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Research Paper

Control loop tuning by thermal simulation applied to the laser transformation hardening with scanning optics process

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HIGHLIGHTS

- Laser transformation hardening with scanning optics (LTHS) is a novel manufacturing process.
- A close loop temperature control for LTHS process has been developed.
- The control constants have been tuned by means of numerical thermal simulations.
- The developed method has been validated by comparing real and simulated results.
- Complex parts for the automotive industry have been hardened with the developed system.

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ABSTRACT

Laser transformation hardening with scanning optics (LTHS) is a novel manufacturing process on a very preliminary stage of introducing it in the surface treatment industry. The key to ensure the success in this process is the control of the process temperature. Thus, in this article, a close loop temperature control for LTHS process has been developed, tuned and tested in complex parts. On the one hand a PID temperature control has been implemented in a laser machine-tool. On the other hand, the same temperature control has been programmed in a numerical simulation software for LTHS process. In order to minimize experimental work, by means of using a novel method, the control constants have been tuned by means of thermal simulations. This method has been validated by comparing the results of the variation of different parameters in both cases, real and simulated. To complete the work, as the last test of the developed temperature control, different complex parts representing hardened parts for the automotive industry have been hardened with the developed system.

1. Introduction

Laser transformation hardening (LTH) is a process based on a controlled heating and a later cooling of the surface, achieving a metallurgic transformation on the surface of the part. The heat source is a high power laser, since it is one of the most selective and controllable heat sources in the industry. The result of the process is the enhancement of the mechanical properties of the material, ensuring a higher wear resistance and an improved fatigue life creating a hardened and a compressive residual stresses layer in the surface [1]. Monitoring the process is essential since the temperature on the surface must be always below the melting point but higher than the transformation temperature. The temperature control also becomes a difficult task due to the interdependence of the mechanical properties, the microstructure and the temperature field in the process. This relationship is called Metallo-Thermo-Mechanical coupling and a deeper study of the effects can be found in Ref, 2. Thus, Yislab et al. [3] although study the interdependence between the temperature field and thermal stress field during a laser process.

The introduction of a control algorithm on the temperature enables the automation of the LTH process as the material has the proper metallurgical distribution and adequate mechanical properties, regardless the geometry or the material of the part. One of the main objectives for controlling the temperature of the process is the necessity of adjusting the parameters of the process to unexpected conditions, such as variation in roughness or geometry. If the laser power is set constant, the temperature could vary significantly near part corners or edges. Sometimes to avoid this effect a thermal camera is needed. Laser hardening process is used in the industry for surface hardening of small parts, bearing and ball screw races, die and molds, etc. All these applications need a passive or active temperature control in order to maintain the same treated area properties regardless the geometry of the part. Seifter et al. [4] calibrate temperature measurement devices for laser heat treatments.

Laser hardening process is gaining industrial interests in the last years, since it is possible to process complex 3D shapes with a

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minimum heat affected zone and thermal distortions in comparison with more traditional hardening techniques. Propawe in Ref. 5 shows equipment requirements and different applications of laser hardening process.

Furthermore, in recent years a series of systems based on moving optics for guiding high power lasers are being developed and industrialized. These systems are also called scanners and they are usually coupled to the wrist of a serial robot [6] or in the spindle of a machine tool [7]. The main characteristic of the scanners is the ability to move and guide the laser beam with very high accuracy and speeds (above 10,000 mm/s). The agility of the movements is obtained by the rotation of two mirrors with very low mass and inertia. Thus, these rotations are converted into very fast linear movements in the part, corresponding with X and Y axes. In Fig. 1a a 2D scanner scheme is shown. The main advantage of scanners is the high processing speed and the working distance, which use to be far from the area to be processed, being able to process difficult-to-access zones maintaining the quality of the laser beam. Díaz-Tena et al. [8] use an industrial high power laser beam with scanning optics to provide a rapid and free form engraving on a resin mask without affecting the specimen surface.

At the present, there are several emerging industrial processes based on the use of scanners in different manufacturing areas, particularly in the automotive industry, such as remote laser welding or large areas marking with moving scanner optics. Gradually these systems are being introduced in other industrial sectors such as the die and mold manufacturing industry where laser remote processes are being applied for texturing [9], polishing [10] or drilling [11]. In contrast, remote treatment processes development are still on a very preliminary stage, with some research performed to evaluate the process capabilities [12,13].

As it can be observed in Fig. 1b, laser transformation hardening with scanning optics process (LTHS) presents a combination of two speeds: the scanning speed and the machine feed rate. The characteristic parameter of this process is the scanning speed (V_S), usually measured in mm/s representing the guiding speed of the laser beam. This speed needs to be very fast, since the treated area is defined by this laser sweep, therefore V_S is controlled by the mirrors of the scanner and it can reach up to 10,000 mm/s. Furthermore there is a feed rate (V_F), measured in mm/min, which is the federate motion of the robot or machine tool and represents the speed of the laser sweep line translation.

In addition, the interest of laser hardening process lies in the possibility of direct integration of a very flexible laser heat source on the production line without a quenching medium, as well as the possibility to produce different microstructures in the part getting a soft core with a hardened surface layer with compressive residual stresses. During laser hardening process fixed optics are needed to find the optimal intensity distributions of the transformed laser beam that could produce the target transient temperature fields in the part. In Ref. 14 a laser Gaussian beam was transformed into concentric multi-circular patterns by means of a high cost diffractive fixed optic to produce a shaped thermal load. However, LTHS process presents the same advantages than laser hardening but the optics can be programmed to different track widths. In addition, solid state lasers such as fiber or disk lasers can be used for hardening while conventional laser hardening is only performed with direct diode lasers.

One of the most relevant aspects on LTHS is the in-process temperature control requirement. The process temperature must be verified during the whole process in order to avoid surface melting. The temperature control becomes harder if the laser beam moves rapidly, so the tuning of the temperature control loop is one of the most challenging aspects on the LTHS process. In all the implemented controls a non-contact temperature measurement technique is used, such as pyrometers or thermographic cameras. Purtonen et al. [15] review the different sensors used for monitoring laser processes.

The main advantage of the pyrometers is their rapid response as well as the capability of not interfering in the process. There are several types of pyrometers, being ratio pyrometer (also known as 2-color-pyrometer) one of the most widely used for laser surface treatment processes. These pyrometers measure IR radiation at two different wavelengths and by doing so the temperature becomes independent of the emissivity of the object. The main drawback of the pyrometers for laser surface treatment processes is that measure of the temperature is limited to a single point. For a continuous temperature measurement in the treated area, thermographic cameras

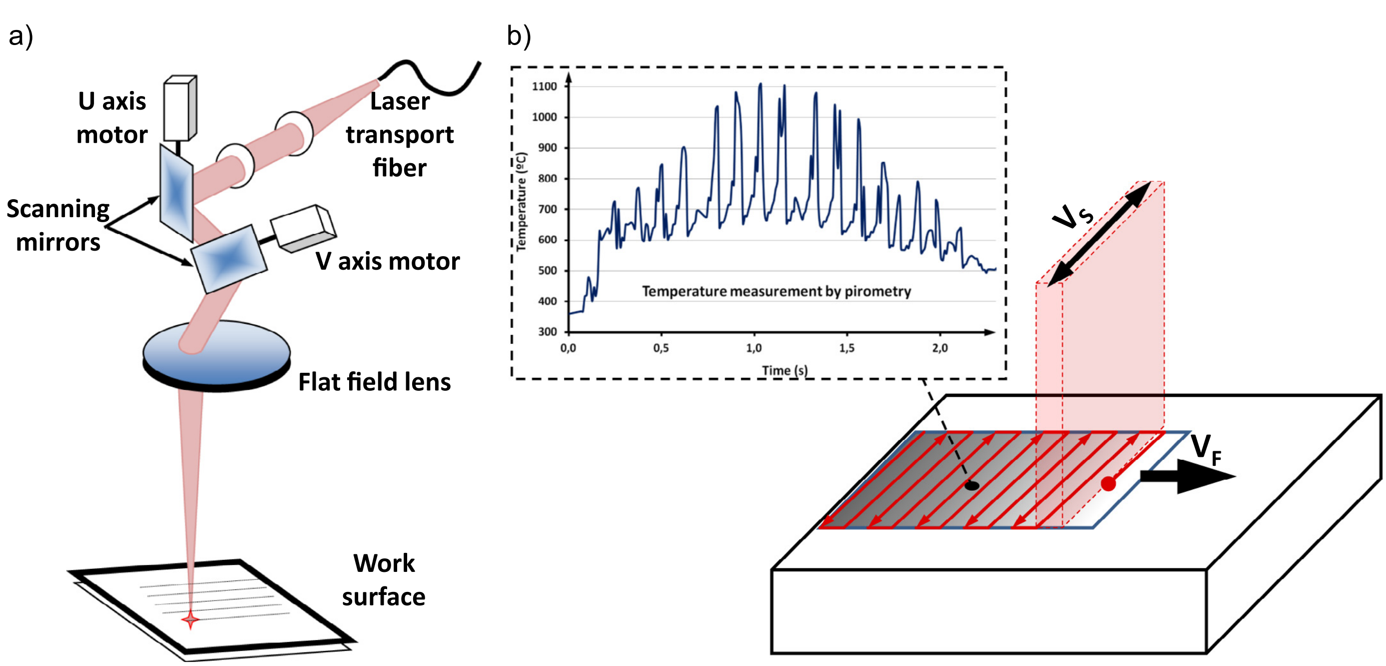

Fig. 1. (a) A 2D scanner components; (b) thermal field generated in a part point.