

PROBLEMS ASSOCIATED WITH A ROBOT LASER CELL USED FOR HARDENING

PROBLEMATIKA ROBOTSKEGA LASERSKEGA KALJENJA

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Laser hardening is a surface-hardening process. It is used exclusively on ferrous materials suitable for hardening, including steel and cast iron with a carbon content of more than 0.2 %. This article describes robot laser hardening, the results of previous work, research and experience with robot laser hardening. The second part of the paper describes the problems associated with robot laser hardening at different angles. We wanted to find the impact of the angles on the hardness of the material. Therefore, we directed the laser beam at different angles, including perpendicular, in the process of hardening. We made test patterns of a standard label on the materials of DIN standard 1.2379.

Keywords: hardening, robot, laser, parameters

Lasersko kaljenje je proces površinskega utrjevanja. Uporablja se izključno za železne materiale, ki so primerni za kaljenje in vsebujejo več kot 0,2 % ogljika. V članku opisujemo robotsko lasersko kaljenje, navajamo rezultate dosedanjega dela in raziskav ter izkušnje z laserskim kaljenjem. Drugi del opisuje problematiko robotskega laserskega kaljenja pri različnih kotih. Želeli smo ugotoviti, kako kot laserskega žarka vpliva na trdoto materiala. Kot laserskega žarka smo spreminjali glede na smer potovanja, kakor tudi pravokotno na smer potovanja laserskega žarka. Naredili smo vzorce standardne oznake po DIN standardu 1.2379.

Ključne besede: kaljenje, robot, laser, parametri

1 INTRODUCTION

Laser hardening¹⁻⁵ is a metal-surface treatment process that complements the conventional flame- and induction-hardening processes. A high-power laser⁶⁻¹⁰ beam is used to heat the metal surface rapidly and selectively to produce hardened case depths of up to 1.5 mm with hardness values of up to 65 HRC. This has a hard martensitic microstructure providing improved properties, such as wear resistance and increased strength. To harden the workpiece, the laser beam usually warms the outer layer to just under the melting temperature (about 900 °C to 1400 °C). Once the desired temperature is reached, the laser beam starts moving. As the laser beam moves, it continuously warms the surface in the processing direction.^{11,12} The high temperature causes the iron atoms to change their position within the metal lattice (austenization). As soon as the laser beam moves away, the hot layer is very rapidly cooled by the surrounding material in a process known as self-hardening. This rapid cooling prevents the metal lattice from returning to its original structure and producing martensite. The laser beam hardens the outer layer or case of the workpiece. The hardening depth of the outer layer is typically from 0.1 mm to 1.5 mm. However, on some materials, it may be 2.5 mm or more. A greater hardening depth requires a larger volume of the surrounding material to ensure that the heat dissipates quickly and the

hardening zone cools fast enough. Relatively low power densities are needed for hardening. At the same time, the hardening process involves the treatment of extensive areas of the surface. That is why the laser beam is shaped so that it irradiates an area that is as large as possible. This irradiated area is usually rectangular. Scanning optics are also used in hardening. They are used to move a laser beam with a round focus back and forth very rapidly, creating a line on the work piece with a power density that is virtually uniform. This method makes it possible to produce hardened tracks up to 60 mm wide.

2 EXPERIMENTAL METHOD AND MATERIALS PREPARATION

A robot laser cell can be used to provide the heat necessary for a treatment process. The absorbed radiation from the laser of the laser cell heats up the surface layer to a temperature where austenite can form. In this work we research how the parameter of angle impacts on the hardness of the material. We used a RV60-40 robot laser cell from Reis Robotics, which is a leading technology company for robotics and system integration. The articulated-arm robot series is the most important robot kinematics for industrial use. As 6-axis universal robots with high path speeds and large work envelopes the RV-robots are especially suited for the

tough demands of path-related tasks. The design based on FEM and CAD stands out due to its excellent static and dynamic behaviour. Their robotic automation solutions are used by all major application fields, such as solar energy, foundry, welding and hardening. The Reis Robotics group comprises three German subsidiaries and eight international subsidiaries as well as representative agencies in many countries. The laser beams have a rectangular shape. We used 5 mm × 13 mm optics, which means that with this optic we hardened a width of approximately 13 mm. Robot lasers work continuously with wavelength of 700–1000 nm. The maximum power

of a robot laser cell is 3000 W. However, we hardened specimens with a 2000 W output power. The specimen was material of DIN standard 1.2379. We hardened the material at 2 mm/s using 1100 °C. There are different and interesting problems regarding the robot laser hardening of metals. The problem can be represented geometrically, as seen in **Figures 1 to 3**.

Similar problems arise in the following situation. We harden materials at an incidence angle of $\varphi \neq 90^\circ$. **Figure 3** shows the situation where we changed the angles in different directions. We see that the upper part of the beam has a longer travel time than the lower part of the beam. This means that the lower part of the hardened piece is better than the upper. The workpiece will not be evenly hardened and the final result of the laser hardening will not be good.

To analyse the results we used the method of intelligent system, i.e., a neural network. Neural networks are model-less approximators; they are capable of performing an approximation – modelling operations regardless of any relational knowledge of the nature of the modelled problem. This relational knowledge is typically represented by a set of equations describing the observed variables and constants used to describe the system’s dependencies. A common use of neural networks is multi-dimensional function modelling^{13,14}, i.e., the re-creation of the system’s behaviour on the basis of a set of known discrete points representing the various states of the system. We used feedforward neural networks with supervised training algorithms.

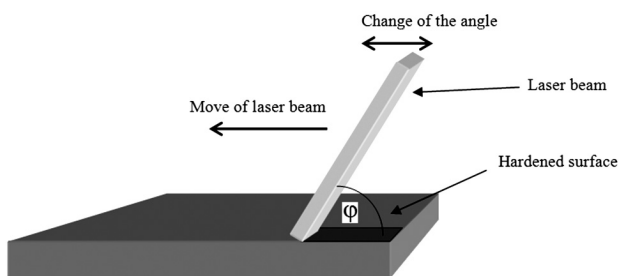


Figure 1: Problem 1 of the robot laser hardening: the variation of the incidence angle $\varphi \in (0^\circ, 90^\circ)$ between the right-hand side of laser beam and the material surface

Slika 1: 1. Primer laserskega kaljenja: spreminjanje vpadnega kota $\varphi \in (0^\circ, 90^\circ)$ med desno stranjo laserskega žarka in površino materiala

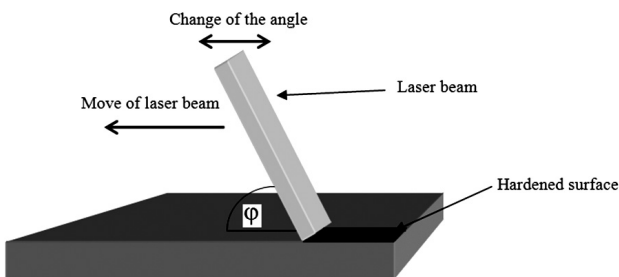


Figure 2: Problem 2 of the robot laser hardening: the variation of the incidence angle $\varphi \in (0^\circ, 90^\circ)$ between the left-hand side of laser beam and the material surface

Slika 2: Drugi primer laserskega kaljenja: spreminjanje vpadnega kota $\varphi \in (0^\circ, 90^\circ)$ med levo stranjo laserskega žarka in površino materiala

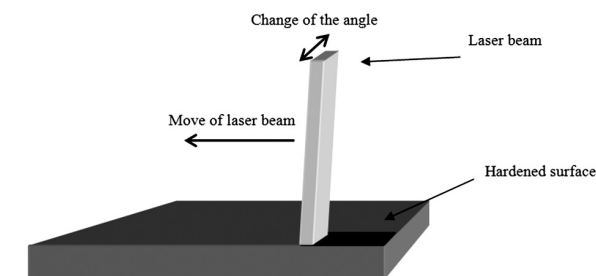


Figure 3: Problem 3 of robot laser hardening: the lateral incidence angle of the laser beam on the material surface and the beam movement direction

Slika 3: Tretji primer laserskega kaljenja: spreminjanje lateralnega vpadnega kota laserskega žarka glede na površino materiala in smer gibanja žarka

3 RESULTS

We are interested in the hardness of the robot laser-hardened material as we change the incidence angle of the laser beam on the substrate material. We have two options. Firstly, we can change the angle with regard to the direction of the laser beam. Here, we also have two options. In this situation we have conducted tests for angles of $\varphi \in \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ between the right-hand side of the laser beam and the material surface (**Figure 1**). However, we have conducted tests for angles of $\varphi \in \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ between the left-hand side of laser beam and the material surface (**Figure 2**). This means that we made six tests for each option. In these two options the width of the hardening is unchanged. Second, we can change the angle with regard to the perpendicular direction of the laser beam. We have conducted tests for angles of $\varphi \in \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$. In these options we have different widths of hardening, because we change the angle with regard to the perpendicular direction of the laser beam. The results are presented in **Figure 9**. We varied the amounts of power supplied to the laser beam when we made tests on the tool steel 1.2379. In all the tables we present the hardness before hardening, after hardening and the average hardness after hardening.

3.1 Variation of the incidence angle with regard to the direction of the laser beam

Again, we have two options (Figures 1 and 2). First, we change the angle with regard to the direction of the laser beam (the problem is presented in Figure 1). The results of the measurements are shown in Table 1.

Table 1: Relationship between the angles and the hardness
Tabela 1: Povezava med kotom φ in trdoto

$\varphi/^\circ$	Hardness after hardening (HRc)	Average hardness after hardening (HRc)	Hardness before hardening (HRc)
15	62, 63, 62, 56	61.5	9
30	59, 59, 59, 63, 62	60.4	9
45	61, 61, 61, 60, 61	60.8	9
60	61, 62, 61, 50, 56	58	9
75	61, 62, 61, 50, 61	59	9
90	61, 61, 61, 48, 62	58.6	9

All the data from Table 1 we analysed with the neural network. Figure 4 shows the relationship between the incidence angle and the hardness.

Second, we changed the angle with regard to the direction of the laser beam (the problem is presented in Figure 2). The results of the measurements are shown in Table 2.

Table 2: Relationship between the angles and the hardness
Tabela 2: Povezava med kotom φ in trdoto

$\varphi/^\circ$	Hardness after hardening (HRc)	Average hardness after hardening (HRc)	Hardness before hardening (HRc)
15	61, 69, 52, 57, 56	55	9
30	54, 57, 58, 56, 56	56.2	9
45	51, 56, 56, 49, 54	53.2	9
60	52, 55, 54, 54, 56	54.2	9
75	50, 55, 56, 23, 43	45.4	9
90	58, 59, 57, 60, 59	58.6	9

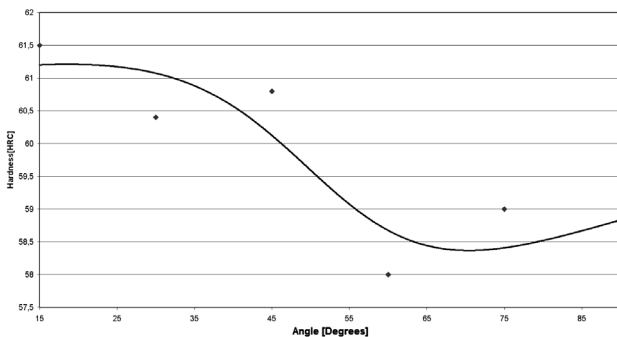


Figure 4: Relationship between the angles and the hardness. The modelling of the relationship was obtained using the four-layer neural network (from Table 1).

Slika 4: Razmerje med vpadnimi koti in trdoto. Modeliranje razmerja je bilo narejeno s štiri-nivojskim nevronskega sistema (podatki so v tabeli 1).

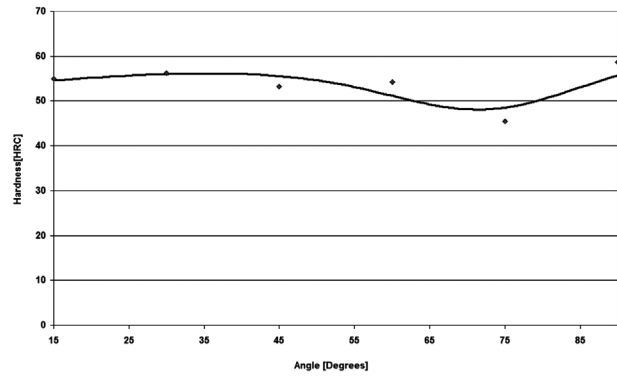


Figure 5: Relationship between the angles and the hardness. The modelling of the relationship was obtained using the four-layer neural network (from Table 2).

Slika 5: Razmerje med vpadnimi koti in trdoto. Modeliranje razmerja je bilo narejeno s štiri-nivojskim nevronskega sistema (podatki so v tabeli 2).

All the data from Table 2 we analysed with the neural network. Figure 5 shows the relationship between the incidence angles and the hardness.

3.2 Variation of the incidence angle with regard to the perpendicular direction of the laser beam

In this case we changed the angle with regards to the perpendicular direction of the laser beam (Figure 3). We chose the same angles of $\varphi \in \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$.

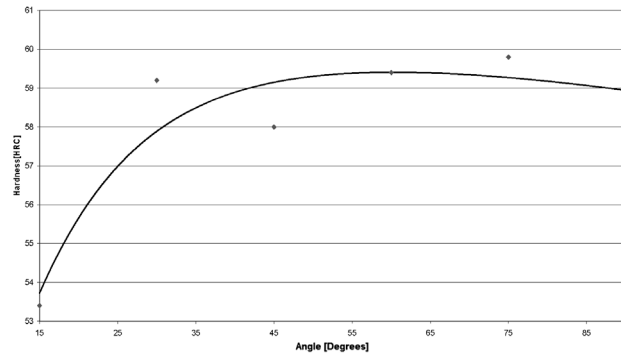


Figure 6: Relationship between the angles and the hardness. The modelling of the relationship was obtained using the four-layer neural network (from Table 3).

Slika 6: Razmerje med vpadnimi koti in trdoto. Modeliranje razmerja je bilo narejeno s štiri-nivojskim nevronskega sistema (podatki so v tabeli 3).

Table 3: Relationship between the angles and the hardness
Tabela 3: Povezava med kotom φ in trdoto

$\varphi/^\circ$	Hardness after hardening (HRc)	Average hardness after hardening (HRc)	Hardness before hardening (HRc)
15	49, 48, 49, 61, 60	53.4	9
30	56, 57, 57, 63, 63	59.2	9
45	54, 56, 55, 64, 61	58	9
60	56, 57, 58, 63, 63	59.4	9
75	57, 57, 59, 63, 63	59.8	9
90	57, 60, 58, 58, 60	58.6	9

90°}. There is no need to consider two options since those options are symmetrical.

All the data from **Table 3** we analysed with the neural network. **Figure 6** shows the relationship between the incidence angles and the hardness.

4 DISCUSSION

By using angular functions we can calculate the width of the hardening at a certain angle. Here, the following information is already known: the width of the optics (d) and the angle (φ) under which the hardening is conducted. The hardening width is calculated. The width of the beam optics represents one side of a right-angle triangle, the angle (φ) of hardening is the right-angle triangle's opposite side, which was marked with the width of the optics (d). The beam hardening of the workpiece is the hypotenuse of the right-angle triangle, denoted by x . After delivery the sinus is

$$\sin \varphi = d/x, d \in \{5, 8, 13, 16, 23, 28\} \text{ mm}, \varphi \in (0^\circ, 180^\circ) \quad (1)$$

By changing the angle φ of the longitudinal hardening of the workpiece, we can achieve different degrees of hardness in the materials (section 3.1). By changing the angle φ with regard to the transverse hardening and the different sizes of optics, we can achieve a different width of hardening at a given time. **Figure 7** shows that the maximum power is used when the laser beam falls below the minimum angle in our study, i.e., 15°. In this position we achieve the area of hardening, but for that we require more time and power. An imprecisely measured width due to the hardening occurs as a small deviation from the calculated width of the hardening with equation (1). However, the measurement results are fairly accurate. We are interested in conditions that return better results. In our case the most favourable solution to the problem is the hardness of the material.

Figure 8 shows the relationship between the hardness and the angle of hardening. In this graph we can see a comparison of the three different types of robot laser hardening by changing the angle of the laser beam.

Figure 9 presents the relationship between the width and the angle of hardening with regards to the perpendicular direction of the laser beam.

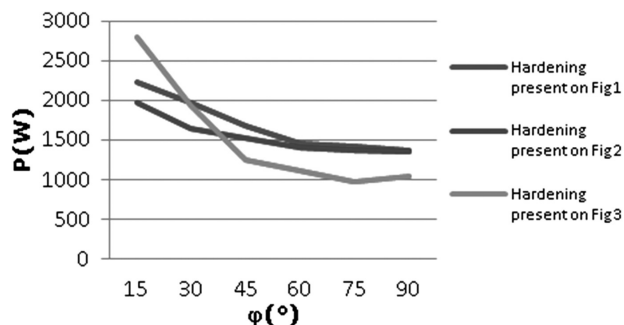


Figure 7: Relationship between the power and the angles of hardening
Slika 7: Razmerje med močjo in kotom, pod katerim kalimo

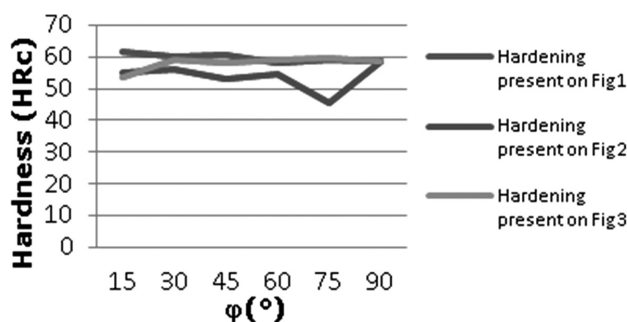


Figure 8: Relationship between the hardness and of the angle of hardening

Slika 8: Razmerje med trdoto in kotom, pod katerim kalimo

cular direction of the laser beam. We can see that by increasing the angle, the width of the hardening decreases, which we can prove with equation (1).

We analysed the graph with two different methods. First, we used linear regression. Second, we used the modelling of the relationship that was obtained by the four-layer neural network. For **Figures 4, 5** and **6** we calculated the correlation coefficient, which represents the size of the linear connection of the hardness and the fractal dimension. The correlation coefficient R for graph 1 is -0.8324 , for graph 3, -0.88263 and for graph 5, 0.65799 . We can see that the correlation coefficients are not similar. Because the correlation coefficients are not 0, the variable hardness and the angles of hardening are correlated. Smaller values of the angles tend to be linked to the hardness values, which tell us that there is a negative correlation coefficient. This is presented in **Figures 4** and **6**. But in **Figure 5** we have a different situation – a positive correlation coefficient. The purpose of this work has been to study how the angles of the robot laser cell impact on the hardness of the specimens. The presented problem could be solved in order to modify the laser beam's intensity across the width. This means that the first laser beam is divided into several parts. Then each part of the laser beam is divided into the

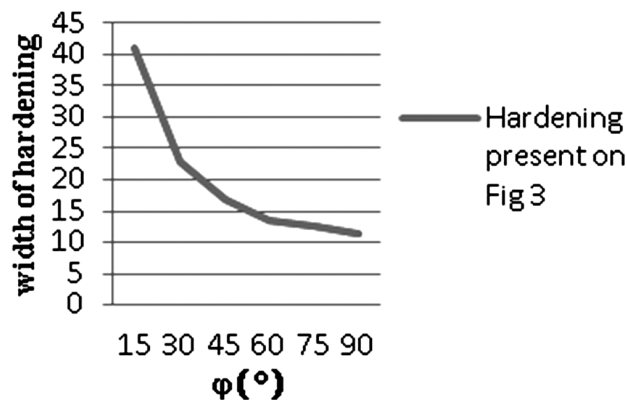


Figure 9: Relationship between the width and the angle of hardening with regards to the perpendicular direction of the laser beam

Slika 9: Razmerje med širino kaljenja in kotom kaljenja glede na pravokotno smer kaljenja laserskega žarka

specified strength. The part of the laser beam that made the longest journey gave most of the power to that part of the beam, and the part that had the shortest path to the device, gave the smallest amount of laser beam intensity.

5 CONCLUSION AND FUTURE WORK

Robot laser hardening is very useful in the automotive (e.g., machine parts for transmission shafts, axles, running surface, torsion springs, gears), military and aerospace industries. The process has several advantages over conventional induction hardening. However, even in the robot laser-hardening process there are problems, as described in this paper. Thus, we still have enough unsolved problems in robot laser hardening. Robot laser cells have several parameters that affect the final result of the hardening. These laser parameters are the power, the energy density, the focal distance, the energy density at the focus, the focal position, the temperature and the speed of germination. In the future we want to explore how different angles of the laser beam in the hardening process affect the hardened patterns in:

- dual robot laser-beam hardening (laser beam is divided into two parts),
- pixel robot laser hardening,
- robot laser hardening with changes to the velocity and the temperature of the laser beam.

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