Laser welding of 4330V steel with a micro-additive of vanadium

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Abstract. This article presents the results of a test of laser welding of high-strength low-alloy steel with a micro-additive of vanadium. Steel 4330V is a delivery material after heat treatment. Welded joint was made by laser welding using a TruDisk 12002 disc laser. As a result of welding, a joint was formed which was subjected to visual and penetration tests from the face side, as well as macro and microscopic tests. Impact tests were carried out at reduced temperature in the weld and in the heat affected zone (HAZ). The resulting joint was also subjected to the Vickers hardness test, bend test and the tensile strength test. This research show how the low-alloy high-strength material behaves during welding without processing before and after welding. In results after welding show incomplete penetration from the root side. No cracks on the weld face. In HAZ hardness was of 520HV 0.5 and tensile strength of joint was on level 1077 MPa.

1. Introduction
Laser welding is a very modern and clean process of joining materials without the use of filler metal. Due to the high power density at the level of 10^3-10^{11} W / mm^2, it is possible to make thick welded joints without additional material, with I chamfering, with a thickness of up to 25 mm. Disc lasers are usually used for laser welding processes due to the high power and shape of the laser spot, which guarantees a narrow and deep fusion into the base metal. Laser welding is characterized by rapid times of heating the material to the melting point, and due to the heat capacity of the material and the fact that a small heated affected zone (HAZ), the liquid metal solidifies very quickly. Such sharp welding heat cycles also apply to HAZ. Therefore, you need to know how a given metal behaves during laser welding. Especially when we are using heat-treated material [1-8].

Steel 4330V is a heat-treated material with high strength and plastic properties. This material contains 0.3% carbon and 0.06% micro vanadium additive. As a result after heat treatment a material with a tempered martensite structure is obtained. Unfortunately, the very fast heating and cooling processes affect the microstructure and properties of this steel. And the standard heat-up-cool-charts for steel are not applicable to laser processes with short heat-up and cool-down times. Understanding the behavior of 4330V steel during laser welding gives an idea of how to obtain a welded joint of appropriate quality and properties [9-12].
2. Experimental Section
The aim of the research was to determine the effect of laser welding of 4330V steel on the quality of the resulting welded joint. 4330V steel is a material with a tempered martensite structure with a micro-addition of vanadium. The figure 1 shows the microstructure of the material and the view vanadium in the material from the EDS analysis. The chemical composition of 4330V steel is not typical for well-weldable steels (table 1), therefore, during welding with conventional methods, it requires pre- and post-welding treatments to obtain the correct joint. However, due to the high strength and plastic properties (see table 2), the aim is to make the correct joints with a minimum number of additional treatments, therefore the behaviour of this material under the influence of laser welding was checked.

![Figure 1. Microstructure of base metal; view of EDS analysis: microaditive vanadium.](image)

Table 1. Chemical composition of investigated steel 4330V.

| Contents of Chemical Elements, % by Weight |
|------------------------------------------|
| C   | Cr | Ni | Mn | Mo | Si | P | S | Cu | Al | Nb | Ti | V |
|-----|----|----|----|----|----|---|---|----|----|----|----|----|
| 0.31| 0.99| 1.84| 0.9 | 0.43| 0.26| 0.012| 0.00| 0.17| 0.03| 0.029| 0.008| 0.06|

Table 2. Mechanical properties of the investigated steel 4330V.

| Yield strength, R_{0.2}, [MPa] | Tensile strength, Rm, [MPa] | Elongation, A, [%] | Work of braking, KV, -40°C, [J] | Hardness (HV) |
|-------------------------------|-----------------------------|-------------------|-------------------------------|---------------|
| 935                           | 1050                        | 19                | 89                            | 340           |

*a converted value (ksi to MPa; HRC to HV according ISO 18265 standard)

2.1. Welding process
The welding process was performed with a 12kW Trumph TruDisk 12002 disc laser cooperating with a KUKA KR30HA robot. Before the target welding was performed, trial melting was performed in order to establish the basic welding parameters. The figure 2 shows trial remelting. Then, a butt joint was made without the use of additional material. Argon gas with a purity of 99.999% was used as a gas shield. The material in the form of sheet metal with a thickness of 10mm and dimensions 230x85mm is connected along the longer edge. The edges of the joint were prepared on I. Welding was performed on one side. Run-up and run-out plates were used to obtain the correct joint along the entire length. Welding parameters are shown in the table 3.
Table 3. Welding parameters.

| Weld  | Power [W] | Welding speed [m/min] | The diameter of the focus of the laser beam [mm] | The optical fibre diameter [μm] |
|-------|-----------|-----------------------|-----------------------------------------------|-------------------------------|
| 1     | 6000      | 1.2                   | 0.4                                           | 200                           |

Figure 2. View of testing laser remelting: 3kW; 4kW; 5kW; 6kW.

3. Results and discussion

3.1. Visual and penetrate testing
As a result of welding, a weld was obtained, which was subjected to visual testing. Visual tests were performed on the basis of ISO 13919 standard. The tests were carried out in visible light with the intensity of 720lux. As a result of the tests performed, no visible defects disqualifying the joint from further tests from the face side were revealed (figure 3). Only a incompletely filled groove of the face at the level of 0.1 mm was found, qualifying the joint at level B (ISO 5817 standard), and a few traces of metal spatter. The face side joint showed incomplete penetration from the root side not meeting the quality level D. In industrial practice, such a joint would be scrapped. However, due to the nature of the research on the material, penetrant testing (PT) was performed using the colour method. The MR Chemie penetrant kit (MR70, MR79, MR68NF) was used. The test was performed in accordance with the ISO 3452 standard from the face side. Figure 4 show penetrant testing. Only an apparent indication was obtained, resulting from the flow of penetrant from under the spatter. The sample from the face side meets the requirements of the standard at the 2X level, which corresponds to the quality level B. No cracks were found in the weld face.

Figure 3. View of weld after welding. Face and root.
Figure 4. View of penetrant testing. Face of weld.

3.2. Macro and microscopic research
Macro and microscopic examinations were performed with the use of light microscopes (Olympus SZX9, NIKON ECLIPSE MA100). The sample was mounted in a thermosetting resin and then ground and etched with 4% nitrile. As a result of light microscopy tests on the cross-section of the weld, an incomplete remelting from the side of the ridge was revealed (it was welded in about 9 mm from the face), additionally, a symmetrical arrangement of the weld with a narrow HAZ area of 1 mm was found. The tested cross-section did not show gas pore and material sticking (figure 5). The weld width was from about 3mm at the top to 1mm at the bottom of the joint. As a result of microscopic examinations in the weld and HAZ (figure 6), large martensite grains were visible, which may indicate changes in properties in this area and for hardening of this area.

Figure 5. View macro of weld.

Figure 6. HAZ and weld after welding.
3.3. Impact tests basing on ISO 148

The impact toughness test was carried out on samples with a reduced cross-section (55x10x7.5), it resulted from incomplete root remelting. The samples were made in accordance with the standard, and the test was carried out using a Sunpoc JB 300B hammer with the initial energy of the hammer 150J, based on ISO 148 standard. The test was performed at temperature -40 degrees Celsius. As a result of the conducted tests, the average result of the breaking work in the weld was obtained 4-6 J, and in the HAZ at the level 20-59 J. Sample breakthroughs were brittle (figure 7(b)) and mixed (figure 7(a)).

![Figure 7](image)

**Figure 7.** Samples after impact test.; impact in HAZ; impact in weld.

3.4. Bending test basing on PN-EN ISO 5173

The bending test was performed on the face and root sides (figure 8). The material has been performed to remove face welding defects. The thickness of the samples was 7mm and the width was 20mm. The test was performed on a hydraulic press. The former was 30mm in diameter and the distance of the bending rollers was 45mm. Unfortunately, as a result of the test, cracks appeared. They were characterized by a fragile breakthrough.

![Figure 8](image)

**Figure 8.** Samples after bend test.

3.5. Vickers hardness tests basing on PN-EN ISO 9015-2

Hardness tests were carried out using a Vickers WILSON WOLPERT Micro Vickers 401MVD hardness tester. The tests were carried out in two measuring lines every 0.2 mm. Measurements were made 2 mm from the face and root of the joint (figure 9). The load was 0.5 kg. The conducted tests confirmed the results of microscopic examinations and impact tests. The material in the HAZ and in the joint has been significantly hardened (figure 10). The hardness in HAZ was even 550 HV0.5, and in the weld it was at the level of 520 HV0.5.
3.6. Tensile strength test basing on ISO 6892
Tensile strength tests were carried out on non-standard samples, due to the possibility of the maximum force of the breaking testing machine and the strength of the base metal. The samples in the breaking area had a cross section of 5 x 5 mm. During the test, the breaking occurred in the base metal, and the average value of the breaking force was 1077MPa. Figure 11 show test diagram.

Figure 9. Hardness Vickers measurement.

Figure 10. View of hardness measurement.

Figure 11. Tensile strength diagram.
4. Conclusion
Laser welding is a complicated process of joining materials. As a result of the conducted research, full remelting was not obtained. This could have been avoided by using higher welding parameters. The correct shape of the face was obtained without excessive shape defects. In terms of material, 4330V steel has maintained its continuity. There were no cracks after welding, but rapid heating and cooling caused structural changes in the weld and HAZ, which significantly hardened the material and decreased impact properties. After the welding process, the tensile strength remained at the level of the base metal around 1077 MPa. When analysing all test results, it should be stated that the heat treatment process needs to be considered, because even high-energy welding has led to structural changes leading to a reduction in the operational properties of the joint.

5. References
[1] Banasik, M.; Stano, S. 2011 The disk lasers – heat source for welding processes. *Przegląd spawalnictwa* 7 pp. 17-21.
[2] Wyszyński, D. 2016 Laser welding – selected methods. *Przegląd Spawalnictwa* 12 pp. 28-32.
[3] Kurc-Lisiecka, A.; Lisiecki, A. 2020 Laser welding of stainless steel. *J. Achiev. Mater. Manuf. Eng.* 98(1) pp. 1-9.
[4] Kurc-Lisiecka, A.; Lisiecki, A. 2019 Hybrid laser-GMA welding of high-strength steel grades. *Mater. Perform. Charact.* 8(4) pp. 614-625.
[5] Górka, J.; Stano, S. 2018 Microstructure and Properties of Hybrid Laser Arc Welded Joints (Laser Beam-MAG) in Thermo-Mechanical Control Processed S700MC Steel. *Metals* 8(2) 132.
[6] Węglowski, M.S.; Stano, S.; Michta, G.; Osuch, 2010, W. Structural Characterization of Nd:YAG Laser Welded Joint of Dual Phase Steel. *Archives of Metallurgy and Materials* 55(1) pp. 211-220.
[7] Zhang, S.; Sun, J.; Zhuc, M.; Zhan, L.; Nieab, P.; Liab, Z. 2020 Fiber laser welding of HSLA steel by autogenous laser welding and autogenous laser welding with cold wire methods. *Journal of Materials Processing Technology*. 275.
[8] Kubiak, M.; Piekarska, W.; Stano, S. 2015 Modelling of laser beam heat source based on experimental research of Yb:YAG laser power distribution. International. *Journal of Heat and Mass Transfer* 83 679-689.
[9] Żuk, M.; Górka, J.; Czapyński, A.; Adamjak, 2016 M. Properties and structure of the weld joints of quench and tempered 4330V steel. *Metaliurgija* 55 pp.613-616.
[10] Żuk, M. 2016 Wpływ obróbki cieplnej po spawaniu na własności i strukturę złączy ze stali 4330V. *Przegląd spawalnictwa* 5 pp. 71-75.
[11] Żuk, M.; Węględacz, B.; Stano, S. 2020 Hybrid welding of steel 4330V. *IOP Conference Series: Materials Science and Engineering* 916 012125.
[12] M. Żuk, J. Górka, and W. Jamrozik 2019 Simulated Heat-Affected Zone of Steel 4330V. *Materials Performance and Characterization* 8(4) pp. 606-613.