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Discrete spot laser hardening and remelting with a high-brilliance source for surface structuring of a hypereutectoid steel

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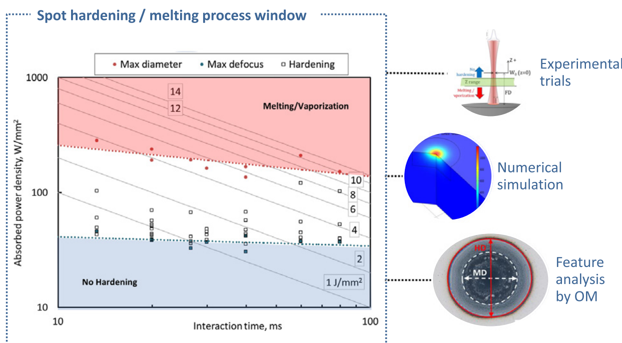
HIGHLIGHTS

- Process windows for spot hardening and melting determined
- Diameter and depth of the laser treated region numerically and experimentally evaluated
- Key parameters for the simulation evaluated fitting experimental data.
- The proposed tuning procedure based on multi-objective optimization revealed effective.
- The fabrication of bio-mimetic surfaces is possible implementing the process maps.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work the single-pulse laser irradiation of a hypereutectoid steel was investigated using a fiber laser source, in a range of process parameters enabling surface hardening and remelting. Effects of laser power, pulse energy and defocusing distance were investigated using a numerical/experimental approach. Laser surface treatments were conducted on uncoated samples without any gas shielding, changing both the laser power and the pulse energy, and exploring a wide range of defocusing distances. Numerical simulations were conducted using a finite element model calibrated by means of an optimization procedure based on a specific calculation algorithm and using a subset of experimental data producing surface melting. Using both simulations and experiments, the process operating windows of the discrete spot laser treatment were determined: it was found that, when varying the laser power between 250 W and 750 W, melt-free hardened zones are produced with a maximum extension between 0.7 mm and 1.0 mm; on the contrary, in case of more tightly beam focusing conditions, surface melting occurred with a size of the re-melted areas ranging between 1.0 mm and 1.4 mm. Results further showed that a small change (generally 2–3 mm) of the defocusing distance suddenly brings the material from melting to a non-hardening condition.

1. Introduction

Laser technology allows autogenous and selective treatment of discrete and well-defined surface areas which acquire, after the laser

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Table 1
Chemical composition of the investigated alloy (AISI/SAE 52100).

C	Si	Mn	Cr	P	S	Mo
0.93–1.05	0.15–0.35	0.25–0.45	1.35–1.80	<0.025	<0.015	<0.10

process, special properties like e.g. increased hardness, wear-resistance and fatigue strength.

Generally, a laser surface treatment process consists of scanning a continuous wave laser beam, with definite spatial intensity profile, across the area to be treated. The absorbed laser energy determines a rapid heating of a thin surface layer followed by an abrupt cooling due to thermal conduction into the substrate. In particular, laser hardening is very useful to induce martensitic transformation on ferrous alloys with controlled hardness, width and shape of the treated zone, without employing any quenching media [1]. High power diode lasers are usually preferred to CO_2 and Nd:YAG laser sources for this kind of applications thanks to the lower investment cost, the better absorbed wavelength and the more evenly distributed beam intensity profile.

One of the main drawbacks of such a laser surface treatment is that, when multiple passes are required to treat larger areas, an undesired "back tempering" of the overlapping zone between adjacent paths is determined. In addition, the resulting hardness profile is not homogeneous across the scanned path, especially if a beam spot with energy unevenly distributed across its area is adopted. In order to limit such problems, rectangular shaped beam spots, with a Gaussian intensity distribution in the scan direction and top-hat in the transverse one, are usually preferred [2]; beam shaping lenses and/or diffractive optical elements have allowed to spatially and exactly tailor the contour avoiding the presence of the overlapping region. This approach has been also employed to treat small areas with complex geometries, such as the ring-shaped valve seats [3]. On the other hand, when large areas have to be treated, a matrix of non-overlapping laser treated zones over the workpiece surface can be created, using single laser pulses: in such a way a regular pattern of irradiated discrete spots is obtained [4,5].

Although the process is more complicated because new variables are introduced, like e.g. the spot shape (e.g. stripes, single spots) and the portion of irradiated area, as well as the distance between adjacent treated zones [6,7], this approach prevents the back tempering effect and brings new features to the laser treated area. Sorgente et al. [8] investigated the laser surface hardening produced by a single pulse out of a fiber laser source. The dimensions of the hardened zone and its hardness were then acquired and related to the laser pulse energy and power, to the microstructure of the material in the as received condition and to the roughness on the specimen before the laser treatment. Paczkowska [9] distinguished ranges of laser beam parameters that could be useful in selecting the type of laser heat treatment of gray iron, i.e. remelting, alloying, hardening from the solid state, tempering the surface layer. Some overlaps of the process windows were found which were ascribed to differences in thermo-physical properties between types of investigated gray irons or differences of the surface absorption radiation coefficient.

Tailoring the type of surface modification according to a local set of laser process parameters allows developing artificial structures possessing characteristics similar to some well-known biological systems (bio-mimetics). For example, studying the cuticle of some insects, a surface structure was recognized consisting of a matrix embedded with units of different microstructure [10]. Such a combination was found to enhance the ductility, mechanical strength and wear resistance of the cuticle. This has led some research groups to reproduce such structures on metal workpieces by alternating laser hardened or laser melted areas to untreated ones. The laser modified zones, also called bionic units, which generally cover up to 20–30% of the overall surface, are characterised by a higher hardness originated by the martensitic transformation or, in case of re-melting, by the grain refinement; while the remaining part of the untreated surface acts as the ductile matrix. The tensile properties of such biomimetic samples have been investigated finding that the reinforcement units determine a redistribution of stresses which results in a delay of necking and a significant increase of ductility and strength [11]; in addition, tests revealed that biomimetic samples possess an improved wear resistance, which might be exploited to increase the lifetime of tools [12]; the frictional wear resistance and the thermal fatigue resistance of brake drums can be also enhanced [13]; finally, it has been demonstrated that H13 tool steel biomimetic specimens with striation-shape and diamond-shape laser melting patterns exhibit reduced crack growth during thermal fatigue [14].

In the present paper a laser surface treatment (LST) of uncoated AISI 52100 steel samples has been investigated. Single spot laser experiments were conducted and the main process parameters were varied in a wide range, ensuring enough energy density and irradiance to produce either hardening without melting or re-melting of the irradiated surface layer. Differently from what largely diffused in literature, a high power CW fiber laser source was used. The morphology (size, shape) of the LST sample was evaluated by measuring the surface and in-depth hardness profiles: experimental data could be thus used for tuning a thermal Finite Element (FE) model of the LST which estimated the optimal laser process parameters for producing hardened zones with desired diameter and depth.

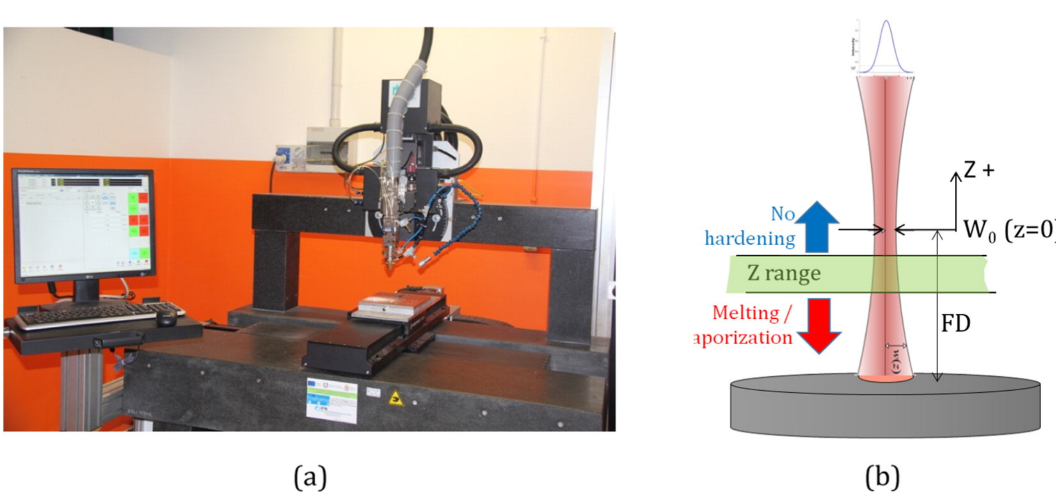

Fig. 1. Experimental setup (a) and scheme of the laser spot treatment (b).