Hybrid welding of steel 4330V

M Żuk\textsuperscript{1}, B Wyględacz\textsuperscript{1} and S Stano\textsuperscript{2}
\textsuperscript{1}Silesian University of Technology, Department of Welding, Konarskiego 18a, 44-100 Gliwice, Poland
\textsuperscript{2}Research Network Łukasiewicz- Welding Institute, Błogosławionego Czesława 16-18, 44-100 Gliwice, Poland

E-mail: marcin.zuk@polsl.pl

Abstract. The article describes the hybrid welding process (Laser-MAG) of 4330V steel. This steel is a high-strength, micro-alloy material with tempered martensite structure. The microstructure of tempered martensite is obtained through the heat treatment process and through the vanadium micro-additive. Due to the high carbon content (approx. 0.3%), this material causes problems during welding and requires heat treatment before and after welding. The material's high strength and plastic properties make this material desirable on the market. Hybrid welding is a process of joining materials, where a laser beam is used to achieve deep penetration into the material, and the use of a MAG welding source results in an additional electric arc that supports the melting process of the base metal and the additional material completes the weld. Using a robotic station for hybrid welding, a 11mm thick butt joint was made of 4330V steel without heat treatment processes before and after welding. The joint was welded from two sides. After welding, a number of tests were performed to determine the properties after welding. Visual and penetration testing, macro and microscopic tests, Vickers hardness test, tensile strength test and bending test on both sides were performed. The tests showed a properly made joint with numerous splashes, but unfortunately transverse cracks in the weld were detected which resulted from the stretching of one weld by the other. Macro and microscopic examinations revealed the correct execution of the joint on a full penetration cross-section, the martensitic structure in the heat affected zone and in the weld was visualized. Destructive testing revealed, among others, an increase in hardness in HAZ (Heat affected zone) to a level of about 500HV, high tensile strength at the level of the base metal. The cracks formed on the face mean that the welding process needs to be refined to eliminate such defects.

1. Introduction

Hybrid laser arc welding (HLAW) is one of the most modern welding methods, where high-energy welding methods such as laser and conventional MAG methods (metal active gas) are used to achieve the required shape of the welded joint. For laser welding, it is possible to achieve deep penetration with a narrow heat affected zone (HAZ). Unfortunately, laser welding requires good surface matching, which results in a higher cost of joint preparation. Using the MAG method introduces additional heat into the joint and widens the HAZ, but it fills the welding groove, so that the joint has the correct geometry without any face imperfections. Hybrid laser welding is most often used for butt welding of thick steel sheets [1-7].

4330V steel is high strength low alloy steel with vanadium micro addition. High strength properties are obtained as a result of the combination of chemical composition and heat treatment of steel during
production. During welding, the material changes its microstructure, which is associated with a change in properties, so the least impact on the welded material is sought [8-11].

2. Experimental Details

The article describes the effect of HLAW welding on the properties and microstructure of steel 4330V (in tables 1 and 2 are presented the chemical composition and properties; in figure 1 are presented microstructure). A butt joint with a thickness of 11mm, bevelled at I, dimensions 230x180mm was made. Welding was made from two sides (welding seam -A-first welding, welding seam -B-second welding). The welding process was performed at the robotized station TRUMPH TruLaser Robot 5120, which included the TRUMPH TruDisk 12002 disk laser (1030nm beam) and the MAG EWM Phoenix 452 RC PULS welding machine. The hybrid head (focal length of the collimator lens \( f_{col} = 200\) mm, focal length of the focusing lens \( f_{foc} = 400\) mm) was connected to the laser using a 0.2mm diameter optical fiber. Positioning of the head and welding gun was operated with a KUKA KR30HA robot. The electrode was inclined at an angle of 65° to the welded surface. The free outlet of the electrode was 18mm and the distance from the end of the wire to the laser beam was \( a = 2\) mm. The laser head first melted the metal, then the welding torch from the MAG device followed, the welding arc additionally melted the metal and the welding wire filled the welding groove. Figure 2 shows the welding process configurations. In the welding process, an extension and coasting plate was used. A 1.2mm Filtech VM20 powder wire was used, which is recommended for welding low-alloy high-strength steels. The shielding gas used during welding was the M21 mixture (Ar 82%, CO\(_2\) 18%), the set flow rate was 18 l / min. The welding process parameters are presented in table 3.

As a result of the welding process, the welded joint shown in figure 3 was obtained. This joint was then subjected to a series of tests. At the beginning, visual and penetration tests of the obtained weld were performed. The tests were carried out from two sides in accordance with PN-EN ISO 17637 and PN-EN ISO 3452 standards. Then it was subjected to destructive tests. The tests carried out include:

- macro and microscopic test using a light microscope, samples were etched with 4% nital
- hardness tests in two measurement lines, 2 mm under surface, based on the PN-EN 9015 standard. Figure 4 shows the hardness measurement diagram.
- tensile strength tests based on EN ISO 6892.
- impact test in weld (VWT 0 / 0.5) and HAZ (VHT 1 / 0.5). Samples with dimensions of 10x10x55 mm, notch type V. The test was performed at a reduced temperature of -40°C, the initial energy of the hammer was 150J. Carried out based on the standard ISO 148.
- bend test with tensile stress from the face (RBB). 45mm spindle diameter. Made based on PN-EN ISO 5173.

![Figure 1. Microstructure of steel 4330V.](image-url)
Figure 2. Welding configuration [12].

Figure 3. Joint after welding.

Figure 4. Hardness measuring configuration.

Table 1. Chemical composition of base metal.

| Specimen       | C  | Cr | Ni  | Mn | Mo | Si | P   | S   | Cu | Al | Nb | Ti | V  |
|----------------|----|----|-----|----|----|----|-----|-----|----|----|----|----|----|
| Standard       | 0.3| 0.75| 1.65| 0.75| 0.4| 0.15| 0.035| 0.035| 0.015| - | - | - | 0.05 |
|                | -  | -  | -   | -  | -  | -  | max | max | -  | -  | -  | -  | -  |
| Tested         | 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 |

- not identified

Table 2. Properties of base metal.

| Conventional yield point $R_{0,2}$ [MPa], | Tensile strength $R_m$ [MPa], | Elongation A, [%] | Impact energy $K_V$, -40°C, [J], | Hardness (HV) $^a$ |
|-----------------------------------------|-------------------------------|-------------------|----------------------------------|--------------------|
| 935                                     | 1050                          | 19                | 89                               | 340                |

$^a$- value converted
Table 3. Welding parameters.

| Welding seam | Beam power [W] | Welding rate [m/min] | Welding feeding rate [m/min] | Welding current [A] | Arc voltage [V] | Energy [kJ/cm] |
|--------------|----------------|----------------------|-----------------------------|-------------------|----------------|---------------|
| A            | 4.5            | 1.1                  | 8.5                         | 270               | 19             | 5,253         |
| B            | 4.5            | 1.1                  | 8.5                         | 270               | 17             | 4,958         |

3. Results and discussion

Visual tests showed considerable spatter (figure 5) on the surface of the joint, in addition there was a defect in the form of wire on the weld surface. The joint showed angular shift of 1°. The face of the weld was made correctly without flooding. The face height on both sides was about 1.2-1.6mm. As a result of penetration tests (figure 6), 3 indications of 9mm in length were detected on surface A. Which disqualified the connector from further operation. They probably resulted from the transverse stretching of the weld as a result of welding on the other side of the joint.

When cutting out specimens for destructive testing, indicative points were bypassed. Macroscopic examination showed porosity in the weld, which may be due to poor parameters or moisture in the welding wire. Full penetration weld was achieved. The joint width was from 2 to 5 mm in width. The heat affected zone propagated into the material about 2mm on each side. Figure 7 shows the cross section of the tested welded joint. Microscopic studies revealed the presence of hardening structures in HAZ and in the weld. Figure 8 presents a view of the microstructure weld and heat affected zones. The hardness tests carried out using the Vickers method showed an increase in the hardness in the HAZ and weld. The first welding seam (A) showed reduced hardness due to tempering. The HAZ area was about 20-40HV harder than the weld. Figure 9 shows the hardness results for the two measurement lines.

As a result of bending tests (figure 10), it has been shown that increased hardness in HAZ affects the plasticity of the entire joint. Joint fracture was obtained regardless of bending side. They occurred in HAZ and showed the brittle nature of the crack (figure 11). In order to examine the impact strength at reduced temperatures, impact tests were carried out. The fracture energy in HAZ was above the limit 27J and average level of 51J was achieved. Unfortunately, due to the large number of gas pores in the weld (figure 11), impact tests have no real value, the breaking work was on average 15J. Samples fracture after impact testing showed the brittle nature of cracks. The tensile strength of the obtained joint met the criteria generally accepted for welded joints, a crack in the base metal and tensile strength of 1140MPa, with an elongation of approximately 11%.

Figure 5. View of spatter on surface joint.
Figure 6. Results of Penetration testing.

Figure 7. Macrostructure of HLAW joint.

Figure 8. View of microstructure: 1 – weld, 2-HAZ.

Figure 9. Results of hardness measurements.
4. Conclusions
As a result of the presented tests, it can be stated that it is possible to weld an 11mm thick welded joint with full penetration, however internal defects force us to check the cause of porosity. The results of visual tests do not clearly reject the joint. In the case of one-side welding, it would be possible to eliminate defects found after penetration tests. Obtained hardness results show the effect of tempering the welding seam A by welding on the other side, which results in a hardness about 30HV lower to hardness of the 2nd welded seam. The hardness in HAZ and in the weld was not at an excessively high level, which enabled its machining by conventional methods. In the bending test, the material obtained a crack in HAZ, which to some extent limits the use of this technology in this state. The tensile strength test was excellent because the break was obtained in the base metal and not in the joint area. In the case of steel with such a chemical composition, with an elevated carbon equivalent, impact of heat treatment after welding on the plastic properties of the welded joint should be evaluated as a further expansion of this work.

5. References
[1] Kik T and Górka J 2019 Numerical Simulations of Laser and Hybrid S700MC T-Joint Welding Materials 12 3
[2] Kurc-Lisiecka A Piwnik J and Lisiecki A 2017 Laser welding of new grade of advanced high strength steel STRENX 1100 MC Arch. Metall. Mater. 62 1651–1657
[3] Grajcar A Morawiec M Różański M and Stano S 2017 Twin-spot laser welding of advanced high-strength multiphase microstructure steel. Opt. Laser Technol. 92 52–61
[4] Naito Y Katayama S and Matsunawa A Keyhole behaviour and liquid flow in molten pool during laser-arc hybrid welding Proc. of the Intern. Con. on Laser Advanced Materials Processing (LAMP 2002), Osaka, Japan, 27–31 May 2002) 4831 357–363.
[5] Murakami T Shin M.H and Nakata K 2010 Effect of welding direction on weld bead formation in high power fiber laser and MAG arc hybrid welding. Trans. JWRI 39 175–177.
[6] Banasik M. and Urbańczyk M 2017 Laser + MAG Hybrid Welding of Various Joints. Biul. Inst. Spaw. 61(1) 6-13
[7] Banasik M, Turyk E and Urbańczyk M 2017 Spawanie hybrydowe laser + MAG elementów urządzeń dźwigowych wykonanych ze stali ulepszonej cieplnie S960QL. *Prz. Spaw.* 89(5) 23-27

[8] Grajcar A and Różański M 2014 Spawalność wysokowytwarzalnych stali wielofazowych AHSS, *Przeg. Spaw.* 3 22–27

[9] Górka J 2015 Weldability of thermomechanically treated steels having a high yield point, *Arch. of Metall. and Mater.* 60 469–475

[10] Żuk, M Górka J Czupryński A and Adamiak, M 2016 Properties and structure of the weld joints of quench and tempered 4330V steel. *Metalurgija.* 55 613–616

[11] Górka, J 2016 Microstructure and properties of the high-temperature (HAZ) of thermomechanically treated S700MC high-yield-strength steel. *Mater. Tehnol./Mater. Technol.* 50 617–621

[12] *ESAB HLAW - The process* Available at: //www.esabna.com/us/en/automation/process-solutions/hlaw/process.cfm, Accessed date: 08.04.2020