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Customized laser beam intensity distribution for the laser surface treatment of geometrically convoluted components

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ABSTRACT

The Laser Surface Hardening Process of real components must achieve a uniform hardened profile to get constant mechanical properties and must deal with the energy distribution in the proximities of geometrical singularities to prevent them from overheating. Classical approaches like the overlapped laser tracks or uniform beams by fixed optical arrangements introduce the problems of annealing and lack dynamic adaptability capability, respectively. The present work uses a galvanometric scanner to get a user-defined laser intensity distribution, by iteratively scan a flat pattern, capable of creating uniform hardened profiles and dynamically adapting in real time to handle geometrical singularities. The experimental setup to obtain it and its characteristics as a function of the scanning frequency of the flat pattern are presented. Experimental results were obtained in crankshafts of automotive engines achieving uniform hardened profiles and good surface finish around the geometrical singularities.

1. Introduction

In the Laser Surface Hardening of medium to high carbon steels, a laser beam, with appropriate characteristics, traverses the surface of the material raising locally the temperature above the critical temperatures provided by the equilibrium diagram and below its melting point. Once the laser beam has passed, a fast self-quenching of the treated regions happens due to the high thermal conductivity of metals. The overall thermal cycle results in a martensitic micro-structure up to 3 mm under the treated surface, associated with a higher hardness than the initial ferritic-perlitic micro-structure, as it is explained in Ion's book (2005) considering the main parameters of the process. It improves the resistance of the treated components for wear, with interesting applications in the automotive engine components, such as the crankshaft or the valves, as Slatter et al. (2009) detail in their study about laser hardening of automotive components.

The Laser Surface Hardening process for steel components in industrial applications must fulfill three major requirements according with the review of Kennedy et al. (2004) focused on high power diode lasers. Firstly, uniformity of the martensitic transformation profile under the treated surface to get constant mechanical properties along and across it. Secondly, capability to prevent geometrical singularities being overheated until melting, since real components may have sharp edges or holes, with a lack of bulk material around them for the heat to diffuse. Thirdly, short cycle time for the sake of productivity. The design, optical handling and dynamic control of the laser beam play a crucial role in the fulfillment of the three established requirements, in combination with the proper selection of the process parameters, as Cordovilla et al. (2015) highlight showing the influence of the heating rate on the austenite formation and on the development of an oxide absorptive layer.

The use of gaussian or top-hat beams, as they are provided naturally by the typical laser equipment, is limited by their size (diameter of several millimeters) in comparison with the extension of the surface in which a real component may need to be treated. The overlapping of laser tracks to cover wide extensions is studied by García-Beltrán et al., (2007) based on the critical equilibrium diagram or by Lakhkar et al. (2008) considering the diffusion of the carbon. Despite having the capability to cover large extensions and adapt to the geometry of the treated part, this procedure limits the productivity of the process and introduces the annealing between consecutive tracks as a very harmful problem against the uniformity of the transformation profile as it is shown by Cordovilla et al. (2016), where the physical limitations of the overlapped process are highlighted.

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Optical elements are applied to modify the shape, size, and, in turn, the energy distribution of the laser beam. The work developed by Martínez et al. (2016) proposes a scanner system to get the laser beam controlled by information generated by numerical simulation. The work by Bayer et al. (2008) presents a line-shaped laser beam from high power diode lasers, with applications in industrial processes. The achievement of a narrow line with uniform energy intensity can be associated, using proper process parameters, with a uniform hardened profile. Unfortunately, this system does not have the capability to tune the laser intensity along the line, lacking, consequently, adaptability to geometrical singularities, as for instance, a region with different thicknesses under the path of the line, and therefore, different heat diffusion conditions. In the work of Laskin and Laskin (2011), again, the focus on the uniformity leads to a fixed setup and a fixed geometry for the laser beam without capability to get either dynamic adaptability or specific thermal cycles for the hardening process.

The work of Leung et al. (2007) combines the thermal analysis with a Diffractive Optical Kinoform to get a Customized Laser Beam. The energy density within it is adapted to the characteristic thermal cycles of the Laser Surface Hardening Process, surpassing the capabilities of uniform beams, but, lacking still dynamic adaptability capability. In the reference of Hagino et al. (2010) in the same way, the laser radiation from the source is driven across a Computer-Generated Hologram to obtain another fixed customized energy distribution for Surface Laser Hardening, aimed at obtaining proper thermal cycles.

Galvanometric scanner technology is available to adapt the characteristics of the laser-material interaction to the specific requirements of different processes under the philosophy of the beam-shaping theory. The work developed by Pütsch et al. (2016) uses scanner technology to locally correct the defocusing of the laser beam due to its projection along curved surfaces in the treatment of complex geometries. The reference of Goppold et al. (2016) uses high-frequency scanning to make the laser beam describe different Lissajous figures. The performance of the figures is experimentally studied for the Laser Cutting process showing advantages over the capabilities of the processes based on conventional beams.

Considering the advantageous characteristics of scanner technology, this work introduces an innovative procedure for beam shaping, enabling the user or the designer of the Laser Surface Hardening Process to achieve high uniformity of the hardened profile, a suitable handling of the geometrical singularities with lack of thermal diffusivity to prevent the melting of the treated regions and the consequent dimensional distortion, and high productivity of the process.

The proposed methodology is based on the galvanometric scanner with two mirrors. It allows for scanning iteratively and with relatively high frequency a user pre-defined pattern projected onto the treated material, by properly driving the beam as it is released from the laser source. If the scanning frequency is high enough, there is no significant cooling between consecutive iterations, thanks to the thermal inertia of the material, and the resulting effect is equivalent, from a thermal point of view, to a constant laser beam, called Equivalent Laser Power Density Distribution, hereafter ELPDD. The shape of the pre-defined flat pattern, which has no theoretical limitations, and the scanning speed in its different sections determines the final energy distribution, which can be dynamically adapted according to the needs in association with software controlling the rotation axes of the galvanometric mirrors of the scanner.

The present work introduces the experimental procedure to build an ELPDD from the original beam as it is released by the laser equipment. The characteristics of the ELPDD are analyzed and the thermal inertia of the treated material is studied as a conditioning factor for the minimum scanning frequency to scan the user-defined pattern. Optimized ELPDD are used for the Laser Surface Hardening Process of real parts, leading to uniform transformation profiles without overheating the critical regions.

2. Material and experimental procedure

The AISI 4140 steel with a normalized microstructure (ferrite + perlite) has been selected as working material for the Laser Surface Hardening tests. This steel is widely used in industrial machinery, as can be seen in the study of Azpeitia et al. (2015), where the microstructure of hardened crankshafts is studied. Its carbon content, around 0.4% wt, ensures a high capability to experiment an increase of hardness as a consequence of the Laser Surface Hardening Process.

The experimental procedure in this work results from the combination of three different approaches: the optical arrangement to handle the original beam from the laser source to obtain an ELPDD is presented. It results from iteratively scanning a user-predefined flat pattern. Secondly, an experimental arrangement is built to determine the minimum iteration frequency to obtain an effective ELPDD from a thermal point of view. A threshold value is derived from the experiments. Finally, the experimental setup for laser hardening tests is presented.

2.1. Optical arrangement to obtain an ELPDD

The laser source used in all the experiments is an IPG Fiber laser with a maximum output power of 6 kW releasing radiation at wavelength of 1075 ± 5 nm. It generates a gaussian beam with a characteristic diameter between 1.5 mm – 3 mm which is transferred, by means of optical fiber or directly from the output of the laser resonator, to a scanner with two galvanometric mirrors which finally project the laser beam onto the treated material. The angle of each mirror with respect to its rotation axis determines the orientation of the outgoing laser beam, while the distance to the treated surface determines the focus. The low inertia and quick response of the servomotors commanding the mirrors is associated with a fast and accurate rotation of them (weight about 40 g, rotor inertia around 0.12 g cm^2, speed in the definition of complex features, such as corners, 2.5 m/s, maximum speed 6 m/s, repeatability < 2 μrad). These features, in combination with the projection of the laser beam on the surface of the material, at a certain distance, allow long distances to be covered in an extremely short time and, if closed loops are described, get equivalent shapes over the scanned pattern. Fig. 1 shows a diagram of the experimental system.

In the design of the ELPDD the most important step is the definition of the flat geometrical pattern along which the galvanometric mirrors must drive the beam that comes from the laser source. This pattern is normally constituted by several paths with specific scanning speed, to adjust the amount of energy provided by the resulting ELPDD at every point of it. The software that controls the servomotors of the scanner uses this information to calculate the combined rotation of the two galvanometric mirrors. The most suitable ELPDD for a given process can be estimated by thermal analysis as it is done in the study of Yanez et al. (2002), for complex geometries or by Skvarenina and Shin (2006) where the evolution of the micro-structure is calculated. Fig. 2 shows two examples of flat geometrical patterns, made of several paths, and the resulting ELPDD, by iteratively scanning them with a prescribed speed for each path. Note that each ELPDD is presented as an irradiance distribution. The mathematical equivalence between the energy distribution of both, the beam from the laser source and the ELPDD, is developed in Section 3.

In the upper part of Fig. 2 the original gaussian beam from the laser source is driven throughout a triangular shape pattern. In the lower part of Fig. 2 a more complex pattern made of five paths is proposed. While any closed pattern can be scanned either clockwise or counterclockwise, in the case of open patterns, such as Fig. 2 bottom, the direction of scanning has to be changed consecutively at each iteration. It does not affect the equivalent irradiance obtained, since it results from a deterministic calculation and the scanner system fits the scanning speed almost instantaneously.

Once a pattern is defined, as the result of several paths traveled