High power diode laser remelting of metals

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Abstract. This article is focused on the laser surface remelting of the steel samples with predefined overlapping of the laser spots. The goal of our experimental work was to evaluate microstructure and hardness both in overlapped zone and single pass ones for three kinds of ferrous metals with different content of carbon, cast iron, non-alloy structural steel and tool steel. High power fibre coupled diode laser Laserline LDF 3600-100 was used with robotic guided processing head equipped by the laser beam homogenizer that creates rectangular beam shape with uniform intensity distribution. Each sample was treated with identical process parameters – laser power, beam diameter, focus position, speed of motion and 40% spot overlap. Dimensions and structures of the remelted zone, zone of the partial melting, heat affected zone and base material were detected and measured by means of laser scanning and optical microscopes. Hardness progress in the vertical axis of the overlapped zone from remelted surface layer to base material was measured and compared with the hardness of the single spots. The most hardness growth was found for cast iron, the least for structural steel. Experiment results will be used to processing parameters optimization for each tested material separately.

1. Introduction
Laser remelting is one of the surface modification methods with aim to change a microstructure of highly stressed, ferrous machine parts and enhance their mechanical and chemical resistance (bearing races, gears, shafts, cylinders, camshafts) [1]. Nodular cast irons and low carbon steels might be suitable materials, because they are difficult hardened by solid state transformations due to extensive or insufficient carbon content. Heating and cooling rates in case of the laser melting are much higher then in case of the usually used conventional methods (oxy-acetylene flame, induction heating and TIG electric arc) that cause extensive heating of material and risk of deformations. Power density of the laser beam is controlled to ensure heating slightly above material melting point without vaporization. Laser beam with uniformly distributed intensity is created by various methods of beam shaping to ensure constant depth of the remelted zone [2], [3]. Main methods are defocusing by focal plane shift above surface, optical integration by segmenting the beam into a large number of portions and superposing the individual segments on the same focal plane using a beam integrator, scanning by two perpendicular galvo-mirrors respectively. Because dimensions of the homogenized laser beam is

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about some millimetres, large work pieces have to be remelted by deposition of tens laser spots with optimal overlapping. Part of the once remelted material at the first spot boundary is heated again during the second spot deposition. The goal of our experimental work was to evaluate microstructure and hardness both in overlapped zone and single pass ones for three different kinds of ferrous metals, cast iron, non-alloy structural steel and tool steel.

2. Experiment

2.1. Material

Samples with approximate length 150 mm and width 80 mm were prepared from three kinds of the ferrous metal semi-product plates of the thickness 15 mm (figure 1), specifically cast iron EN-JS2070, non-alloy structural steel S355 JR and tool steel OH260 (table 1). Each of these materials has a defined position in the iron/carbon alloy phase diagram according a typical content of carbon. EN-JS2070 with carbon content from 3.4 % to 3.85 % is ductile cast iron with pearlitic structure containing nodular graphite inclusions that is used in production of the casts with thickness from 5 mm to 200 mm and mechanically stressed machine parts (gear wheels, drum brakes). S355 JR with carbon content less or equal to 0.24 % is hypo-eutectoid non-alloy structural steel with pearlitic and ferritic structure that is widely used for steel constructions in various industry branches (buildings, bridges, towers, ship desks etc.) [4], [5]. Both mentioned materials are difficult to be hardened due to extensively high and low content of carbon respectively, so laser melting can be suitable way for surface hardness improving.

| material  | carbon (%) | hardness (HV) | output structure | typical application  |
|-----------|------------|---------------|------------------|---------------------|
| EN-JS2070 | 3.4 – 3.85 | 236 - 322     | pearlite with nodular graphite | gear wheel, drum brake |
| S355 JR   | ≤ 0.24    | 170 - 194     | pearlite and ferrite     | bridges, towers       |
| OH260     | 0.77 – 0.85 | 243 - 253     | oil quenched martensite  | cutting and punched dies |

OH260 (steel no. 1.2369, DIN 81MoCrV42-16) with carbon content from 0.77 % to 0.85 % is cold work tool steel with hardness and wear resistance achieved by conventional hardening and oil quenching with martensitic structure to be used for cutting and punches dies.

Figure 1. Scheme of the experiment set-up and remelted surface of the steel OH260.

Figure 2. Robotic guided laser processing head with beam shape homogenizer.
2.2. Laser parameters
The high power fibre coupled diode laser Laserline LDF 3600-100 with maximal power 3 600 W and a beam quality (beam radius times half angle divergence) 100 mm.mrad was used in experiment realized in MATEX PM Facility. Processing head with focus lens distance 200 mm is equipped by beam homogenizer that creates rectangular shape of the beam profile 5 mm x 23 mm with uniform intensity distribution. Connection between laser source and processing head was realized by the optical fibre with diameter 1 mm, relative motion between the beam focus plane and material surface was ensured by computer guided robotic arm (figure 2). Process parameters were kept on the same values, it means laser power $P = 2800 \text{ W}$, speed of the processing head motion $v = 1.5 \text{ m s}^{-1}$ and the spot axis shift $d = 15 \text{ mm}$, that results in 40% overlap.

2.3. Experiment set up
Two spots with preset distance $d = 15 \text{ mm}$ were applied consequently on each of the prepared samples with length 150 mm. Focus plane was positioned on the samples surface, which temperature was controlled by means of the pyrometer not to exceed temperature 1550 °C. Experiment was realized in the natural atmosphere without any shielding gas.

3. Results
The samples were cut in the plane perpendicular to the material surface and to the direction of the laser beam motion. These obtained cross sections are then prepared for microanalysis by the mechanical grinding, polishing with diamond paste and etching by 1% respective 3% solution of HNO$_3$. Dimensions and structures of the remelted zone, zone of the partial melting, heat affected zone and base material were detected and measured by means of the laser scanning microscope Olympus LEXT OLS3100 and optical microscope GX-51 [6]. Hardness was measured both along the second spot axis and the overlapped area by Vickers hardness test for each of the three samples to detect differences in the once and repeatedly remelted regions

3.1. Remelted cast iron sample microstructure
The remelted zone is created by ledeburite that is phase mixture of the cementite and austenite with presence of the martensite. Globular graphite was dissolved in the melt pool and during solidification it was excluded in the form of the dendritic structured cementite (figure 3). The heat affected zone is created by martensite and because the melting temperature was not achieved in this region, globular graphite is present in its original form observable as the black circular shapes as is seen on the figure 4. Transition between remelted and heat affected zone is gradual, presence of the both structures was observed in some places.

![Figure 3](image3.png)
Figure 3. The remelted zone of the cast iron created by mixture of the cementite and austenite with martensite.

![Figure 4](image4.png)
Figure 4. The heat affected zone of the cast iron created by martensite with non dissolved globular graphite.
3.2. Remelted structural steel sample microstructure

The remelted zone of this sample is created by martensite and ferrite (figure 5), where some inclusions of ferrous oxides are present probably due to material interaction with ambient atmosphere. These inclusions have form of the black dots and some group of them is highlighted in the figure by rectangle. The heat affected zone is created by martensite (figure 6), but there is present also ferrite with decreasing amount in direction to base material, so the heat affected zone has no discrete border and can be considered as a transition. The base material structure can be described as alternated layers of the pearlite and ferrite that was created during semi-product forming.

Figure 5. The remelted zone of the structural steel created by martensite and ferrite with ferrous oxides inclusions.

Figure 6. The heat affected zone of the structural steel created by martensite with occurrence of ferrite.

3.3. Remelted tool steel sample microstructure

Structure of this sample is oriented vertically. Martensite was created in the remelted zone and the original cellular structure of the austenite is observable too (figure 7). There are observed white and long segregation strips formed by cementite in the vertical direction going through martensite structure of the heat affected zone up to base material (figure 8). Intensity and broadness of these strips decreases in the direction from the surface to the inner volume of material. Base material has also martensitic structure due to previous heat treatment. Transition between the remelted and heat affected zone is strongly bounded in contrast with that of the structural steel and cast iron, what is observable on the macro photographs of the overlapped regions.

Figure 7. The remelted zone of the tool steel created by martensite and original cellular structure of the austenite.

Figure 8. The heat affected zone of the tool steel created by martensite with vertical cementite white strips.
3.4. Overlapped zones microstructure
Microstructure of the overlapped zones is created by the same crystallographic phases as the particular spots in case of all three samples; differences were found only in the phase’s boundaries and transitions. In case of the cast iron, the boundary of the remelted layer of the first spot was overlapped by zone of partial melting of the second one. Continuous transition between spots with mixing of structures, growing from two different directions was observed in the region of the spot overlap in case of the structural steel (figure 9). Apart of this remelted zone of the second spot overlies the first one with significant boundary where micro cracks were detected in case of the tool steel (figure 10).

![Figure 9](image9)

**Figure 9.** The overlapped region of the structural steel sample with continuous transition.

![Figure 10](image10)

**Figure 10.** The overlapped region of the tool steel sample with significant boundary and micro cracks.

3.5. Hardness measurement
The Vickers hardness test was at the first time realized inside the second spot deepest region in the direction from the sample surface to the base material with load 9.81 N. Hardness increasing in comparison with the base material was achieved in the remelted and heat affected zones of the all three samples with some differences in the depth dependence progress (figure 11).

![Figure 11](image11)

**Figure 11.** Hardness progress in the second spot vertical axis.
The highest hardness was measured in the remelted zone of the nodular cast iron (1200 HV) that is approximately four times greater than hardness in the base material (282 HV) and approximately twice greater than hardness in the heat affected zone (643 HV). In case of the construction steel hardness in remelted zone close to surface has less hardness (180 HV) then in heat affected zone (267 HV) due to ferrite phase presence and low content of carbon in the base material (204 HV). Hardness of the oil quenched tool steel with output martensitic structure initially grows from the sufficient surface value (591 HV) towards heat affected zone, where it achieves maximal value 760 HV and slowly flows down to base material (286 HV). Following measurement was realized in the vertical axis of the overlapped region to evaluate the influence of the first deposited spot repeated heating to melting temperature while the second one was deposited. Values of the cast iron overlapped region hardness in the various depths are outlined in the table 2.

| Table 2. Cast iron hardness progress in the vertical axis of the overlapped region. |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| No.                             | 1         | 2         | 3         | 4         | 5         | 6         | 7         | 8         | 9         | 10        |
| depth (mm)                      | 0.42      | 0.73      | 0.98      | 1.34      | 1.66      | 2.07      | 2.77      | 3.32      | 4.26      | 5.92      |
| HV (N.mm⁻²)                     | 840.4     | 651.5     | 631.7     | 809.3     | 768.2     | 777.7     | 658.5     | 586.4     | 303.5     | 281.4     |
| deviation (mm)                  | 85.7      | 84.0      | 107.7     | 114.2     | 130.0     | 79.7      | 42.5      | 120.8     | 73.7      | 82.6      |

Strong boundary between the remelted and heat affected zone fully overlies the remelted zone of the first spot (measurement no. 2 and no. 3), where hardness falls down to the typical values for heat affected zone and its increasing is observable in the region below 1.34 mm where typical remelted structure is present again (figure 12). The analogues results were obtain in case of the other experimental materials, structural and tool steels. From obtained results implies, that cast iron is the most suitable material for the laser surface remelting due to hardness increasing above values achievable in the conventionally used hardening process. Structural steel due to low carbon content is material suitable rather for welding than for the surface treatment. Hardness about 775 HV (63HRC) is achieved by heat treatment of the tool steel both by use of the conventional and laser methods.

![Image](image_url)

**Figure 12.** Cast iron hardness measurement in region of the spot overlap.

### 3.6. Surface roughness

The information about surface dimensional and volumetric changes after thermal treatment might be important data for the optimal function of the machine parts that undergone the laser surface remelting, when convection in the melt pool is caused by the surface tension gradient and surface deformations are observed after material re-crystallization [7]. Contact profile-meter Taylor Hobson was used to scanning across the complete remelted region of the two overlapped spots including surrounding non-treated surface in the direction perpendicular to the laser beam movement [8]. Record of five hundreds linear profiles separated of each other by 0.02 mm is used for various plane and three-dimensional displaying of the measured region according user requirements by means of the software tool TALYMAP. Black-and-white 3D axonometric display of the cast iron remelted spots in 10 mm long section is presented on the figure 13 with zoomed vertical axis.
Figure 13. 3D axonometric display of the cast iron remelted region in 10 mm section.

Example of the average profile computing of this scanned area is shown on the figure 14, where result for the cast iron sample is presented. Black curve displays average profile while colored areas correspond to the surface shape changes with respect to non-treated sample plane and they are designed as Area of the hole (red areas) and Area outside (green areas). Maximum depth and height are extracted from measured data respectively and their values can be displayed below graph. The maximal positive difference in these areas dimensions 1.4534 mm² was found out in case of the tool steel, from this value volumetric growth was dedicated, maximal height 415.77 µm is approximately twofold than maximal depth 202.68 µm. The minimum positive difference 0.0004 mm² between areas was achieved in construction steel although its surface was noticeably modified by melt pool convection and maximum depth 177.94 µm is of 11.4 % greater than maximum high 159.71 µm. Negative areas difference 0.42358 mm² was computed in case of the cast iron, where the lowest value of maximum height 17.794 µm and depth 92.876 µm respectively was measured (figure 14).

Figure 14. Average profile of the cast iron remelted region from data measured in 10 mm section.

4. Conclusions
This work has presented high power diode laser remelting of three various ferrous metal samples with different amount of carbon namely specific kind with cast iron, structural and tool steel. To evaluate material properties dependence on the expected hardness progress, processing parameters were kept constant. Two overlapped spots were applied on each sample surface to found changes in microstructure of the first spot after the second one treatment. Due to high heating and cooling rates martensitic microstructure was find in the heat affected zones, surface remelted layers are mixtures of martensite and other metallurgical phases from original structure such as austenite and ferrite. Hardness of the heat affected zone has higher values than in the base material of all three samples; the
maximal increase was detected in case of the cast iron, the minimal one for structural steel respectively. Small hardness decrease at surface remelted zone in comparison with heat affected zone was detected for structural and tool steel. Only cast iron has maximal values of the hardness in the surface remelted layer. Differences between the first and second spot dimensions and structure roughness were also found, probably caused by sample pre-heating during the first laser passing (figure 15). Hardness progress was also measured in the vertical axis of the overlapped zone and it was compared with previous results. Information about surface and dimensional changes was obtained by means of measurement on the contact profile-meter.

Figure 15. Pseudo-photo of the construction steel remelted surface at region 48 mm x 10 mm.

5. References

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