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Welding of Lifting Equipment Structures Made of Steel DOCOL 1300 M

Abstract: Because of their high temporary tensile strength and significant fatigue strength, DOCOL steels from the AHSS group (AHSS – Advanced High-Strength Steel) are often used in the fabrication of mobile platforms. The welding of the above-named steels is difficult due to the dominant martensitic structure and requires extensive experience. The article discusses the identification and adjustment of welding parameters appropriate for steel DOCOL 1300M and presents the assessment of the effect of selected process parameters, i.e. filler metal wires, shielding gas mixture and, primarily, the correct preheating temperature, on the quality of welded joints.

Key words: welding, civil engineering and transport, lifting equipment, steel DOCOL 1300M

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1. Introduction

Steel DOCOL 1300 M having a thickness of 2.1 mm is used, among other things, in the fabrication of hoisting equipment. A very important stage in the production of structural elements is the obtainment of welded joints characterised by previously assumed high tensile strength and appropriate fatigue strength. In order to increase the mechanical properties of joints, the Authors decided to add nitrogen to the shielding gas mixture during the welding process. It was assumed that the addition of nitrogen in the mixture and the thermodynamic conditions of the welding process would enable the nucleation of hard non-metallic inclusions of carbonitrides in the weld. According to reference publications, such inclusions affect the mechanical properties of the weld. A new approach to the MAG welding of steel DOCOL 1300 M is the use of nitrogen in the shielding gas mixture. At the same time, the Authors decided to determine the effect of various filler metal wires with variable carbon contents on the quality of joints. An important element related to the mechanism of nitride and carbide precipitation in the weld is concerned with providing appropriate thermodynamic process conditions including, if necessary, appropriate preheating temperature. The study discussed in the article also involved the examination of the influence of preheating temperature, various shielding gases and filler metal wires on the properties of test joints.

Scientists continue their search for materials characterised by increasingly high tensile strength and fatigue strength, necessary for the fabrication of lifting devices and mobile platforms. High-strength steels (HSS) steels provide a tensile strength of 1000 MPa, yet their fatigue strength is relatively low (below 300 MPa). Because of their high tensile strength (up to 1400 MPa) and, at the same time, high fatigue strength (above 400 MPa), steels from the DOCOL group are increasingly often used in structures of lifting elements, [4]. Steel DOCOL 1300 M is used primarily in thin-walled structures, making it possible to reduce the total weight of the entire structure. Steel DOCOL 1300 M can be welded using universal welding processes, with the MAG method being the most popular of them. Less frequently, steels from the DOCOL group are joined using mmAW processes, the TIG method or laser beam welding [5–7]. According to the manufacturer, steel DOCOL 1300 M is characterised by limited weldability as the tensile strength and unit elongation of welded joints are nearly twice lower than those of the base material. Technical reference publications contain little information related to the welding of steel DOCOL 1300 M. The primary recommendation is concerned with the reduction of linear energy during the welding process [2] (particularly in terms of structures with a wall thickness restricted within the range of 2 mm to 3 mm). Information concerning the welding of structures having thicker walls is nearly non-existent. The purpose of the article and its innovative nature is concerned with the development of a technology for welding joints made of 2.1 mm thick steel DOCOL 1300 M.

2. Materials

The research-related destructive and non-destructive tests involved the use of 2.1 mm thick steel DOCOL 1300 M. The mechanical properties and chemical composition of the steel in the as-received state are presented in Tables 1 and 2.

As can be seen, the tensile strength and yield point are high (above 1000 MPa), which undoubtedly results from the martensitic structure and the chemical composition of the steel (Table 2).

The data contained in the above-presented tables indicate that steel DOCOL 1300 M is characterised by a ten-fold higher titanium content and a significantly higher aluminium content than classical unalloyed structural steels. The pursued combined content of titanium and niobium in steels from the DOCOL group should not exceed 0.45 %. It can also be seen that steel DOCOL 1300 M is characterised

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by a very low sulphur content of 0.002 % (Table 2). Such a chemical composition of steel DOCOL 1300 M can ensure the obtainment of high tensile strength without compromising plastic properties (i.e. a unit elongation of 7 % – see Table 1).

The test involved the MAG welding of joints, performed using Ar + 10 % CO_2 and Ar + 10 % CO_2 + 1 % N_2 shielding gas mixtures. It is recommended that high-strength steels from the DOCOL group be welded primarily with the UNION X96 (G 69 6 M Mn4Ni1.5CrMo) and UNION X90 (G 69 5 M Mn4Ni1.5CrMo) filler metal wires (normalised wire designations in accordance with the EN ISO 14341 standard). The chemical composition of the filler metal wires used in the tests is presented in Table 3.

The data presented in Table 3 reveal the comparable chemical composition of both filler metal wires with slight differences concerning the contents of:
- carbon, chromium and titanium, affecting joint strength,
- molybdenum and nickel, affecting plastic properties of joints.

The assessment of the MAG-based weldability of steel DOCOL 1300 M was primarily focused on the following:
- preheating temperature,
- selection of the filler metal wire,
- selection of the shielding gas mixture.

The parameters of the MAG welding process were the following:
- filler metal wire diameter: 1.0 mm,
- arc voltage: 21 V,
- welding current: 121 A,
- (+) DC source on the electrode,
- welding rate: 350 mm/min,
- filler metal wire feed rate: 4 m/min.

The V-bevelled (60 °) sheets used in the tests of the weldability of steel DOCOL 1300 M had dimensions of 2.1 mm × 300 mm × 400 mm.

3. Test methods

The test joints were subjected to destructive and non-destructive tests. The non-destructive tests were the following:
- visual tests (VT) performed in accordance with the requirements of the PN-EN ISO 17638 standard, assessment criteria were in accordance with the EN ISO 5817 standard,
- magnetic particle tests (MT) performed in accordance with the requirements of the PN-EN ISO 17638 standard, assessment criteria were in accordance with the EN ISO 5817 standard; the tests involved the use of an REM-230 magnetic defectoscope).

The destructive tests were the following:
- bend tests involving specimen width b = 20 mm, specimen thickness 2.1 mm, bending pin diameter d = 15 mm and a bend angle of 180 °). Each specimen was subjected to face bend tests (FBB) and root bend tests (RBB) performed using an INSTRON 3369 testing machine,
- tensile tests performed using the INSTRON 3369 testing machine,
- microscopic observations (LM),
- fatigue strength tests performed using an INSTRON 8874 testing machine.

Each test was followed by the selection of specimens for further stages; the selection criterion was the lack of welding imperfections.

4. Test results and analysis

The designation of the specimens and the results of the non-destructive tests of the mobile platform are presented in Table 4.

The test results (presented in Table 4) revealed that welding parameters significantly affected the quality of the test joints. Improperly adjusted welding parameters led to the formation of small cracks (maximum 3) having a length of up to 4 mm. The formation of the above-named cracks in the joints resulted undoubtedly from the dominant martensitic structure of the test steel. The data contained in related tables revealed that the obtainment of quality welded joints in steel DOCOL 1300 M required the proper adjustment of preheating temperature. The subsequent stage involved the assessment of the quality of the joints in bend tests. The test specimens were only sampled from imperfection-free joints (Table 5).

The test results confirmed that the quality of the joints was affected by welding parameters, with preheating temperature being seemingly the most important factor.

The assessment of the joints in the bend tests was followed by the performance of tensile tests involving only those test joints which were characterised by positive results in all of the previously performed tests. The tensile strength of the joints was measured using the INSTRON 3369 testing machine. As before, subsequent tests only involved the joints free from welding imperfections (Table 5). The test results (mean value from 3 measurements) are presented in Table 6. The analysis involved immediate tensile strength and unit elongation.

The test results revealed that the joints were characterised by favourable tensile strength, yet significantly lower than that of the base material.

The next stage involved the analysis of the joint structure performed using light microscopy (LM).

The observation confirmed that the dominant structure of the joints made of steel DOCOL 1300 M was martensitic (significantly affecting fatigue strength).

The final stage involved fatigue strength tests, performed using the INSTRON 8874 testing machine having an axial force of ±25 kN and a twisting moment of ±225 Nm. The test resulted in the determination of the fatigue liming of joint Y8.

The fatigue strength test, involving the use of a stress of 430 MPa, revealed the formation of cracks in relation to a load cycle number of 1 897 494, i.e. close to the expected value of the steel fatigue limit in relation to 2 million cycles. The foregoing justified the formulation of the conclusion that the material would be characterised by infinite fatigue service life in relation to a stress value of slightly less than 430 MPa. The Wöhler curve developed for the test joint enabled the identification of the joint fatigue service life at a level of 415 MPa. The positive fatigue strength test results of the joint indicated that the structure would satisfy the requirements of operational safety.

5. Summary

High-strength steel DOCOL 1300 M is increasingly often used in the fabrication of lifting equipment and means of transport. The high strength of the steel (approximately 1300 MPa) significantly exceeds that of the welded joint

Table 1. Steel DOCOL 1300 M and its mechanical properties

Yield point R_e [MPa]	Tensile strength R_m [MPa]	Elongation A_5 [%]
1095	1290	7.1

Table 2. Chemical composition of steel DOCOL 1300 M [7]

Steel grade	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Al [%]	Nb [%]	Ti [%]
DOCOL 1300 M	0.14	0.23	1.2	0.008	0.002	0.037	0.015	0.027

Fig. 1. Microstructure of the joint made of steel DOCOL 1300 M: a) specimen Y8 (Table 5)

Table 3. Filler metal wires – chemical composition [8]

UNION	C [%]	Si [%]	Mn [%]	P [%]	Cr [%]	Mo [%]	Ni [%]	Ti [%]
X90	0.10	0.75	1.8	0.01	0.35	0.6	2.35	0.005
X96	0.11	0.82	1.8	0.01	0.45	0.7	2.45	0.007

Table 4. Results of the non-destructive tests (NDT) of the joints made using the Union X 90 filler metal wire (own elaboration)

Specimen symbol	Filler metal wire	Shielding gas	Preheating temperature [°C]	Observation results
Y1	Union X90	Ar + 10 % CO_2	100	Lack of imperfections
Y2	Union X90	Ar + 10 % CO_2 + 1 % N_2	100	Lack of imperfections
Y3	Union X96	Ar + 10% CO_2	100	Cracks
Y4	Union X96	Ar + 10 % CO_2 + 1 % N_2	100	Cracks
Y5	Union X90	Ar + 10 % CO_2	120	Lack of imperfections
Y6	Union X90	Ar + 10 % CO_2 + 1 % N_2	120	Lack of imperfections
Y7	Union X96	Ar + 10 % CO_2	120	Lack of imperfections
Y8	Union X96	Ar + 10 % CO_2 + 1 % N_2	120	Lack of imperfections
Y9	Union X90	Ar + 10 % CO_2	140	Lack of imperfections
Y10	Union X90	Ar + 10 % CO_2 + 1 % N_2	140	Lack of imperfections
Y11	Union X96	Ar + 10 % CO_2	140	Cracks
Y12	Union X96	Ar + 10 % CO_2 + 1 % N_2	140	Cracks

Table 5. Bend test results (own elaboration)

Specimen symbol	FBB	RBB
Y1	positive	negative
Y2	positive	positive
Y5	positive	positive
Y6	positive	positive
Y7	positive	positive
Y8	positive	positive
Y9	positive	negative
Y10	negative	positive

Table 6. Tensile test results of the joints made of steel DOCOL 1300 M (own elaboration)

Specimen symbol	R_m	ε
Y2	735	5.1
Y5	744	5.2
Y6	752	5.2
Y7	768	5.1
Y8	783	5.0

(ok. 750 MPa). The unit elongation of the joint in relation to previously applied welding processes exceeds 5 %. In view of the foregoing, it is necessary to develop new solutions enhancing the weldability of martensitic advanced high-strength steels (AHSS), enabling a simultaneous increase in immediate tensile strength and the improvement of the unit elongation of welded joints. An additional difficulty is encountered when welding structures having thicknesses exceeding 5 mm, for which there are no guidelines. The Authors of the article decided to test various welding process parameters including the composition of filler metal wire and that of the shielding gas mixture as well as the preheating temperature. The above-presented tests revealed that the obtainment of proper welded joints in 2.1 mm thick steel DOCOL 1300 M required preheating at a temperature of 120 °C.

The most favourable test results were obtained in relation to joint Y8 and the following welding process conditions/parameters:

- preheating temperature of 120 °C,
- use of the UNION X 96 filler metal wire,
- use of the Ar + 10 % CO_2 + 1 % N_2 shielding gas mixture.

The UNION X96 filler metal wire was characterised by lower carbon and chromium contents than those of the UNION X90 filler metal wire, which translated into increased strength. The Ar + 10 % CO_2 + 1 % N_2 shielding gas mixture provided nitrogen which bonded with titanium and formed titanium carbonitrides, hardening the weld. Overly low preheating temperature did not provide effective protection against hydrogen accessing the joint, whereas excessively high preheating temperature led to the formation of the excessively wide heat affected zone (HAZ).

REFERENCES

[1] Skowrońska B., Szulc J., Chmielewski T., Golański D.: Wybrane właściwości złączy spawanych stali S700 MC wykonanych metodą hybrydową plazma + MAG. Welding Technology Review, 2017, vol. 89, no. 10, pp. 104–111.

[2] Silva A., Szczucka-Lasota B., Węgrzyn T., Jurek A.: MAG welding of S700MC steel used in transport means with the operation of low arc welding method. Welding Technology Review, 2019, vol. 91, no. 3, pp. 23–30.

[3] Jaewon Lee, Kamran Asim, Jwo Pan: Modeling of failure mode of laser welds in lap-shear speciments of HSLA steel sheets. Engineering Fracture Mechanics, 2011, vol. 78, no. 2, pp. 374–396.

[4] Darabi J., Ekula K.: Development of a chip-integrated micro cooling device. Microelectronics Journal, 2003, vol. 34, no. 11, pp. 1067–1074, https://doi.org/10.1016/j.mejo.2003.09.010.

[5] Prijanovič U., Prijanovič Tonkovič M., Trdan U., Pleterski M., Jezeršek M., Klobčar D.: Remote Fibre Laser Welding of Advanced High Strength Martensitic Steel. Metals 2020, vol. 10, no. 4, pp. 533, https://www.mdpi.com/2075-4701/10/4/533.

[6] Golański D., Chmielewski T.: Skowrońska B., Rochalski D.: Advanced Applications of Microplasma Welding. Biuletyn Instytutu Spawalnictwa, 2018, vol. 62, no. 5, pp. 53–63. http://dx.doi.org/10.17729/ebis.2018.5/5.

[7] Krupicz B., Tarasiuk W., Barsukov V.G., Sviridenok A.I.: Experimental Evaluation of the Influence of Mechanical Properties of Contacting Materials on Gas Abrasive Wear of Steels in Sandblasting Systems. Journal of Friction and Wear, 2020, vol. 41, no. 1, pp. 1–5.

[8] Shwachko V.I.: Cold cracking of structural steel weldments as reversible hydrogen embrittlement effect. International Journal of Hydrogen Energy, 2000, vol. 25, no. 5, pp. 473–480.

[9] Łabanowski J., Fydrych D.: Oznaczanie zawartości wodoru dyfundującego w stopiwie. Prace Naukowe Politechniki Warszawskiej. Mechanika, 2009, z. 229, pp. 75–84.

[10] Lahtinen T., Vilaça P., Peura P., Mehtonen S.: MAG Welding Tests of Modern High Strength Steels with Minimum Yield Strength of 700 MPa. Appl. Sci. 2019, vol. 9, no. 5, art. no. 1031.

[11] Matlock D.K., Speer J.G., de Moor E.: Recent AHSS Developments for Automotive Applications: Processing, Microstructures, and Properties, Addressing Key Technology Gaps in Implementing Advanced High-Strength Steels for Automotive Lightweighting February 9–10, 2012, USCAR Offices, Southfield, MI.

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