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# 10. MODERN WELDED CONSTRUCTIONS FOR A SMART CITY AND THE TRANSPORT OF THE FUTURE

## 10.1. Introduction

As a result of updating the regulations on exhaust emissions in road transport, numerous additional components are installed in motor vehicles, such as: exhaust gas catalysts, diesel particulate filters, additional exhaust system components, e.g. injectors. On the one hand, these components significantly reduce the emission of harmful substances, and on the other, they contribute to increasing the total weight of the vehicle. According to literature data, the weight of heavy goods vehicles with additional components installed, it can increase by even 200 kg[4].

To prevent this from happening, vehicle manufacturers and constructors are looking for solutions to reduce the weight of the vehicle, i.e. making the structure slimmer, while maintaining its appropriately high functional properties. Therefore, in recent years there has been a rapid development of materials used for the production of thin-walled vehicle structures. These structures are usually made using the following bonding methods[5]:

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[4] 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, p. 104–111. http://dx.doi.org/10.26628/ps.v89i10.825; Skrzymowski W.: Podesty ruchome i przejezdne budowa i eksploatacja. Wydawnictwo i Handel Książkami „KaBe" s.c., Krosno 2011; Polko W.: Konserwacja podestów ruchomych przejezdnych, Wyd. Kabe, Krosno 2015.

[5] 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, p. 104–111. http://dx.doi.org/10.26628/ps.v89i10.825.

- MIG / MAG shielding gas welding,
- TIG welding,
- submerged arc welding,
- laser welding,
- MMA welding,
- electron beam welding,
- plasma and microplasma welding,
- spot and seam welding.

The mentioned processes are applicable to the construction of most means of road, air and sea transport[6]. Welding processes include: truck frames, skeletons of self-supporting bodies, passenger car bodies, self-unloading bodies, fixed bodies (tanks, containers), cabins, elements of mobile platforms, etc.[7].

Striving to reduce the total weight of vehicles and increase the safety of their use has translated into an increased interest of manufacturers in new grades of steel that can be used in the automotive industry. This trend concerns especially high-strength steels such as HSS (High-Strength Steel) and AHSS (Advanced High-Strength Steel). The use of high-strength steels in means of transport allows for a significant reduction in vehicle weight, which translates into a reduction in fuel consumption and the reduction of harmful gas emissions to the environment. These steels are being used more and more in the construction of means of transport due to their high[8]:

- temporary tensile strength,
- yield point,
- fatigue strength,
- impact strength.

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Implementation of high-strength steels into vehicle structures made it possible to reduce the thickness of metal sheets of vehicle load-bearing structures, with a simultaneous increase in mechanical properties in comparison with unalloyed steels[9]. Therefore, HSS and AHSS steels have found application as a new material used in the production of mobile platforms. The strength properties of these steels, especially their high immediate tensile strength at the level of 1400 MPa, made it possible to design a thin-walled pole-boom structure with significantly increased load capacity and operating range, compared to the structure used so far[10]. An example of a movable platform with the possibility of extending the mullion-boom is shown in Figure 10.1.

The advantages determining the rapid development of HSS and AHSS steels in the automotive industry are also their easy forming and machining.

Welding of high-strength steels is not well known yet, which translates into a limitation of their use in welded structures. Welded joints of high-strength steels are characterized by worse mechanical properties than the parent material, especially lower tensile strength and impact strength[11]. Moreover, the connectors are prone to breakage. This is due to the dominant martensitic structure in the parent material and the presence of coarse ferrite in the joint structure.

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[11] Darabi J., Ekula K.: Development of a chip-integrated micro cooling device. Microelectronics Journal, 2016, Vol. 34, Issue 11, p. 1067–1074, https://doi.org/10.1016/j.mejo.2003.09.010; Hadryś D.: Impact load of welds after micro-jet cooling. Archives of Metallurgy and Materials, 2015, Vol. 60, Issue 4, pp. 2525–2528, https://doi.org/10.1515/amm-2015-0409.

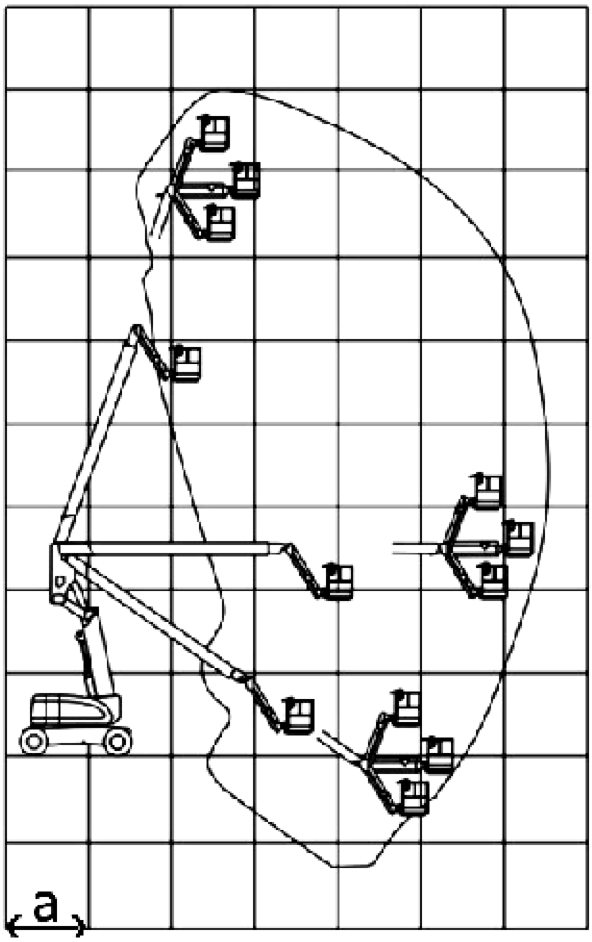


Fig. 10.1. Working area for the cantilever mobile platform, where a = 1 m
Rys. 10.1. Obszar roboczy dla podestu ruchomego przejezdnego wysięgnikowego, gdzie a = 1 m
Source: Based on https://www.jlg.com/pl-pl/equipment/engine-powered-boom-lifts/telescopic/400-series/400s-2015.

The aim of the study is to select welding parameters for selected steel grades from the HSS and AHSS groups intended for use in the construction of modern means of transport. It was decided that the new proposed material and technological solution should meet the passive safety requirements of the obtained welded structure, the measure of which, in welded structures, is good impact strength and fatigue strength of joints.

## 10.2. Materials used for research

To assess the weldability, it was decided to select the following new grades of high--strength steels: S 960 QL (representative of the HSS material group) and DOCOL 1200M and DOCOL 1400M steels (steels from the AHSS group). The mechanical properties of the tested HSS and AHSS steels, as delivered, are shown in Table 10.1.

Table 10.1

Selected HSS i AHSS steels and their mechanical properties

| Steel grade | YS, MPa | UTS, MPa | Elengation $A_5$,% |
|---|---|---|---|
| DOCOL 1400 | 1155 | 1380 | 7.3 |
| DOCOL 1200 | 1007 | 1220 | 10.5 |
| S 960 QL | 975 | 1107 | 9.1 |

Source: Own study.

High tensile strength and correspondingly high plastic properties (Table 10.1) result from the chemical composition of the tested steel grades. The information contained in Table 10.2 shows that these steels contain a much higher content of titanium than classic unalloyed structural steels and a controlled, low sulphur content of 0.001–0.002% in the case of AHSS steel (Table 10.2). These elements, to a large extent, determine the mechanical properties of the discussed steel grades.

Table 10.2

Selected HSS i AHSS steels and their chemical composition

| Stal | C, % | Si,% | Mn,% | P, % | S,% | Al,% | Nb,% | V, % | Ti,% |
|---|---|---|---|---|---|---|---|---|---|
| S960 QL | 0.12 | 0.25 | 1.3 | 0.02 | 0.01 | 0.015 | 0.05 | 0.05 | 0.017 |
| DOCOL 1200M | 0.14 | 0.21 | 1.3 | 0.008 | 0.001 | 0.045 | 0.015 | 0.02 | 0.025 |
| DOCOL 1400M | 0.17 | 0.2 | 1.4 | 0.009 | 0.002 | 0.04 | 0.015 | 0.01 | 0.025 |

Source: 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, p. 23–30.

Plates were prepared and welded for testing the weldability of HSS and AHSS steels 4 mm thick, with a V-bevel with an angle of 60 °. The joints were made using the MAG (Metal Active Gas) process with shielding gas in the form of the recommended mixture: 90% Ar + 10% $CO_2$. The UNION X96 electrode wire was selected for welding the steel. The chemical composition of the electrode wire is given in Table 10.3.

Table 10.3

Electrode wire UNION X96 – chemical composition

| C, % | Si, % | Mn, % | P, % | Cr, % | Mo, % | Ni, % | Ti, % |
|---|---|---|---|---|---|---|---|
| 0.11 | 0.8 | 1.8 | 0.01 | 0.45 | 0.65 | 2.45 | 0.007 |

Source: Own study.

The analysis of the information provided in Table 10.3 shows that the carbon content in the electrode wire is similar to the content of this element in the tested high-strength steels, while the content of other elements is at a different level. First of all, nickel, chromium and molybdenum are additionally introduced in the electrode wire to increase the strength and plastic properties of the weld metal. Welding for all tested materials was carried out with the use of a forming copper backing. The samples of all joined steels were prepared in two variants:

- without preheating,
- with a preheating of 105°C, of a drying nature, which mainly leads to a reduction in the hydrogen content in the weld
- without preheating,
- with a preheating of 105°C, of a drying nature, which mainly leads to a reduction in the hydrogen content in the weld.

The MAG welding parameters of the tested steels were as follows:

- the diameter of the UNION X96 electrode wire was 1.0 mm,
- arc voltage was 18.5 V,
- welding current 122 A,
- the dirrect current source (+) on the electrode,
- the welding speed for each material was changed twice: 330 mm/min and 430 mm/min.

The samples prepared in this way were sent for testing.

## 10.3. Research

After welding the samples with the MAG process with shielding gas in the form of the recommended mixture 90% Ar + 10% $CO_2$MAG non-destructive testing (NDT) was carried out, which included:

- visual examination (VT); according to the requirements of PN-EN ISO 17638, evaluation criteria according to EN ISO 5817,
- magnetic particle testing (MT; according to PN-EN ISO 17638, the test was assessed according to EN ISO 5817, with a device for testing with a magnetic flaw detector, type REM – 230.

The research was aimed at selecting joints without welding defects and incompatibilities. Only properly made joints were qualified for further analysis. The temporary tensile strength test of the welded elements of the mobile landing was carried out on the INSTRON 3369 testing machine, with three tests for each sample. Due to the fact that the minimum strength of 550 MPa corresponds to the required tensile strength of the materials used for the mobile landing elements, joints with strength equal to or higher than this level were submitted for further tests. A bend test was performed on these materials.

The parameters of the samples were as follows: sample width b = 20 mm, sample thickness 3 mm, pin d = 14 mm, support spacing d + 3a = 31 mm and the required bending angle of 180°. Five measurements were made in a bending test for each sample from the root side and from the face side. Samples that passed all tests with positive results and were characterized by the best parameters for use in the construction of mobile platforms, they were additionally tested:

- in terms of fatigue strength with the number of load cycles close to the expected value for the steel fatigue limit for 2 million cycles.
- and then subjected to an impact test. The impact test was performed at -20°C and 0°C.

## 10.4. Results and discussion

The results of non-destructive testing of joints, obtained in accordance with the methodology presented in the previous sections of the study, are presented in Table 10.4.

Table 10.4

NDT results

| Sample | Steel | Pre-heating, 105°C | Welding speed, mm/min | observation |
|---|---|---|---|---|
| Pb1 | S960 QL | no | 330 | cracks |
| Pb2 | DOCOL 1200M | no | 330 | good weld |
| Pb3 | DOCOL 1400M | no | 330 | cracks |
| Pz1 | S960 QL | 105°C | 330 | good weld |
| Pz2 | DOCOL 1200M | 105°C | 330 | good weld |
| Pz3 | DOCOL 1400M | 105°C | 330 | good weld |
| Pb4 | S960 QL | no | 430 | cracks |
| Pb5 | DOCOL 1200M | no | 430 | good weld |
| Pb6 | DOCOL 1400M | no | 430 | cracks |
| Pz4 | S960 QL | 105°C | 430 | cracks |
| Pz5 | DOCOL 1200M | 105°C | 430 | good weld |
| Pz6 | DOCOL 1400M | 105°C | 430 | cracks |

Source: Own study.

Based on the information in the table, it can be concluded that the choice of line energy and preheating have a significant impact on the properties of the joint. Dry pre--heating is recommended for correct welding of S960 QL and DOCOL 1400 steels. The value of linear energy has a similar effect on the quality of joints from the analyzed steel grades. Welding with too high a speed of 430 mm/min more often leads to cracks than welding at a lower speed of 330 mm/min. The analysis of the obtained test results showed that only in the case of DOCOL 1200M steel, there were no cracks during welding without preheating and with heating, and no significant influence of the welding speed on the quality of the obtained joints was noted.

After the joints were assessed by non-destructive testing, the temporary tensile strength of the welded elements of the mobile landing was tested. The following samples were tested on the INSTRON 3369 testing machine: Pb2, Pz1, Pz2, Pz3, Pb5, Pz5, the quality of which was satisfactory after the NDT tests (Table 13.4). The results of the endurance tests (average of 3 tests) are presented in Table 10.5.

Table 10.5

Tensile resistant results

| Sample | Steel | UTS | $A_5$ |
|---|---|---|---|
| Pz1 | S960 QL | 611 | 7.8 |
| Pb2 | DOCOL 1200M | 711 | 8.3 |
| Pz2 | DOCOL 1200M | 719 | 8.2 |
| Pz5 | DOCOL 1200M | 703 | 8.2 |
| Pb5 | DOCOL 1200M | 701 | 8.2 |
| Pz3 | DOCOL 1400M | 903 | 6.6 |

Source: Own study.

The tabular data shows that only in the only case, for DOCOL 1400M steel, a very high tensile strength of over 900 MPa was obtained. After welding DOCOL 1200M steel, regardless of the parameters used (linear energy, preheating), the temporary tensile strength of over 700 MPa was always obtained. The strength of the joint made of 960 QL steel was over 600 MPa. By analysing the results, it can be concluded that the obtained values of the tensile strength of the joints are significantly lower than the tensile strength of the parent material (see Table 13.1). The results of the measurements show that all joints had acceptable strength for the construction materials intended for the analysed means of transport. All joints had a tensile strength well above the required 550 MPa. Moreover, it was found that all the tested samples had relatively good and comparable plastic properties.

Then, a bend test was carried out for all tested joints at the required bending angle of 180°. In the bending test, 5 measurements were made for each sample from the root side and from the face side. Regardless of the type of steel used, no cracks were found in the joints in the joints and in the HAZ, both on the root and face sides. No other non--conformities were found either. This means that the evaluation of the tests is positive for all tested materials.

The penultimate stage of the research was to check the fatigue strength. Joints made of S960 QL, DOCOL 1200 and DOCOL 1400 steel were tested and they were made with a welding speed of 330 mm/min and with the use of preheat at 105°C. These joints were selected because they had the best strength properties, as determined in previous tests, and were free from welding imperfections.

The fatigue test with a fixed value of stress applied at the level of 250 MPa for steel S960 QL (sample Pz1), showed the occurrence of cracking at the number of load cycles 1 913 257, close to the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that with a stress value slightly below 250 MPa, the material will have an infinite fatigue life. The fatigue limit of the tested welded joint of S960 QL steel was estimated at 225 MPa.

The fatigue test with the applied stress at the level of 450 MPa for the DOCOL 1200M steel (sample Pz2), showed the occurrence of cracking at the number of load cycles 1,893,201, as low as the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that at a stress value slightly below 450 MPa, the material will have infinite fatigue life. Therefore, the fatigue limit of the tested welded joint of DOCOL 1200M steel was estimated at 430 MPa. The fatigue test with the applied stress at the level of 500 MPa for the DOCOL 1400M steel (sample Pz3), showed the occurrence of cracking at the number of load cycles 1,845,378, close to the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that with a stress value slightly below 500 MPa, the material will have infinite fatigue life. In this case, the fatigue limit of the tested welded joint of DOCOL 1400M steel was estimated at 480 MPa.

Positive results of the joint fatigue strength tests allow for a statement that the design of the means of transport will meet the conditions of operational safety. It is noteworthy that the greatest difference between joints made of steel from the HSS group and steel from the AHSS group is related to with fatigue life to the disadvantage of joints made of HSS steel. The final stage of the research was the impact toughness test, which was carried out at -20°C and 0°C. As in the previous test, the MAG joints with preheating were tested and marked as: Pz1, Pz2, Pz3. The results of the impact toughness tests are presented in Table 10.6.

Table 10.6

Impact toughness results

| Symbol próbki | Materiał | KV (at -20° C) | KV (at 0° C) |
|---|---|---|---|
| Pz1 | S960 QL | 32 | 52 |
| Pz2 | DOCOL 1200M | 49 | 61 |
| Pz3 | DOCOL 1400M | 39 | 53 |

Source: Own study.

Based on the information in Table 13.6, it can be concluded that the impact toughness at 0° C is above the required value of 47 J. This means that the welded structure of the means of transport made of the tested materials with selected MAG process parameters will be characterized by resistance to cracking under dynamic loading. and therefore the safety of its use will be ensured. The best impact strength has a joint made of DOCOL 1200M steel, where the high second class of impact strength is met. High impact toughness values are related, among others, to with the amount of heat input for the steel grades to be welded and properly selected linear welding energy, which is influenced by the selected process parameters: welding speed and welding current. Thus, it can be unequivocally stated that appropriate bonding parameters were selected and applied to make the joints.

## 10.5. Summary

Increasingly used materials in the construction of means of transport are high--strength steels HSS and AHSS. These steels are dominated by a martensitic structure which does not correspond to good weldability. In order to obtain the correct joints with the best mechanical properties, it is very important to select the most important welding parameters (e.g. sheet bevelling, chemical composition of electrode wires, type of shielding gas, linear energy of welding, setting the preheating temperature, controlling the temperature of inter-stitching). For high-strength steel structures proposed in the construction of means of transport (e.g. for elements of a mobile landing) with sheets of different thickness, a detailed weldability analysis should be performed separately. Based on the presented research and analysis of the obtained results, it can be concluded that to obtain the correct joint from the tested steels with a thickness of 4 mm, it is recommended to use the MAG welding speed at the level of 330 mm / min and the use of preheating at the level of 105°C. All tested joints made of various types of high--strength steels showed good mechanical properties and met the requirements for materials, for example intended for mobile platforms. The recorded tensile strength values of the tested joints were clearly lower than those obtained for the native materials, while the determined immediate tensile strength was in all cases above 600 MPa. Thus, high-strength steel couplings can be used in the construction of means of transport. The joints have relatively good plastic properties, which was confirmed by the results of the bending and impact tests. The safety of the welded structure is confirmed by the high fatigue life of the tested joints and their high impact strength. Joints made of AHSS steel have significantly higher fatigue strength compared to the tested joint made of HSS steel. Based on the fatigue tests, it can be concluded that the most responsible welded structures of transport means should be made of steels from the AHSS group. The best weldability of all tested steel grades with a thickness of 4 mm has the DOCOL 1200M steel.

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