Jozef Meško[1], Ružica R. Nikolić[2], Branislav Hadzima[2]

LASER CUTTING OF THE Zn COATED STEEL
LASERSKO SEČENJE POCINKOVANOG ČELIKA

Originalni naučni rad / Original scientific paper
UDK /UDC:

Rad primljen / Paper received: 4.10.2019

[1]) University of Žilina, Faculty of Mechanical Engineering, Žilina, Slovakia
[2]) University of Žilina, Research Center, Žilina, Slovakia
email: ruzicarnikolic@yahoo.com

Keywords
- laser cutting
- Zn-coating
- assist gas
- coating degradation
- numerical simulation

Ključne reči
- lasersko sečenje
- Zn prevlake
- pomoćni gas
- degradacija prevlake
- numerička simulacija

Abstract

Modern surface treatment technologies are used in many branches of industry as automotive, airplane, food production and others. Surface treatment technologies on one hand improve existing materials and products, while on the other hand are essential for the implementation of innovative products based on particular properties of layers and coatings. Laser beam cutting technology has previously appeared to be inapplicable for cutting steels coated with zinc. Zinc degrading from the surface layer, i.e. sublimed directly, causes health hazards to operators (so-called zinc fever). The present article examines the interaction between hot zinc coated DX53D steel and the laser CO_2 beam. Selected technological aspects of the laser beam and their influence on the width of the degraded and extruded zinc surface layer are evaluated.

Izvod

Moderne tehnologije površinske obrade se koriste u mnogim granama industrije, na primer automobilskoj, avionskoj, proizvodnji hrane i drugim. Tehnologije površinske obrade s jedne strane, poboljšavaju kvalitet postojećih materijala i proizvoda, a s druge strane su od značaja za uvodjenje inovativnih proizvoda zasnovanih na odredjenim osobinama slojeva i prevlaka. Tehnologija laserskog sečenja se već ranije pokazala kao neprihvatljiva za sečenje pocinkovanih čelika. Cink, koji se raspada sa površinskog sloja, to jest direktno sublimiše, predstavlja opasnost po zdravlje (tzv. livačka ili metalna groznica). U radu je istražena interakcija izmedju prevlake cinka nanete toplim postupkom na čelik DX53D i CO_2 laserskog snopa. Data je procena pojedinih tehnoloških aspekata laserskog snopa i njihovog uticaja na širinu degradiranog i istisnutog pocinkovanog sloja.

INTRODUCTION

Coatings are applied to the original surface of the material and typically have a different chemical composition and structure than the base material. This creates an interface with a significant change in physical-mechanical and chemical properties, which can create problems when applying coated steels in different technologies. The laser beam cutting technology was earlier considered as inapplicable for cutting of the steels coated with zinc. However, here are described two procedures for laser cutting of zinc coated steel with two different assist gases and the properties of the surface layers thus obtained, are compared.

The principle of the laser cutting of metal materials is based on the action of a focused laser beam on the material being cut. When cutting materials in technical practice, the area covered by the focused circle-shaped beam is 0.1 to 0.4 mm in diameter, depending on the design of the cutting device and the thickness of the material to be cut.

The laser beam of the above parameters, impinging on the cut material, causes it to heat up sharply. The cut material is heated to melting point within the order of milliseconds, respectively to evaporating temperature. When the laser beam is impacted on the cut material, an interaction occurs between the cut material and the laser beam itself. The phenomena following during the cutting that affect the cut material properties, depend in particular on the chemical composition of the material to be cut, as well as on the quality of its surface. The surface treated sheets, such as galvanized, coloured and blasted, and the like, can be laser cut under certain limited conditions, /1/.

The zinc protective layer is applied to steel to improve its corrosion resistance. Most often, zinc is applied by galvanizing, namely hot dip galvanizing. Cutting of galvanized sheets is accompanied by melting and evaporating of zinc in the cut zone (melting point of zinc is 420 °C and of steel 1430 °C), which results in forming of droplets of the molten and solidified material at the bottom of the cut. That causes deterioration of the cut quality. Appearance of slag on materials with a thicker layer of deposited zinc can be minimised by reducing the cutting speed. No significant differences in the laser cutting process are observed when different galvanizing technologies are applied. In addition, zinc vapours are harmful to health, thus the adequate suction, filtration and disposal of hazardous vapors must be ensured, in accordance with environmental protection. It is important to note that all metals corrode. The galvanized steels are better protected against corrosion than the unprotected ones, however they can also corrode. They are especially sensitive to corrosion on the cutting edges, /2/.

LASER BEAM INTERACTION WITH CUT MATERIAL

In the thermal separation of metal materials by laser, it is always necessary first to drill a hole in the workpiece material, from which the cutting process continues. The drilling of the hole is based on the principle of the laser drilling, which has slightly different course characteristics than are those of the cutting itself. The incident laser beam transmits the kinetic energy of photons, which is converted into heat that melts and partially evaporates the heated material, /3/.

In the laser cutting process, the material is locally heated above the melting temperature, while a stream of pure inert gas removes the material from the cutting site but does not participate in the cutting process itself. Material separation takes place during the liquid phase, so the process is laser cutting by melting. Nitrogen or noble gases can be used as the cutting gas, depending on the cut object and cut quality requirements. The lower cutting head feed rates may be used with other laser cutting methods as well. The maximal cutting speed increases linearly with laser power and decreases approximately linearly with the thickness of the cut material and with the respective melting temperature of the material. In that case, the laser beam is poorly absorbed. The cut quality deteriorates due to the molten slag at the bottom of the cut, which must be removed. A higher surface roughness is thus created, as well. Such a process is convenient in particular for the formation of non-oxidised cuts of metal materials such as stainless steel, aluminium, brass and galvanized sheet metal, /4/.

In an oxidative laser cutting process, the material at the point of impact of the laser beam is heated to its ignition temperature and burned in a stream of active oxygen gas. The oxidative effect is manifested by the initial oxidation of the laser beam (by decreasing the reflectance coefficient of light) and by formation of additional exothermic reaction heat of combustion, as well, which provides an increase in the cutting speed. Thus, the cutting process results from an exothermic reaction of the material with oxygen, /5, 6/.

The following laser cutting parameters should be set for the cutting of metals:

- the cutting speed
- the laser beam power
- rounding of sharp geometric shapes at border points
- the distance of the ignition from the cutting line
- method of onset from inflammation site to cut curve
- procedure of processing the parts
- way of creating the inflammation for small contours
- the cutting pressure
- the type of assist gas
- change of the used nozzle's cross-section
- the position of the laser beam focus point.

THE EXPERIMENTAL MATERIAL

The technical standard does not prescribe the chemical composition of the DX53D steel, however, the mechanical properties of this material are prescribed and given in Table 1. The chemical composition is determined by spectrometry, Table 2. The microstructure is shown in Fig. 1.

Table 1. Mechanical properties of DX53D steel.

Yield stress, R_{el} or $R_{p0.2}$ (MPa) max.	260
Tensile strength R_m (MPa) max.	380
Elongation A_{80} (%) min.	30
Density ρ (kg/m^3)	7850

Table 2. Chemical composition of the DX53D steel (wt. %).

C	Si	Mn	P	S	Cr	Mo	Ni
0.094	< 0.01	0.249	< 0.01	< 0.01	0.024	< 0.01	< 0.01
Cu	Al	Co	Mg	Nb	Ti	V	Fe
< 0.005	0.068	0.0076	< 0.005	< 0.005	< 0.003	< 0.005	99.51

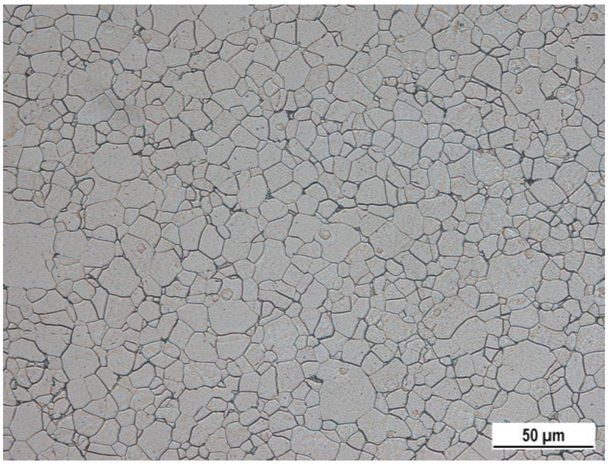

Figure 1. Appearance of steel DX53D microstructure with ferritic matrix (etchant: 1 % Nital).

EXPERIMENTAL MEASUREMENTS PRINCIPLE

Experimental measurements were designed in such a way to simply present the interaction between the amount of heat input into the cut material during the laser cutting and the amount of the degraded and sublimed zinc coating material from the vicinity of the cut. In the first phase, the experimental tests are aimed at measuring the width of the degraded and sublimed zinc coating by use of the confocal microscope.

The impact of the two most important parameters of the laser cutting is investigated, the cutting speed and the assist gas pressure. Dimensions of samples and measured values of coating thickness are shown in Figs. 2 and 3, respectively.

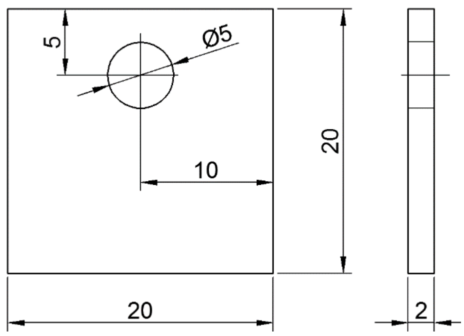

Figure 2. Appearance and dimensions of tested samples (mm).

Measuring of the width of the degraded and sublimed zinc coating by use of the confocal microscope is shown in Fig. 4.

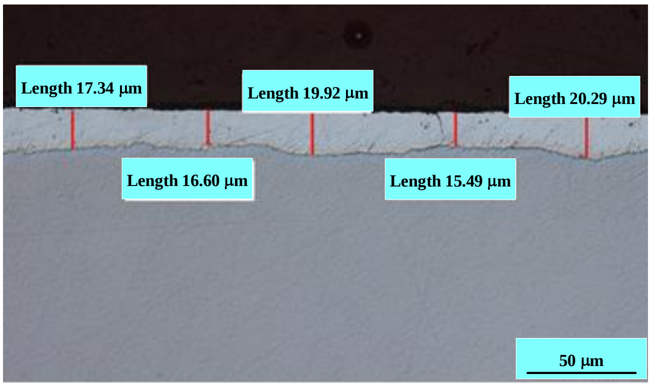

Figure 3. Measurement of Zn coating thickness in micro-ground experimental samples.

The immersion corrosion test was performed in the second phase. The immersion test was conducted for 70 days in the 3 % NaCl solution, as a simulation of real conditions. Removal of corrosion waste products was done in 20 % HCl solution. Experimental results are presented as differences of individual sample mass before and after the corrosion tests.

Experimental parameters

Summary of technological parameters of the melting laser cutting of DX53D steel are given in Table 3. The following parameters are applied:

- p – assist gas pressure,
- v_c – cutting speed,
- ALP – position of focal point,
- D_d – nozzle diameter,
- l_c – width of cut,
- P_l – laser power,
- f – laser frequency.

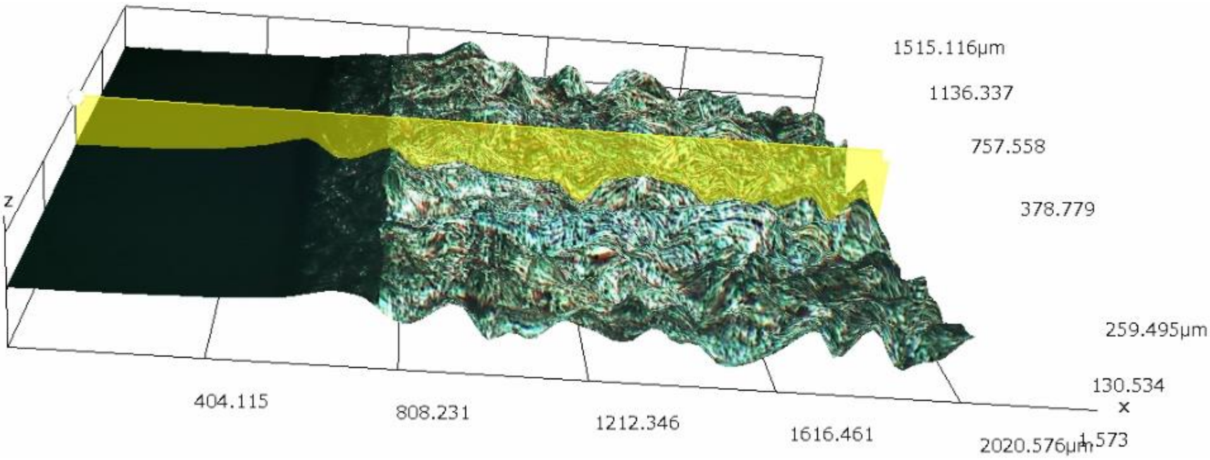

Figure 4. Measuring of the width of degraded and sublimed Zn coating by use of the confocal microscope at the laser beam entrance side.

Table 3. Technological parameters of the laser melting cutting of DX53D steel.

Gas	p (MPa)	v_c (m/min)	ALP (mm)	D_d (mm)	l_c (mm)	P_l (W)	f (Hz)
O_2	0.35-0.6	2.5-5.7	-1.0	1.0	0.25	1200	10000
N_2	1.00-1.8	5.2-6.6	-1.5	1.4	0.25	4000	10000

Measuring the width of the degraded and sublimed Zn coating of tested samples

According to this parameter, it is possible to estimate to a large extent, the width to which the whole cut sample is thermally affected. Graphical comparison of the width of the degraded and sublimed zinc coating dependence on the cutting speed for the two assist gases is shown in Fig. 5a.

From the graph presented in Fig. 5a, it follows that the laser cutting with N_2 assist gas has a beneficial effect on the width of the degraded and sublimed zinc coating region, whereby the width of the heat-affected degraded and sublimed zinc layer increases with cutting speed, on the laser beam entrance side, as well as at the laser beam exit point from the cut part. In the laser cutting, the effect of cutting speed on the amount of degraded and sublimed zinc from the cutting area is less pronounced and practically negligible.

Graphical comparison of the width of the degraded and sublimed zinc coating dependence on the assist gas pressure for two assist gases is shown in Fig. 5b.

From Fig. 5b, one can again see the suitability of using the N_2 assist gas, especially because of the high degraded and sublimed width of zinc coating layer at the laser beam exit side of oxidation cutting with the O_2 gas, while for the safety reasons, the lower values of gas pressure are used with less dispersion of values. For both the laser beam entrance and laser beam exit sides, the width of degraded and extruded zinc coating layer decreases with increasing O_2 assist gas pressure.

In the melting laser cutting, results of experimental measurements of the degraded and sublimed layer of the zinc coating indicate that when cutting the DX53D steel, the lowest values of the degraded and extruded zinc coating width performed at pressure p = 1.3-1.4 MPa, which appears to be the optimal parameter for the assist gas pressure.

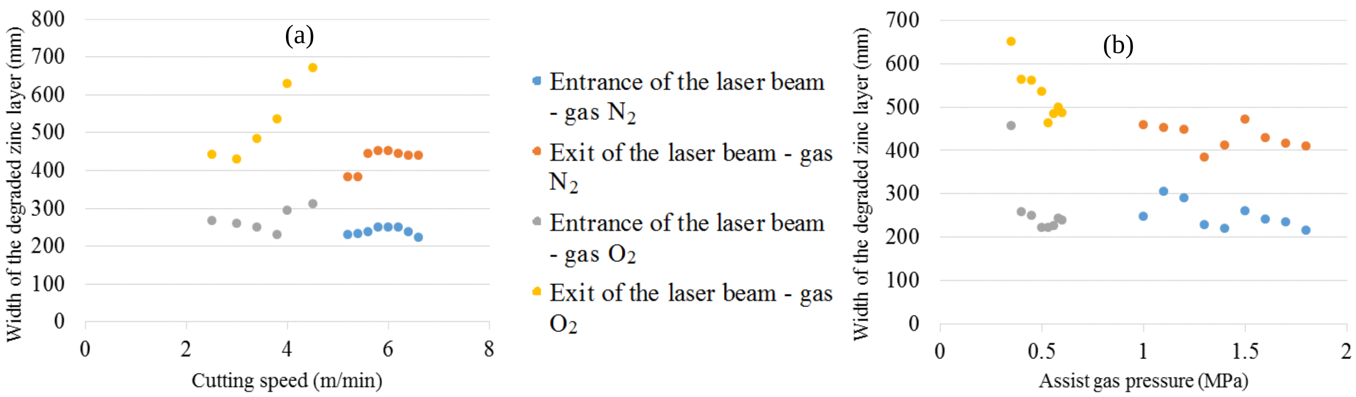

Figure 5. Comparison of the degraded and sublimed zinc coating width dependence on: a) cutting speed; b) pressure for the two assist gases.

RESULTS OF THE CORROSION IMMERSION TEST

Graphical presentation of the corrosion dependence of the degraded material on cutting speed is shown in Fig. 6a. Based on the corrosion immersion test, one can conclude that the smallest corrosion attack is at cutting speed v_c = 6 m/min with application of the N_2 assist gas, and at v_c = 3.4 m/min with the application of the O_2 assist gas.

Comparison of the two assist gases shows that application of the N_2 assist gas less affects the proportion of corrosion in the degraded material, thus adversely less affects the corrosion resistance of DX53D steel. A graphical presentation of the corrosion dependence of the degraded material on the assist gas pressure is shown in Fig. 6b.

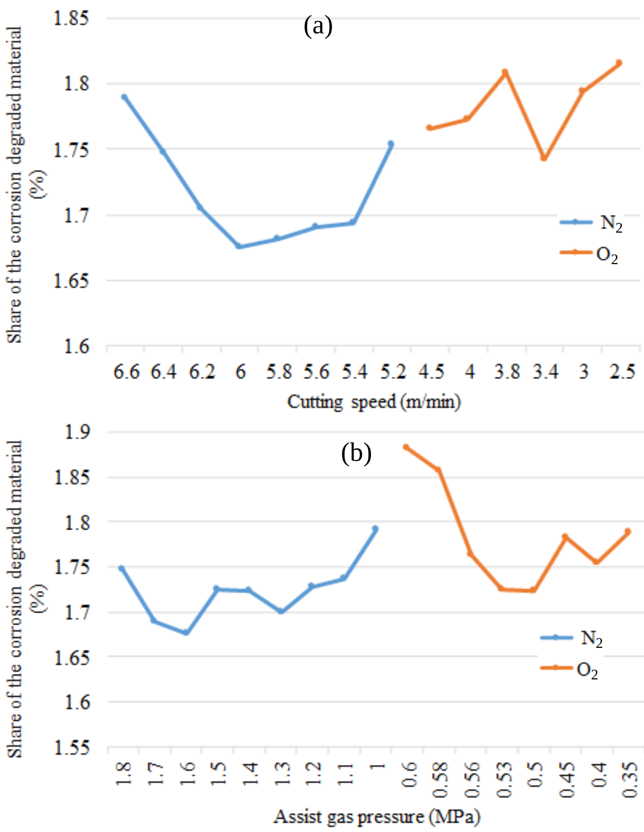

Figure 6. Presentation of degraded material corrosion dependence on: a) cutting speed; b) assist gas pressure.

From experimental measurements one can see that the smallest corrosion attack is for the gas pressure p = 0.5 MPa with application of the N_2 assist gas, and at gas pressure p = 1.6 MPa for the assist gas O_2. By comparing the results of the two applied assist gases one again concludes that the N_2 assist gas less affects the proportion of the corrosion in the degraded material, thus less adversely affects the corrosion resistance of DX53D steel.

NUMERICAL SIMULATION OF THE LASER CUTTING

A classical non-stationary analysis simulation was created for simulating the laser cutting of DX53D steel. This was the complete simulation of the laser cutting process. The said analysis is the reproduction of the thermal effects of the laser beam on the material over time, exactly as it unfolds in the actual laser cutting process. All the relevant phenomena are taken into account, such as structural transformations, nonlinear material behaviour (temperature and phase dependent material properties). The result is a non-stationary temperature field, corresponding to the real conditions, with all the implications of material behaviour.

Figure 7 presents the width of the heat affected zone (HAZ) in the DX53D steel plate model with the moving heat source. According to the performed numerical simulation, the maximum temperature of 1540 °C was found. The status shown is defined at half the cutting time of the plate. With the help of the created numerical simulation one can estimate the amount of heat introduced into the cut material at different distances from the laser beam impact point.

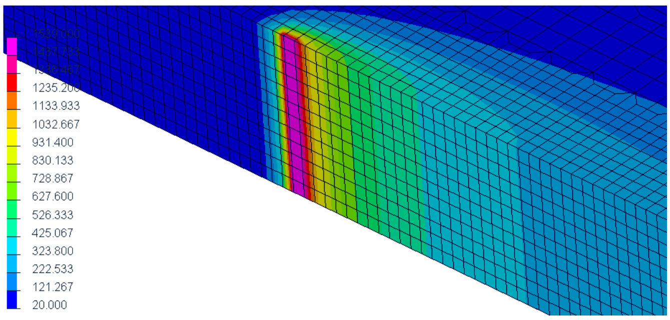

Figure 7. Detailed appearance of the HAZ at 5 s cutting time.

CONCLUSIONS

The laser beam cutting technology was previously considered as inapplicable for cutting the zinc coated steels. Zinc degrades from the surface layer and sublimes directly, causing health hazards to operators (the so-called zinc fever).

The present article examines the interaction between the hot zinc coated DX53D steel and the CO_2 laser beam. The selected technological aspects of the laser beam and their influence on the width of the degraded and extruded zinc surface layer are evaluated.

The width of the heat-affected degraded and sublimed zinc layer increases with increase in the cutting speed, both on the laser beam entrance and exit sides. In the laser cutting, the effect of the cutting speed on the amount of degraded and sublimed zinc from the cutting area is less pronounced. The N_2 assist gas has a beneficial effect on the width of the region of the degraded and sublimed zinc coating. The suitability of using the N_2 assist gas is especially emphasized due to the large degraded and sublimed width of the zinc coating layer at the laser beam exit side in the case of oxidation cutting with the O_2 gas.

What concerns the influence of the assist gas pressure, the experimental measurements show that assist gas pressure p = 1.3-1.4 MPa appears to be the optimal parameter since it produces the lowest values of the degraded and extruded zinc coating width.

The corrosion immersion test is conducted for 70 days in 3 % NaCl solution to simulate the real conditions. Removal of corrosion waste products is done in the 20 % HCl solution. Based on the corrosion immersion test, it is concluded that the smallest corrosion attack is at cutting speed of v_c = 6 m/min with application of N_2 assist gas, and at v_c = 3.4 m/min with application of O_2 assist gas. Comparison of two assist gases shows that application of N_2 less affects the proportion of corrosion of the degraded material, thus less adversely affects the corrosion resistance of DX53D steel. The smallest corrosion attack is at gas pressure p = 0.5 MPa for application of N_2 assist gas and at p = 1.6 MPa for O_2 assist gas.

A classical complete non-stationary analysis simulation was performed for the laser cutting of DX53D steel, as an exact reproduction of laser beam thermal effects on the material over time. The mesh is very fine in the vicinity of the cutting edge, with the 3D elements, the size of 0.15 mm. According to the performed numerical simulation, the maximal temperature of 1540 °C is found, defined at the half of the plate cutting time. The created numerical simulation can be used for estimating the amount of heat introduced into the cut material at different distances from the impact of the laser beam.

ACKNOWLEDGEMENTS

Research presented in this paper is partially financially supported by project KEGA 014 ŽU - 4/2016 (K-16-00-00) and by the project of Operational Program Research and Innovation: "Research and development activities of the University of Zilina in the industry of 21st century in the field of materials and nanotechnologies," No. 313011T426, co-funded by European Regional Development Fund.

REFERENCES

1. AIRPRODUCTS, Gases for laser cutting, http://www.airproducts.com/Industries/Construction/construction-Metal-Fabrication/product-list/laser-cutting-construction-metal-fabrication.aspx?itemId=0866B41845644B6D95DEEAA7E2C94211 (accessed 02.10.2019)
2. Berns, H., Thiesen, W., Ferrous Materials - Steel and Cast Iron, Springer-Verlag, Berlin, Heidelberg, 2008. doi: 10.1007/978-3-540-71848-2
3. Caristan, C.L., Laser Cutting Guide for Manufacturing, SME, Dearborn, Michigan, USA, 2004.
4. Kanematsu, H., Barry, D.M. (Eds.), Corrosion Control and Surface Finishing - Environmentally Friendly Approaches, Springer, Japan, 2016. doi: 10.1007/978-4-431-55957-3
5. Lawrence, J. (Ed.), Advances in Laser Materials Processing 1st Edition - Technology, Research and Application, Woodhead Publishing, 2010.
6. Minarik, V., Technology Lasers (in Czech), Czech Welding Society http://www.cws-anb.cz/t.py?t=2&i=228 (accessed 02.02.2018)