

MICRO AND NANOHARDNESS TESTING OF LASER WELDS

Hana SEBESTOVA¹, Radim CTVRTLÍK², Hana CHMELICKOVA¹, Jan TOMASTÍK¹

¹ Palacky University of Olomouc, Faculty of Science, RCPTM, Joint Laboratory of Optics of Palacky University and Institute of Physics of the ASCR, 17. listopadu 12, 771 46 Olomouc, Czech Republic

² Institute of Physics of the Academy of Sciences of the Czech Republic, Joint Laboratory of Optics of Palacky University and Institute of Physics of the ASCR, 17. listopadu 50a, 772 07 Olomouc, Czech Republic

E-mail: hana.sebestova@upol.cz

Local mechanical properties of pulsed Nd:YAG laser bead-on-plate welds on 0.6 thick AISI 304 stainless steel were investigated. Conventional Vickers micro-hardness, based on measurement of dimension of residual indent, and depth sensing nanoindentation were used. Measurements were performed on both transversal and longitudinal weld cross sections. Seam welds performed with the pulsed laser reached very inhomogeneous microstructure resulting from the principle of successive pulses landing on the material surface whereas each pulse partially overlaps and re-melts the area melted by the previous one. This led to the fluctuations in both Vickers microhardness and indentation hardness of the weld metal.

Key words: Vickers microhardness, depth sensing indentation, laser welding.

1. INTRODUCTION

Laser welding is a high power density technology of materials joining that has many advantages in comparison with conventional fusion welding methods, for example high accuracy, flexibility, repeatability and especially very narrow heat affected zone which results in minimal workpiece distortions [1].

Hardness tests are widely used for weld mechanical properties evaluation and thus its quality estimation. Typical increase of weld metal hardness followed by its decrease in heat affected zone can be observed in most of conventionally prepared weld joints [2]. In case of laser welding, much higher cooling rates are present and thus different weld characteristics can be expected. Especially thin sheets (< 1.5 mm) seam welding with a pulsed laser results in very small-sized welds with heat affected zone often unobservable using light microscopic techniques [3]. In such cases utilization of micro- and especially nanoindentation techniques is appropriate for reliable measurement of mechanical properties of the welded material [4–8].

2. EXPERIMENT

Pulsed Nd:YAG laser LASAG KLS 246-102 with maximal average power 150 W was used for bead-on-plate welding of 0.6 mm thick AISI 304 stainless steel sheets. Pulse repetition frequency 13 Hz, welding speed 4 mm·s⁻¹ and working distance 4 mm under the focal plane were kept constant during all experiments. Protective argon gas (8 l·min⁻¹) was applied coaxially with the laser beam. Other processing parameters are concluded in Table 1. Fig. 1 presents used laser system. Experimental set-up is displayed in Fig. 2.

Table 1

Applied processing parameters

Sample no.	Pulse length [ms]	Pulse energy [J]	Average power [W]	Peak power [kW]
I	2.6	3.5	45.5	1.35
II	3.9	4.7	61.1	1.21
III	3.4	5.9	76.7	1.74
IV	3.4	6.2	80.6	1.82

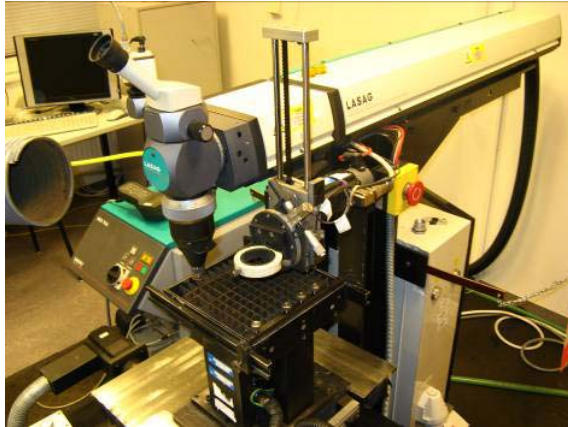


Fig. 1 – Laser system LASAG.

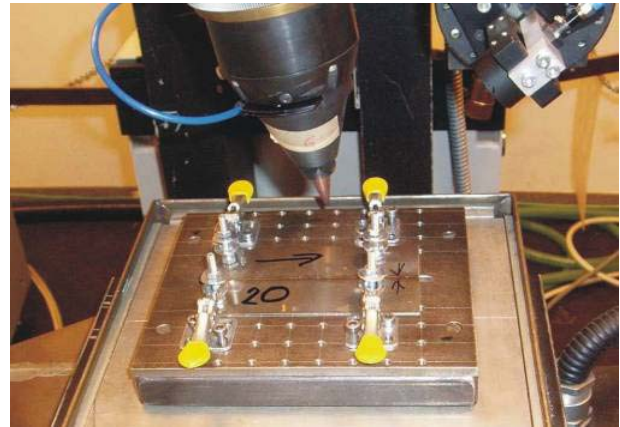


Fig. 2 – Experimental set-up.

3. HARDNESS MEASUREMENT

Laser welds were cut perpendicularly and selected welds both longitudinally to the welding direction to study its local hardness properties in detail. Polished samples of basic material and laser weld cross sections mounted in cold casting resin were etched with a mixture of hydrochloric and nitric acid (3:1) to induce their microstructure.

3.1. Vickers microhardness tests

First, basic material microhardness was evaluated using automatic hardness tester LECO AMH43 with Vickers indenter at applied load of 500 mN. Fifteen measurements were performed. The average value reached (270 ± 25) HV 0.05.

Second, metallographic specimens of cross sections perpendicular to the welding direction were analysed. Weld microhardness was measured along the centre of the weld cross section from its surface to the root in discrete points spaced by 70 μm or 100 μm , respectively. Supplemental measurements were performed perpendicularly, in the centre of the metal sheet. Fig. 3 presents weld perpendicular cross sections micrographs with the designation of indents positions and corresponding values of measured microhardness.

Laser power applied in case of sample I and II was insufficient for the full penetration. Thus only few indents lie in the weld metal. Sample I weld metal microhardness is within the tolerance limit of basic material microhardness. Little decrease of microhardness was detected 50 μm far from the weld line although no visible heat affected zone was observed using light microscope. Measurements performed in the centre of the metal sheet confirmed this decrease.

Sample II exhibits generally lower microhardness in both weld metal and basic material and it is almost constant for all investigated positions from the weld surface towards its centre. Local decrease was detected only in the centre of the metal sheet close to the weld root.

Typical microstructure of pulsed laser seam weld perpendicular cross section can be found at sample III, which results in not uniform values of weld metal local microhardness. Comparing sample III and IV corresponding to nearly similar welding conditions, very different microhardness values were detected. This is probably thanks to the different cross section position and grain orientation effect resulting from relatively small pulse overlap (63 %). Sample IV was the only one exhibiting weld metal microhardness increase and it reached about 20 %.

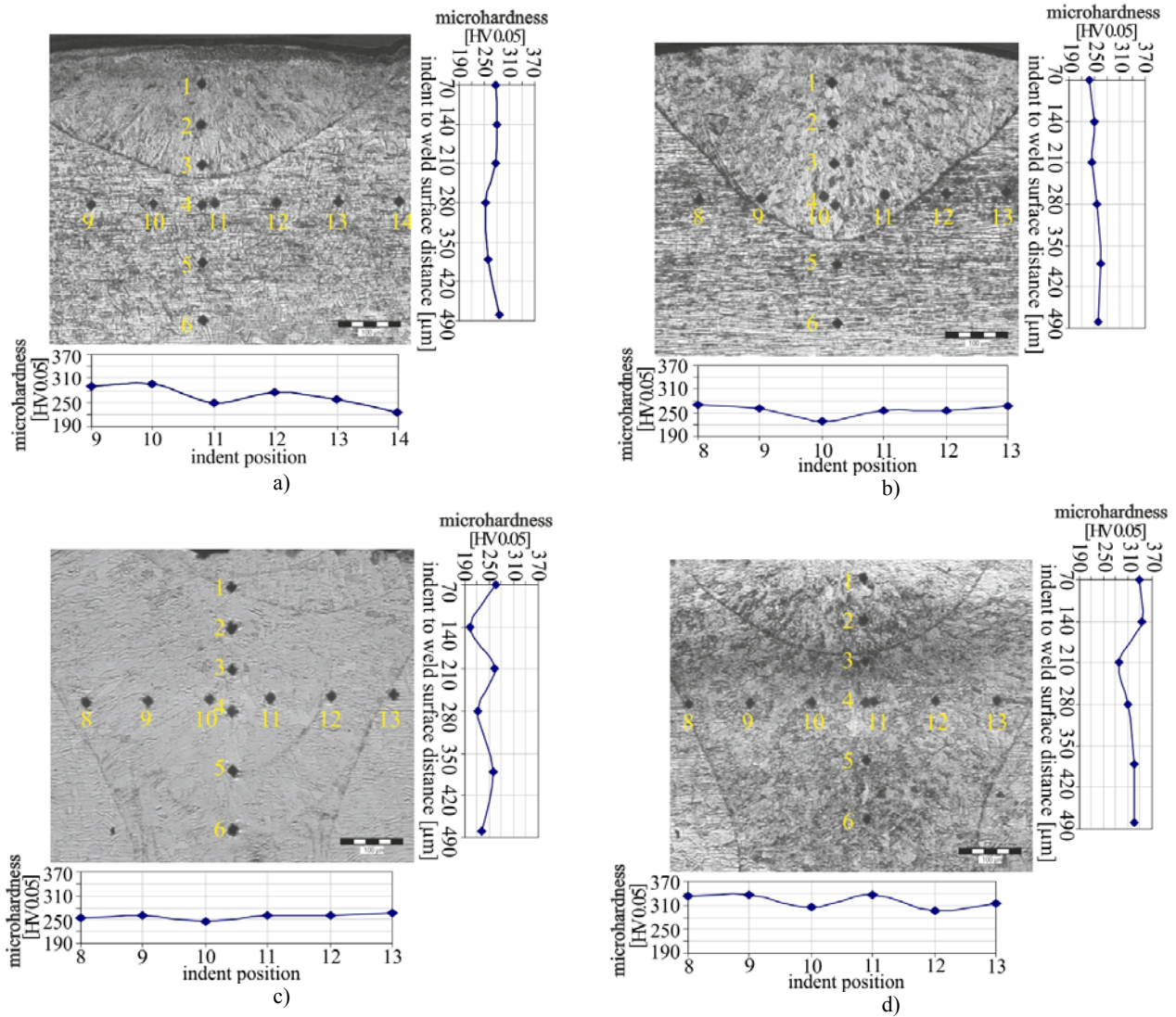


Fig. 3 – Weld perpendicular cross sections with results of Vickers microhardness tests of sample no.: a) I; b) II; c) III; d) IV.

3.2. Depth sensing indentation tests

Nanoindentation (depth sensing indentation) is a contact based technique widely used for evaluation of mechanical properties at small scales. During a typical test a diamond tip of known geometry is pressed into the sample surface, while the indentation load and depth are continuously recorded. Unlike traditional hardness measurements it allows evaluation of reduced elastic modulus or creep characteristics. Therefore it can provide us with new information about fine welds properties.

Selected samples of laser welds were also examined by the nanoindentation to study local weld properties in detail. The measurements were carried out using the fully calibrated NanoTest NTX system (MicroMaterials). Room temperature indentation with Berkovich indenter was performed at different loads. Measured indentation curves were analysed using standard method [9-10].

First, basic material and sample II indentation hardness and elastic modulus were evaluated at load of 50 mN. Basic material indentation hardness reached (2.6 ± 0.3) GPa and its reduced elastic modulus was (205 ± 11) GPa. Selected region of sample II covering both weld metal and basic material was investigated. 48 indents with spacing of 30 μm were performed over the area of 60×450 μm. The positions of indents together with measured data of sample II are displayed in Fig. 4.

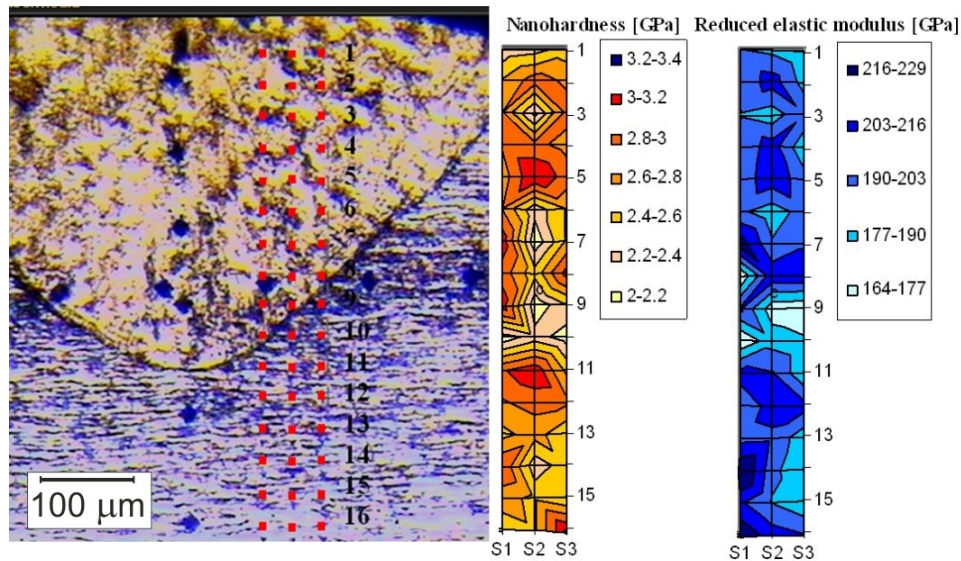


Fig. 4 – Sample II micrograph with indentation hardness and reduced elastic modulus data (measured at 50 mN).

Higher spatial resolution of nanoindentation revealed local decrease of hardness and reduced elastic modulus at the weld line of sample II. To confirm this result, sample III was investigated. Weld metal, heat affected zone and weld line were analysed on perpendicular weld cross section of sample III. Maximal indentation load was 50, 80 and 250 mN. Spacing between indents was 30 μm . Several regions of sample III were investigated in series of indents perpendicular to the weld line. An overview of regions, those nanohardness results are presented in this paper, with their designation and position towards the weld is depicted in Fig. 5.

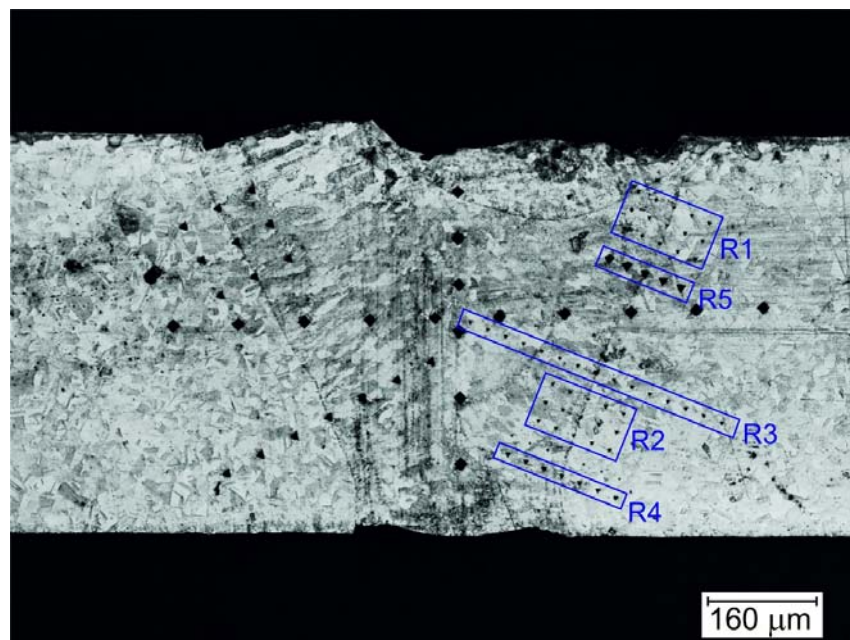


Fig. 5 – Sample III micrograph with investigated regions designation.

First, the same maximal load (50 mN) was applied as in the case of sample II. Local mechanical properties were analysed near the top, in the central and in the root region of the weld. Figs. 6 and 7 present details of investigated regions R1 and R2 with measured indentation hardness data. Very diverging values were reached at corresponding positions at region R1 both R2. Indentation hardness decrease at the weld line was identified only individually, thus general decrease of hardness on the weld line was not proved.

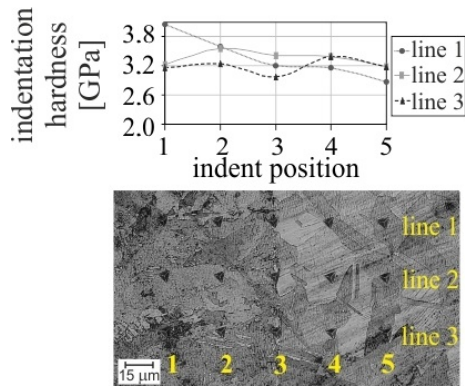


Fig. 6 – Detail of investigated region R1 of sample III with indentation hardness data (measured at 50 mN).

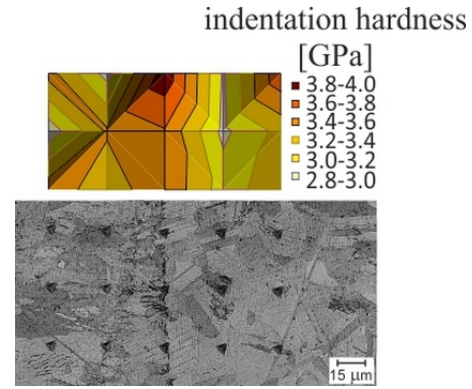


Fig. 7 – Detail of investigated region R2 of sample III with indentation hardness data (measured at 50 mN).

Depth sensing indentation provides us also with the creep data. Fig. 8 presents indentation hardness measured in region R3 of sample III together with three creep curves corresponding to the indent position 6 (weld metal), 8 (weld line) and 10 (heat affected zone/basic material). Analysed creep curves were shifted to start at the same depth, so as their shape could be easily compared. Higher hardness corresponded to the lower creep.

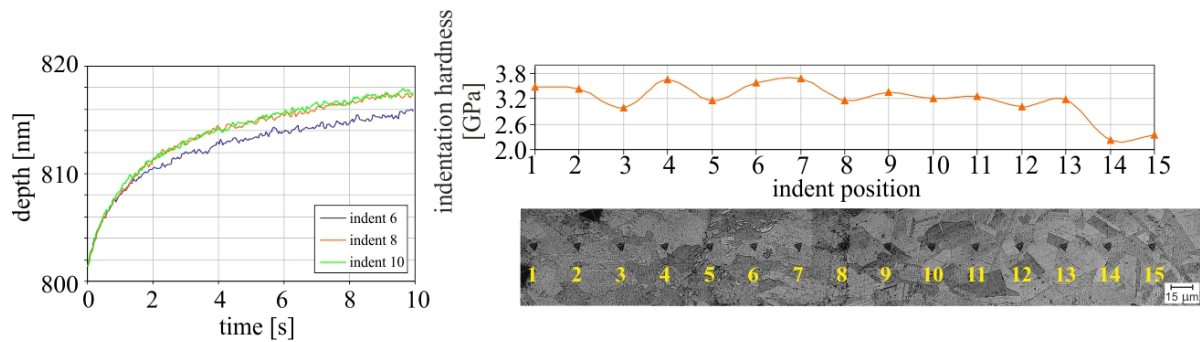


Fig. 8 – Detail of investigated region R3 of sample III with indentation hardness data and creep curves (measured at 50 mN).

Complementary measurements were performed with maximal applied load of 80 mN in region R4 (Fig. 9) and 250 mN in region R5 (Fig. 10), respectively. It is evident that increase of indentation load does not have any effect on hardness values.

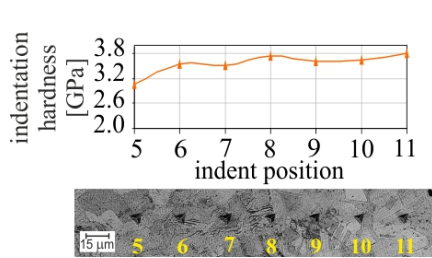


Fig. 9 – Detail of investigated region R4 of sample III with indentation hardness data (measured at 80 mN).

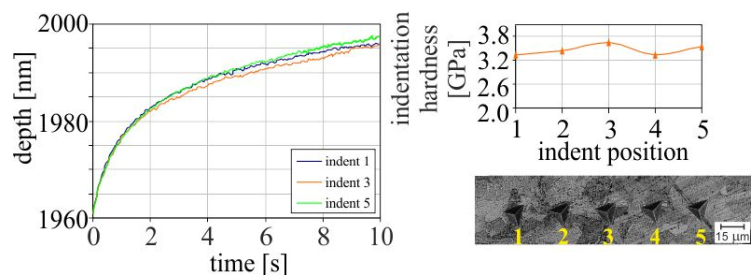


Fig. 10 – Detail of investigated region R5 of sample III with measured indentation hardness data and creep curves (measured at 250 mN).

Indentation hardness measured at sample III is generally higher in comparison to the sample II, which was also revealed by Vickers microhardness measurements.

Weld off-axis longitudinal cross section was prepared to study the effect of individual laser pulses on weld mechanical properties at the borders between regions melted by consecutive laser pulses. Both indentation hardness and reduced elastic modulus were investigated along the line with indents spacing of

60 μm with maximal applied load of 250 mN. Positions of indents together with measured data are displayed in Fig. 11. Seam welds performed with a pulsed laser have very inhomogeneous structure resulting from repetitive melting of the weld metal. Thus very different data can be found when different perpendicular cross sections of the one weld are analysed. About 10% fluctuation of indentation hardness data measured on longitudinal cross section can be observed. This fluctuation does not strictly correspond to the periodicity of the weld structure.

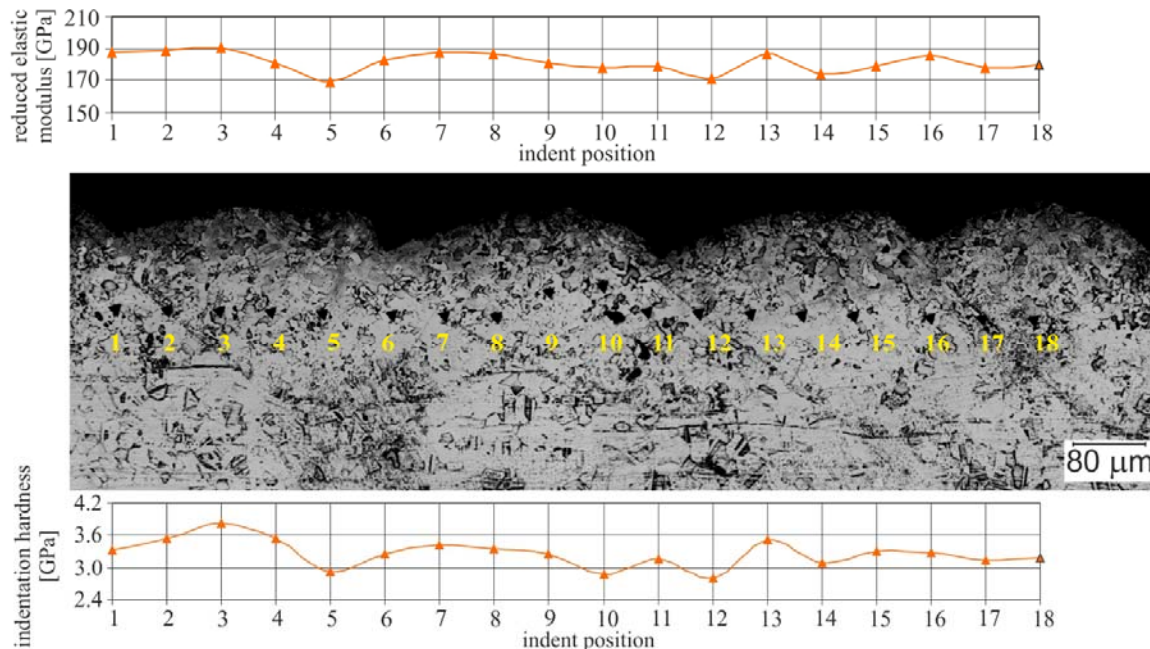


Fig. 11 – Weld off-axis longitudinal cross section with results of sample III indentation hardness and reduced elastic modulus measurements (measured at 250 mN).

4. CONCLUSION

Bead-on-plate welding experiments were carried out with different energies and pulse lengths. After the preparation of metallographic specimens Vickers microhardness and depth sensing indentation tests were performed. Basic material microhardness reached (270 ± 25) HV 0.05. Weld metal microhardness increase (+20 %) was detected only at sample IV, while other samples exhibit rather decrease (II, III) or almost no change. Typical microstructure of pulsed laser seam weld perpendicular cross section can be found at sample III, which results in not uniform values of weld metal local microhardness. Comparing sample III and IV corresponding to similar welding conditions, very different microhardness values were detected. This is probably thanks to the grain orientation effect resulting from relatively small pulse overlap (63 %). To reach average weld metal microhardness, more cross sections of the one sample would have to be evaluated.

Comparing depth sensing indentation data with respect to the indents positions, no definite relation was found. Hardness of adequate regions significantly fluctuates, which corresponds to the Vickers microhardness measurements. Individual grain orientation probably influences local hardness. Although applied maximal loads were quite high, the benefit of depth sensing indentation towards Vickers microhardness test is the possibility of reduced elastic modulus or creep characteristics measurement.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support by the Operational Program Education for Competitiveness – ESF (CZ.1.07/2.4.00/17.0014) and by the Technology Agency of the Czech Republic (TA01010517).

REFERENCES

1. DULEY, W. W., *Laser welding*, Wiley, 1999.
2. Jenney, C. L., O'Brian, A., *Welding Handbook*, Volume 1 – Welding Science and Technology, AWS, 2001.
3. STEEN, W. M., *Laser Material Processing*, Springer, 2003.
4. CHEN, J., SAND, K., XIA, M. S., OPHUS, C., MOHAMMADI, R., KUNTZ, M. L., ZHOU, Y., MITLIN, D., *Transmission Electron Microscopy and Nanoindentation Study of the Weld Zone Microstructure of Diode-Laser-Joined Automotive, Transformation-Induced Plasticity Steel*, Metallurgical and Materials Transactions A, **39A**, pp. 593-603, 2008.
5. HERNANDEZ, V. H. B., PANDA, S. K., OKITA, Y., ZHOU, N. Y., *A study on heat affected zone softening in resistance spot welded dual phase steel by nanoindentation*, Journal of Materials Science, **45**, 6, pp. 1638-1647, 2010.
6. CABIBBO, M., FORCELLESE, A., EL MEHTEDI, M., SIMONCINI, M., *Double side friction stir welding of AA6082 steels: Microstructure and nanoindentation characterization*, Materials Science & Engineering A, **590**, pp. 209–217, 2014.
7. CHARITIDIS, C. A., DRAGATOGIANNIS, D. A., KOUMOULOS, E. P., KARTSONAKIS, I. A., *Residual stress and deformation mechanism of friction stir welded aluminum alloys by nanoindentation*, Materials Science & Engineering A, **540**, pp. 226–234, 2012.
8. KOUMOULOS, E. P., CHARITIDIS, C. A., DANIOLOS, N. M., PANTELIS, D. I., *Nanomechanical properties of friction stir welded AA6082-T6 aluminum alloy*, Materials Science & Engineering B, **176**, pp. 1585–1589, 2011.
9. OLIVER, W. C., PHARR, G. M., Pharr G.M., *Improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments*, Journal of Materials Research, **7**, 6, pp. 1564-1580, 1992.
10. OLIVER, W. C., PHARR, G. M., *Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology*, Journal of Materials Research, **19**, 1, pp. 3-20, 2004.

Received February 24, 2014