controlled by the speed of the beam movement and by the temperature. To improve control, the process is typically monitored using a pyrometer linked to the laser source and operated by robot. By regulating the power input, this control loop can maintain a fixed surface temperature, thus providing uniform hardness and preventing local melting.

In the heating step, austenitizing temperature, that is, a temperature above Ac3, must be achieved in the surface layer of steel. Rapid heating with a laser beam is one of the factors which minimize the distortion of the part heated. As the material around the laser spot remains cold, it does not expand, and the distortion does not occur. Another difference from the other surface hardening techniques lies in the heat removal mechanism which is based on self-quenching. It involves rates of several thousand °C/sec. There is no need for cooling the surface using a liquid supplied from outside because the interior of the part remains cold and absorbs the heat by conduction at a sufficient rate (i.e., cooling by convection). One can therefore assume that phase transformation begins from within the part and the surface is the last to cool down. It has at least one major effect - laser beam hardening is much more favorable to the material in terms of crack susceptibility than other techniques. The steep thermal gradient from quenching causes severe (tensile) stresses which lead to surface crack initiation. In laser hardening, however, the cooling process begins by heat removal to the cold interior of the workpiece. The temperatures thus equalize gradually from within the part. This minimizes the resulting stresses and eliminates cracking.

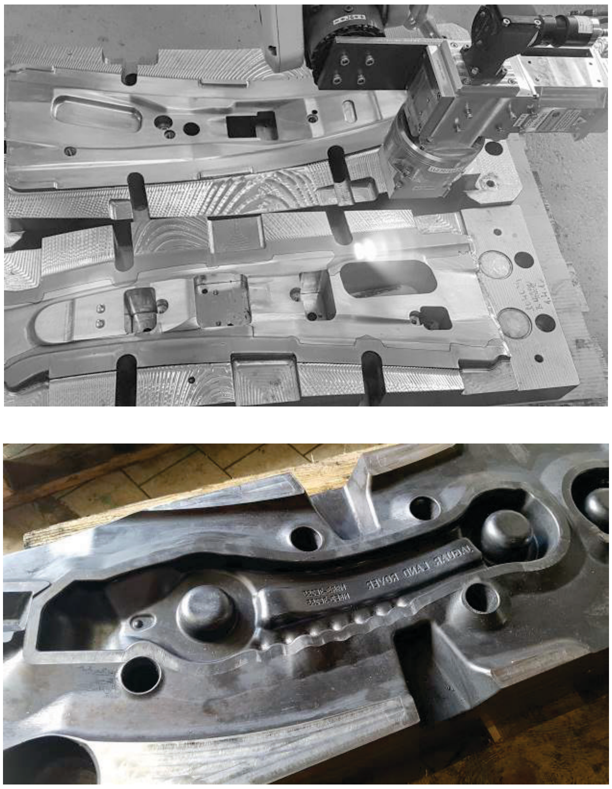

Fig. 2. A typical example of forming tools processing. Laser hardening can increase service life by up to 50%.

LASER CLADDING

The surface can be thought of as the most important part of every engineering component. Unlike the rest of the component's volume, the surface is exposed to wear and becomes the place where most cracks form and corrosion initiates. The surface's particular properties are dictated by its non-symmetric bonds. Whereas the neighborhoods of atoms within the material and their bonds with neighboring atoms are symmetric, the atoms on the surface are only bonded with the interior of the body. In terms of surface-altering techniques, perhaps the greatest rival of the laser cladding process is the ***high-velocity oxyfuel spraying process*** (HVOF). Fundamental differences between these processes arise from their different principles. Laser claddings are metallurgically bonded to the substrate. It means that some mixing of the substrate with the cladding material occurs. This provides high adhesion of the cladding layer. Coatings deposited by the HVOF process do not undergo such dilution and are only bonded through limited diffusion between the materials. The advantage of HVOF is that it produces coatings with compressive stress, unlike other thermally sprayed coating processes. ***Plasma transfer arc*** is one of the most frequently used weld cladding processes. Its relatively large power density, however, alters the substrate surface to the depth of several millimeters. In ***laser cladding*** (Fig. 3), the energy of the laser beam continues to have effect even at the moment the molten powder adheres to the substrate. The resulting layers are therefore dense with practically zero porosity. By contrast, HVOF coatings show high porosity and fail to provide corrosion protection. Once the molten powder impinges on the surface, no additional energy is supplied or available to facilitate perfect bonding of the molten particles and the substrate.

Over the last four years, the price of laser cladding services dropped to half and the process is becoming ever more widespread in industry. Today, the main applications are in the field of repair of forming molds and dies, the mining industry or turbine blades.

Additive manufacturing (AM) is one of most popular technologies of today. The laser also plays a major role in the production of metal parts with this technology. Both in the case of the SLM method (selective laser melting) and in the case of DLMD (direct laser metal deposition, Fig. 4), metal powder is sintered using a laser beam, as the name of both technologies implies [8,9]. Layer by layer is applied gradually until a new part is created. Basically, it is just an extension of laser cladding to a 3D dimension.

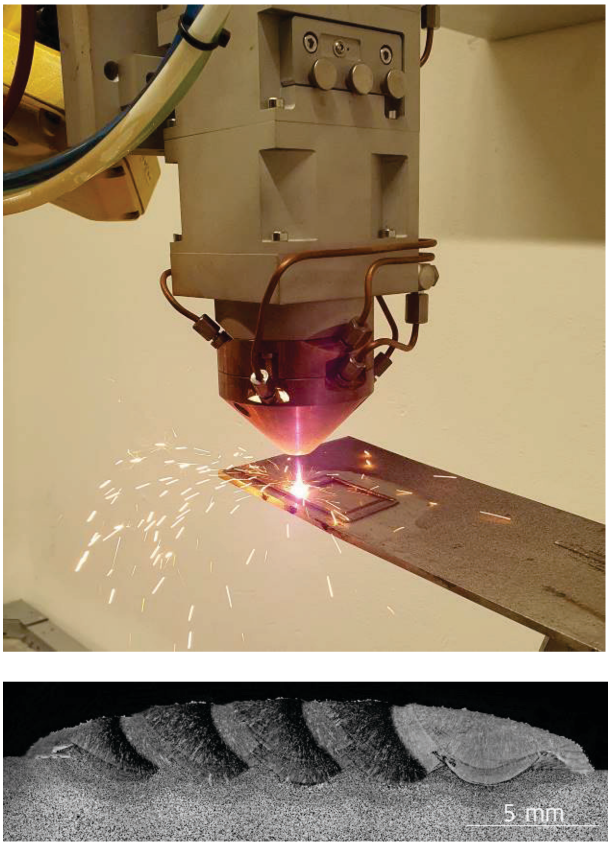

Fig. 3. *Laser cladding process (above) and cross section of the cladded layer (below)*

Fig. 4. *Additively manufactured functional mold for aluminum die casting with internal channel structure*

LASER WELDING

The main advantages of laser welding are low heat input and a different joint geometry. The energy of the laser beam is up to 4 orders of magnitude higher than that of arc methods, and the heat input is therefore several times smaller. Less heat in the join means less impact on the weld's surroundings, finer structure, less deformation and lower residual stresses. The different geometry of the joint (Fig.5), i.e. the ratio between the width and depth of the weld, brings additional profit with regard to deformations and process productivity. An example, susceptibility of stainless steels to intergranular corrosion increases, when staying at critical temperatures (around 450°C, 570°C and 600°C) after a time of more than 0,7 seconds, reaching the maximum with a delay longer than 2 seconds. When welding run at speeds above 2m/min, sufficient cooling speed (depending also on wall thickness) can leads to 2-3 times higher corrosion resistance of laser stainless steel welds compared to classic ones [10].

Faster cooling speed leads to the formation of non-equilibrium structures and a different phase composition than we are used to, resulting also to different mechanical properties [11]. High-strength steels are specific to their fine-grained and multiphase structure. Therefore, the arc fusion welding techniques these properties significantly degrade and welding methods must be properly improved, especially in terms of the heat input. One of the most appropriate ways is laser or electron beam welding. Although laser welding is mainly introduced in series production, thanks to the availability of technology and falling production costs, it is increasingly used in small-series and piece production.

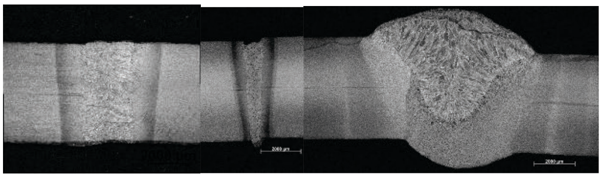

Fig. 5. *Laser (left), electron (middle) and arc (right) welds on 5mm plate from S355 steel grade*

CONCLUSION

We can list dozens of other applications of lasers in engineering production. From the main applications most often used in industrial production listed above, it is clear that even in these areas there are many unexplored places for research and development. There is also huge scope and potential in the search for the development and new applications of laser technologies in industry.

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