Influence of temperature and speed of the laser head on the final structure surface hardened steel ČSN 12050 (EN 10083-2 steel 1.1191)

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Abstract. Laser technologies are listed as unconventional methods of machining and heat treatment, which allows many advantages. In the area of heat treatment the laser technology allows a wide range of surface hardening. It provides a very fast and effective approach where the region of influence of the material is quite narrow. The method is also possible for hardening parts and materials which were not possible to process with the conventional processes. To get the required depth and quality of the hardened layer it is necessary to set up properly the laser process parameters (temperature in the process area, feed rate of the laser head, etc.), which varies for different materials. The paper presents a test for optimal process parameters for surface hardening of the material ČSN 12050 (EN 10083-2 steel 1.1191). The surface structure for temperatures of 900, 1100, 1200 and 1300°C and laser head feed rates of 0.18, 0.3 and 0.42 m/min were tested. Best results were obtained for a temperature of 1300°C and a feed rates of 0.18 m/min.

1 Introduction
The surface quality is one of the most important factors for the machine part life time, because near all fatigue cracks were initialized at the surface [1]. Therefore is taken high care to increase resistance of materials surface layers. It could be achieved by chemical-thermal treatment or hardening. Actual rise the trend for use of laser technology for surface hardening. It represents one of the top approaches of surface heat treatment. Despite to some technology limitations, the sophisticated laser hardening approach allows a lot of options, which were not possible with common processes. [2] The main advantages of laser hardening are high heat up rates (the heat up rate is around 1000°C/s), high effectivity, a thin heat effected layer and the option to process complex shaped parts. An advantage from the ecological and economical point the absence of the additional hardening medium. This laser technology uses the self-hardening process of the material. Another benefit is that the deformations caused by the laser-temperature treatment were significantly reduced. Further the laser spot size could be easily modified by changing the required lens. [3,4] Due to the common use of industrial robots and a high parameter level control, the repeatability of the hardening process is quite high. [5]

To obtain precise and homogenous hardened regions of required depth it is necessary to set up carefully laser parameters of temperature (eq. power), the feed rate of the laser head etc. [6,7,8] These parameters are different for various material. The goal of this article is a determination of optimal process parameters for different surface hardening of steel CSN 12050 (EN 10083-2 steel 1.1191).
2 Experiment of the parameter setup for laser hardening

Steel defined by CSN 12050 (EN 10083-2 steel 1.1191 – see Table 1) was used for the experiment. To perform the experiment four temperatures and three laser beam feed rates were chosen (see Table 2). The used laser was a Nd:YAG laser Laserline LDF 4000 with a maximum power of 4 kW and a wavelength of 1020 – 1060 nm. Size of the laser spot was 4 by 16 mm. The sample surface temperature was permanently measured by the pyrometer LASCON (Mergenthaler GmbH) with a feedback to the laser power steering system to ensure constant temperature during the whole process. The feed of the laser head was provided by the industrial robot KUKA KR60 HA with an position accuracy of ±0.05 mm.

The determination of the depth of the hardened layer was determined from hardness gradient measurements. For this purpose was used the micro hardness tester MicroMet 6000, with an applied load of 1 kg (HV1) and a gradient step of 0.1 mm. For the evaluation for a fully hardened area was taken in account the ČSN EN 10328 that the hardness of 550 HV is an agreement as the lowest hardness for martensite. The hardness of 300 HV was then considered as the lowest level for bainitic structure for carbon steel. The depth of heat-treatment was determined by images taken by the optical microscope Nikon Epiphot 200 (LOM). Details of the microstructure of the samples was taken by the electron microscope Tescan Vega SB (SEM). The samples were prepared by a standard metallographic procedure and etched by Nital 3%.

### Table 1. Nominal chemical composition of steel CSN 12050.

| Chemical element | C (mass.%) | Mn (mass.%) | Si (mass.%) | P (mass.%) | S (mass.%) | Cr (mass.%) | Mo (mass.%) | Ni (mass.%) |
|------------------|------------|------------|------------|-----------|-----------|------------|------------|------------|
| Content min      | 0.42       | 0.5        | 0.40       | 0.030     | 0.035     | 0.40       | 0.10       | 0.40       |
| (mass.%) max     | 0.50       | 0.80       | 0.40       | 0.030     | 0.035     | 0.40       | 0.10       | 0.40       |

### Table 2. Tested feed rates of the laser beam for selected hardening temperatures.

| Velocity (m/min) | Temperature (°C) |
|------------------|------------------|
|                  | 900              | 1100            | 1200          | 1300          |
| 0.18             | Sample V1        | Sample V2       | Sample V3     | Sample V4     |
| 0.3              | Sample V5        | Sample V6       | Sample V7     | Sample V8     |
| 0.42             | Sample V9        | Sample V10      | Sample V11    | Sample V12    |

3 Optimization of process parameters for surface laser hardening of steel CSN 12050

3.1 Initial state of the material and the desired optimal state

The structure of the unprocessed steel CSN 12050 is shown in Figure 1. The structure is formed by ferritic and pearlitic grains. After the application of volumetric hardening (stay at a 820°C for 0.5 h and then cooled in water), a structure of martesite should appear in the whole volume like in Figure 2.
3.2 The material after laser surface hardening tests

The process of laser hardening formed in the heat treated side few layers. On the border a martensitic or bainitic structure was formed which changes with increased deepness in layers with decreasing hardness of lower bainite and further non heat effected structures of the material. The thickness and presence of the layers is obvious from the used measurement method of the hardness gradient and also from the later image analysis done by LOM and SEM. The formation and quality of the layers is dependent on the experimentally tested parameters of surface temperature and feed rate.

For the test sample V1 with the temperature of 900°C and the lowest feed rate of 0.18 m/min the analysis get the inability of trough-hardening of the material layer to the martensitic structure. Figure 3 shows the hardness gradient measurement where the maximum reaches a value of 404 HV1. If it is considered that the lowest hardness for the bainitic structure is 300 HV, then the bainic layer reaches a depth about 400 µm. To the same conclusion leads the microscopic analysis shown in Figure 4a where clearly visible bainitic needles were recognizable.
For the lowest feed rate of 0.18 m/min and the highest applied temperature of 1300°C the look of Figure 6 shows that a martensitic trough-hardening of a depth of 780 µm was reached. Figure 7 from the microscope shows that a bainitic layer below the martensitic was formed in a total depth of 1147 µm. In the transition between the base and heat affected region were visible martensitic needles and tiny regions of residual austenite. The highest hardness of this martensitic structure was 666 HV1.
For sample V9, the highest feed rate of 0.42 m/min and the lowest temperature of 900°C a depth of 240 µm for the martensitic layer was obtained (see Figure 7). The total hardened layer depth was 311 µm (see Figure 8). The highest value of hardness reached for sample V9 was 598 HV1. From Figure 8 is obvious that the austenitization process of the base material has not occurred in the heat affected region. Figure 8a shows a martensitic hardened layer with white pieces of the original ferrite. For some regions are noticeable location of lighter pieces between martensite, which represent remaining austenite. In the transition region between the hardened layer and the base material the insufficient austenitization is even more distinguishable.
Figure 7. Record of the hardness progress through the material of Sample V9 (0.42 m/min, 900°C).

Figure 8. Thickness of the heat effected Sample V9 (a, LOM, magnification 100x) and detail of the martensitic structure of the hardened region of Sample V9 with recognizable ferritic pieces and regions with residual austenite (b, LOM, magnification 500x).

For Sample V12, the highest feed rate of 0.42 m/min and the highest applicable temperature of 1300°C, was the steel martensitic hardened to a depth of 1070 µm (see Figure 9). The martensitic layers passes to bainitic layers which reached a depth of 1202 µm in the hardened material (see Figure 10). The highest measured hardness reached 674 HV1.
Figure 9. Record of the hardness progress through the material of Sample V12 (0.42 m/min, 1300°C).

Figure 10. Thickness of the heat affected region of Sample V12 (LOM, magnification 100x).

Final measured values from all tested samples were summarized in Table 3 for trough-hardened depth, in Table 4 for heat affected depth and Table 5 for maximum reached values of hardness.

The tables serve as a guideline for optimal choice of the laser technology parameters for resulting the quenching parameters, time consumption to a quality factor.

Table 3. Final depths of trough-hardening of tested samples for chosen laser technology parameters.

| Velocity (m/min) | Depth of trough-hardening (µm) |
|-----------------|-------------------------------|
|                 | 900  | 1100 | 1200 | 1300 |
| 0.18            | -    | 630  | 710  | 780  |
| 0.3             | 210  | 600  | 710  | 690  |
| 0.42            | 240  | 730  | 870  | 1070 |
Table 4. Final heat effected depths of tested samples for chosen laser technology parameters.

| Velocity (m/min) | Heat effected depth (µm) |
|------------------|--------------------------|
|                  | Temperature (°C)         |
| 0.18             | 900 1100 1200 1300       |
| 0.3              | 415 824 966 1147         |
| 0.42             | 340 731 870 942          |
|                  | 311 862 985 1202        |

Table 5. Maximum reached hardness of the tested samples for chosen laser technology parameters.

| Velocity (m/min) | Maximum reached hardness (HV1) |
|------------------|--------------------------------|
|                  | Temperature (°C)               |
| 0.18             | 900 1100 1200 1300             |
| 0.3              | 404 652 660 666                |
| 0.42             | 570 610 646 577               |
|                  | 598 660 671 674               |

For comparison it is noted that the original material without any other processing was measured 277 HV1.

4 Summary
From tested laser technology parameters at tests samples of steel CSN 12050 was obtained that for lower surface temperatures original ferrite grain remnants had remained. Their presence is given due to insufficient temperature or time of austenitization of the matrix.

By the gradient-hardness measurement was found that the martensitic layer had the highest depth for the feed rate 0.42 m/min and applied temperature of 1300°C eq. sample V12. For these laser parameters was obtained the highest hardness of the processed area.

The lowest decrease of hardness with increasing distance from the hardened surface was detected for the Samples V4 and V8, the lower feed rate of 0.18 and 0.3 m/min and the highest temperature of 1300°C. For Sample V4 was the hardness only slightly lower than for Sample V12. The depth of the martensitic region was for Sample V4 only 780 µm, but the sum of the martensitic and bainitic layers was for Sample V4 and V12 similar.

From the evaluation of measurements and further analysis the optimal laser-hardening technology parameters for steel CSN 1205 were a feed rate of the laser head/beam of 0.18 m/min and an applied surface temperature of 1300°C – sample V4. This sample had not the highest hardness of all tested samples, but it is still quite high and the decrease of hardness was detected as relative evenly declining.

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