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Effect of laser heat treatments on the hardness of tool steels

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Abstract: The application of laser heat treatments (LHT) has been growing attention in the last years, due to the effectiveness of localized hardening that can improve the tribological properties of steels. AISI P20 mod. steel is commonly used for plastic injection moulds applications and can be heat-treated to achieve high hardness values. This work presents an experimental investigation on the laser local heat treatments effect on the hardness of AISI P20 mod. steel parts, using a high-power diode laser. Different heat treatments at 1060 ºC and 1100 ºC using a feed rate of 10 mm·s^{-1} and 15 mm·s^{-1} were applied on the steel. The LHT were assessed through the hardness mapping trough depth and width. The results showed that the hardness of as-received P20 mod. tool steel is approximately 300 HV, and after LHT occurred an increment to around 625 HV with a fair hardness distribution. LHT had a minimum of 0.8mm and a maximum of 1.0mm depth.

Keywords: Laser, Local heat treatment, Hardness, Mould steel.

1. Introduction

Plastic injection moulds are projected to be used for numerous million rounds in plastic products mass production. These tools are subjected to strong thermo-mechanical loads which negatively affect their surface quality and strength, and consequently the productivity [1]. Damage of the moulds surface can be predominantly caused by wear, fatigue cracks, and corrosion. A particular relevant related issue occurs at parting line where wear leads to the increase of burrs. To overcome this problem, adopting thermo-mechanical treatments have been explored to improve injection moulds surface [2].

Among other surface treatments, laser-based surface treatments are one of the most effective ways to increase the properties of metallic parts [3]. Laser surface hardening has been implemented in a wide range of industrial applications, in particular metal industry [4]. Laser processes provide distinct advantages for localized processing of complex areas due to fast heating, high precision, and superior manufacturing efficiency enhancing the usability and the quality of mould steels [5,6].

During heat treatment, through the combination of time and controlled temperature, the desired mechanical properties are obtained with minimal influence in the steel shape, due to the precise input of energy. The final surface of the material also does not need post-processing, once it will be smooth after laser treatment [7].

The hardening of the material is induced by high temperatures used in the treatment, due to the rapid cooling rate, as well as the quenching of the treated area. This treatment is mainly applied in ferrous alloys, such as stainless steels, tool steels and cast irons, once undergo a martensitic transformation which leads to the formation of a very hard surface layer [8,9]. The hardenability and phase transformation are also dependent on the laser processing parameters, i.e., the laser power, the wavelength, the beam shape and area, the scan velocity, and the focusing conditions. Optimum process conditions, width and depth prediction are required to improve wear resistance and higher fatigue strength of steels [4].

P20 modified steel was used in this study since it has advantages of high resistance to thermal fatigue and thermal shock, high abrasion, and heat resistance, and are widely applied in moulds industry [6].

The aim of this work was to investigate the influence of localized laser treatments on the surface of steels using different parameters, such as temperature and velocity and choose optimal parameters to improve surface hardness. Furthermore, microhardness and roughness of the heat-treated surfaces were also evaluated. This work allows to show that LHT is an effective technique used to improve the tribological properties and to increase the service life plastic injection moulds.

2. Experimental Procedure

2.1. Materials

In the current research a commercial mould steel (AISI P20 modified) was used to study the influence of laser thermal treatments. P20 mod. steel is commonly used in the manufacturing of tools for injection moulds. The chemical composition is given in table 1.

Table 1. Chemical composition of the P20 mould steel (wt%).

Steel	C	Si	Mn	Cr	Mo	Ni	V
P20 mod.	0.40	0.30	1.45	1.95	0.20	1.05	-

2.2. Laser heat treatments

Laser heat treatments (LHT) were carried out employing a LDF 4500-60 diode laser from LASERLine. The laser head was mounted on a six-axis robot and equipped with a pyrometer and camera. The spot size was fixed in 15.2 mm and 7.2 mm, the maximum laser beam power was 4.5 kW, with a combined wavelength from two 960 nm and two 1020 nm diode emitters, controlled in a closed loop to keep temperature constant. In the experiments, the rectangular laser beam was moved in a single linear path, with a transverse scanning motion. The representation of the described laser system is presented in figure 1.

The experimental work was split into four experimental series (2^2 factorial design), in which different input parameters were adjusted. The only constant parameters were the spot size and the laser beam power. Two different temperatures t_l = 1060 ºC and t_2 = 1100 ºC and two scanning laser beam speeds v_l = 10 mm·s^{-1} and v_2 = 15 mm·s^{-1} were used.

2.3. Microhardness testing

To characterize the steels and the heat affected zone, Vickers microhardness tests were carried out with a Struers Type Duramin-1 microhardness tester. An indentation load of 2.0 kgf and a holding time of 15 s, according to ISO 6507-1:2018 was applied. Hardness measurement profiles were obtained manually moving the Vickers indenter along multi transversal and longitudinal lines from the specimen surface and transverse sections.

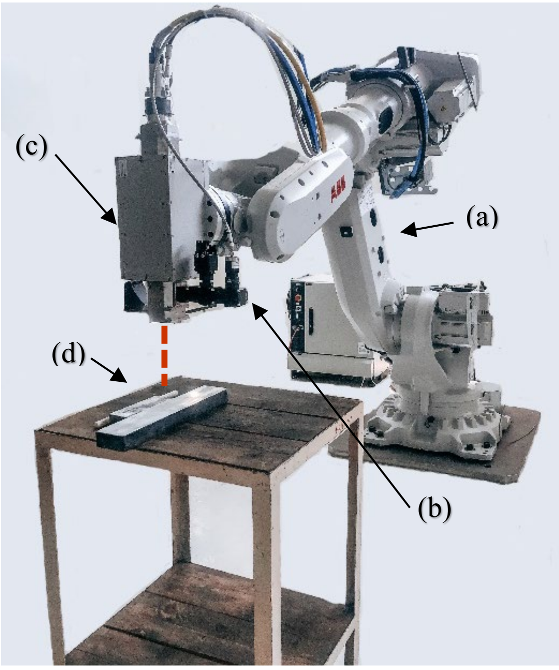

Figure 1. Laser heat treatment process. **(a)** six axis robot, **(b)** pyrometer, **(c)** laser head, **(d)** specimen steel.

2.4. Roughness measurements

The specimen surface roughness was measured before and after laser treatment by using a portable surface roughness tester TIME TR220, calibrated and verified by Innovatest. Roughness measurements were acquired along the longitudinal and transversal direction of the milled specimen, also aligned with the laser scanning motion. Each measurement was conducted five times and the reported results are the final average surface roughness (Ra) value.

3. Results and discussion

Microhardness profiles were measured to identify how microstructure changes with laser heat treatment. For each experiment, several indentations were made and measured.

Figure 2 represents an exemplary location of indentations, performed on a specimen section, cut using a Accutom-5 cut-off machine with plenty refrigeration. The calculation of indentations was performed by pixel count on a picture figure overlaid with a regular grid. A cubic interpolation was made to adjust the measured points to a regular mesh of 0.25 mm in distance to laser centre and 0.05 mm in depth. The hardness was mapped directly on the laser treatment (on the top of the surface) and on four layers of a cut section.

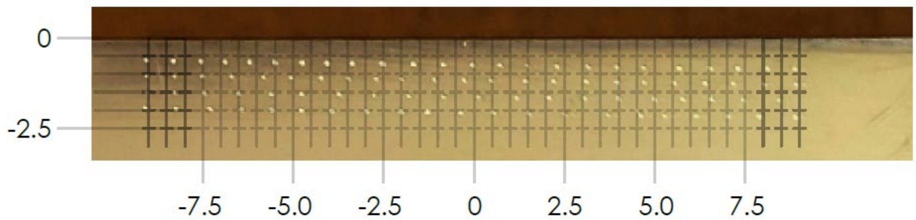

Figure 2. Representation of indentations locations of the heat treatment cross-sectional testing piece.

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The P20 mod. hardness distribution after LHT at 1060 ºC (a, b) and 1100 ºC (c, d) using 10 mm·s^{-1} (a, c) and 15 mm·s^{-1} (b, d) laser beam scan speeds are show in figure 3. The hardness profiles obtained showed the influence of the LHT on the top and on the cross-sectional areas.

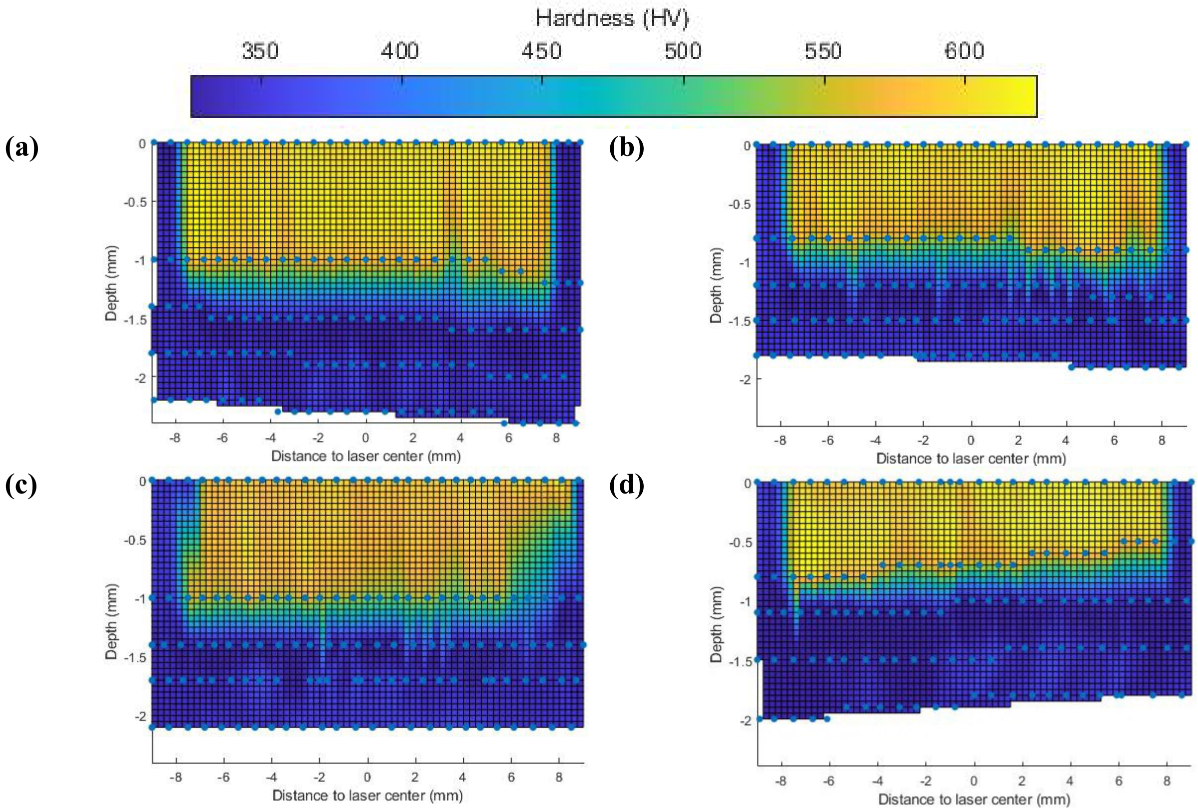

Figure 3. Hardness profiles of P20 mod. steel at different temperatures and laser beam speeds. (a) 1060 ºC, 10 mm·s^{-1}, **(b)** 1060 ºC, 15 mm·s^{-1}, **(c)** 1100 ºC, 10 mm·s^{-1}, **(d)** 1100 ºC, 15 mm·s^{-1}.

The microhardness of the P20 mod. base metal was approximately 300 HV. As expected, the hardness surface profiles showed an increase of hardness within the tempered zone. On the top of the testing piece, it was possible to observe that hardness of the heat-treated zone increased from approximately 300 HV to around 625 HV at both 1060 ºC and 1100 ºC.

At a depth of 1.0 mm, the hardness varies from 576 HV to 588 HV using 10 mm·s^{-1} laser beam speed, followed by a decrease of hardness at 1.2 mm depth until reaching the base metal hardness of around 300 HV. At 15 mm·s^{-1} laser beam speed, the laser heat treatment reaches 0.8mm depth, with a hardness variation from 588 HV to 608 HV, also proceeded by a hardness decreasing until 300 HV.

The results clearly confirmed that LHT increased 108% on the P20 mod. hardness at 1060 ºC and 1100 ºC comparing to the base metal hardness before heat treatment, on the top of the testing piece. This hardness increase may be explained by the phase transformation from ferrite to martensite that occurred during LHT [10]. Although the hardness increased similarly in all tests, using 10 mm·s^{-1} laser beam scanning speed showed that LHT can reaches a higher depth than 15 mm·s^{-1} scanning speed.

Table 2. Roughness values before and after LHT.

P20 mod.	Longitudinal	Transversal
R_a (Before LHT) µm	0.10 ± 0.02	0.39 ± 0.03
R_a (After LHT) µm	0.31 ± 0.01	0.43 ± 0.04

The surface average roughness (Ra) for P20 mod. are summarized in table 2. Along the longitudinal direction of the laser scanning motion, the Ra values increasing from Ra 0.1 μm to Ra 0.31 μm, representing a 210% increase after LHT, comparing to metal base value. Along transversal motion, roughness increased from Ra 0.39 μm to Ra 0.43 μm, indicating a 10% increase from base metal to LHT surfaces. As previous mentioned, this can be a result of a phase transformation to martensite, that leads to a higher roughness.

4. Conclusions

This work allowed to obtain a deeper knowledge concerning laser heat treatments characterization for plastic injection moulds application. The influence of laser heat treatment on the microhardness distribution and roughness of AISI P20 mod. mould steel using a high-power diode laser was investigated.

Based on the obtained results, the depth of the LHT was around 1.0mm maximum. Different laser beam scan speeds used in this experimental investigation demonstrated a slightly better distribution and depth on the hardness profiles at lower scanning speed.

For the laser heat treated P20 mod. steel, a 108% increase in hardness was observed after inducing by LHT. The surface hardness increased from around 300 to 625 HV. As expected, hardness values dropped to the base metal values at the boundary between the LHT zone and the base metal region.

The effect of LHT was also observed on surface roughness of P20 mod. steel, showing an 210% roughness increase along longitudinal laser scanning motion, after LHT while reducing the ratio between the longitudinal and transversal roughness.

Future studies will focus on the property's differences and microstructure between metal base surface and LHT surface. Deformation analysis due to residual stresses caused by the LHT shall also be investigated.

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