Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 124 **2024**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2024.124.15

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Szczucka-Lasota, B., Węgrzyn, T. Dissimilar Hardox and low-alloy steel in excavator structures. *Scientific Journal of Silesian University of Technology. Series Transport*. 2024, **124**, 217-227. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2024.124.15.

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DISSIMILAR HARDOX AND LOW-ALLOY STEEL IN EXCAVATOR STRUCTURES

Summary. In the structure of excavators and other transport vehicles, it is observed that there is an increasing necessity to weld elements from the Hardox steels. The paper verifies the possibility to obtain accurate DMW (dissimilar metal welds from totally different grades of Hardox 450 steel with S355J2 steel). The microstructure and mechanical tests of the obtained various welds were analysed. Argon-based shielding gases with micro nitrogen additions were used for MAG welding. Gas mixtures with micro nitrogen additions of up to even 2000 ppm and their use in welding are an absolute novelty. The purpose of the manuscript was to find the correct parameters of making dissimilar joints with such modern mixtures and to determine the most suitable mixture for welding Hardox steel and low-alloy steel for use in the automotive industry.
Keywords: transport, excavator, welding

1. INTRODUCTION

Mixed joints made of Hardox steel and a low-alloy steel are very important for automotive applications [1-2]. Dissimilar metal welds (DMW) could be used in various means of transport:

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pressure vessels, automotive industry, heavy equipment, crushers [3-4]. Automotive request for DMW is noticeably increasing due to many advantages such as obtaining good mechanical properties of joints, considering significant economic benefits [5]. In the last 15 years, progress has been observed in the structure of vehicle in road transport. In civil engineering and transport, structures and vehicles are constantly modernized [6]. The excavator (Fig 1.) is an important example because this vehicle type requires modern materials with respect to its cost reduction while maintaining technical requirements [7-8].

Fig. 1. The production of excavators

Modern designing is related to descending number of supports for various vehicle bodies [9-10]. This could be achieved by the application of Hardox. This grade of steel is used for the construction of concrete mixers. Hardox steel is also classified as a wear resistant material. Hardox steel could be pointed by the following advantages [11-12]:

- high-impact toughness,
- tribological properties,
- high-yield stress,
- high-ultimate tensile strength,
- excellent hardness,
- longer service life.

Low-alloy steel, on the other hand, has worse mechanical properties, but has many advantages. It is well weldable and a much cheaper material. In many constructions in the automotive industry, the combination of common material characteristics can be very beneficial (Fig. 2).

Fig. 2. Dissimilar metal welds (DMW) of excavator components

The article focuses on the selection of mixed welding parameters for excavator structures. The manuscript shows the investigations results and their analyses. The conducted analyses made it possible to find the proper solution of excavator construction elements welding. The joint were made of two mixed various steel grades (Hardox 450 with S355J2). It was decided to create mixed Hardox/low-alloy steel joints using the MAG process with modern gas mixtures with micro nitrogen additions.

2. MATERIALS AND PROCESS

Two grades of steel were selected to the investigation (Tab. 1). The chemical composition of both materials is not the same. Hardox group are rather difficult to weld because of hard martensite structure, that could provoke incompabilities [8-10]. Low-alloy steel is treated as material easier to weld.

Tab. 1

Weight chemical comp. of tested materials [%]

Steel grade	C	Si	Mn	P	S	Mo	Ni	Cr
Hardox 450	0.26	0.7	1.6	0.026	0.011	0.6	1.5	1.4
S355J2	0.21	0.43	1.51	0.29	0.024	0.03	0.31	-

In Hardox450 the linear energy during welding should be limited to 4.3 kJ/cm level [3-5], while in S355J2 steel welding, there are no special restrictions.

Dissimilar metal welds are not fully described in literature. Low-alloy steel might be welded using the low-hydrogen and low-nitrogen methods [6-7].

MAG welds were made using the two steel grades: Hardox 450 and S355J2. The characteristic of tested materials is presented in (Tab. 2).

Tab. 2

The selected properties of materials [9]

Material	YS [MPa]	UTS [MPa]	Hardness, HBW
Hardox 450	1190	1355	220
S355J2	345	610	450

There is a big difference in mechanical properties from both grades of steel.

Two electrode wires were used in investigation: Union X90 and Union X96. The composition of both wires is presented in the Tab. 3.

The welding parameters were rather typical:

- electrode diameter: 1 mm,
- voltage: 19.5 V,

- current: 114.5 A,
- shielding gas flow: 15.5 l/min,
- DC with (+) on the electrode.

Tab. 3

Electrode wires [%]

Filler	C	Si	Mn	P	Cr	Mo	Ni	Ti
Union wire X90	0.11	0.82	1.83	0.012	0.39	0.61	2.33	0.005
Union wire X96	0.13	0.88	1.89	0.013	0.28	0.43	3.33	0.005

The welded samples had dimensions of 800×200×8 mm. In the welding MAG process, a popular gas Ar-18% CO_2 and with two experimental mixtures of Ar-18% CO_2-0.3% N_2 and with Ar-18% CO_2-0.6% N_2 were selected to act as shielding gases. The dissimilar joints were made with a thickness of 8 mm with "V" bevelling (Fig. 3).

The tests included tests:
- non-destructive (NDT),
- destructive tests (DT).

The main NDT observations were based on:
- visual examination (VT),
- magnetic particle testing (MT).

The main destructive tests based on:
- bending test,
- tensile test,
- fatigue test,
- microstructure.

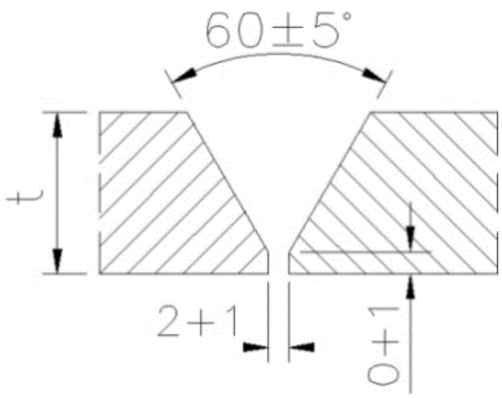

Fig. 3. The welding preparation, thickness t = 8 mm

The NDT examinations were performed in accordance with the relevant standards in the following manner:

- VT using a magnifying loupe with 3 × magnification - observation was done according to PN-EN ISO 17638 standard keeping criteria from EN ISO 5817 norm,
- MT was checked, keeping the PN-EN ISO 17638 norm and main criteria from EN ISO 5817 standard. A magnetic flaw detector REM – 230 was used.

The DT (destructive test) examinations were performed in accordance with the relevant standards in the following manner:

- microstructure using Adler reagent,
- hardness test based on the PN-EN ISO 9015-1:2011 and PN-EN ISO 6507-1:2018-05 norms,
- the tensile test was checked basing on the PN-EN ISO 6892-1:2020 and E 468-90 ASTM,
- the fatigue test was performed using ASTM E468-18 standard,
- the impact toughness test was done using a Zwick Roell machine, HIT450P type based on PN-EN ISO 148-1 standard.

3. RESULTS AND DISCUSSION

The dissimilar metal welds (DMW) with various parameters were completed. The welding speed, type of wire and the type of shielding gas were changed during the tests. The obtained weld joints were tested by NDT methods. Other welding parameters such as voltage, current, and shielding gas flow rate were not changed. The method of bevelling samples was also not changed. The welding process was always correct, and the welding arc was stable. All tests were carried out at room temperature. The sample designation and NDT results are presented in the Tab. 4.

Tab. 4

Designation and NDT results

Sample	Shielding gas	Wire	Speed, mm/min	Observations
P1	Ar-18% CO_2	Union X90	330	cracks in weld
P2	Ar-18% CO_2	Union X90	430	lack of incompatibilities
P3	Ar-18% CO_2	Union X96	330	cracks in weld
P4	Ar-18% CO_2	Union X96	430	lack of incompatibilities
P5	Ar-18% CO_2-0.3% N_2	Union X90	330	lack of incompatibilities
P6	Ar-18% CO_2-0.3% N_2	Union X90	430	lack of incompatibilities

P7	Ar-18% CO_2-0.3% N_2	Union X96	330	lack of incompatibilities
P8	Ar-18% CO_2-0.3% N_2	Union X96	430	lack of incompatibilities
P9	Ar-18% CO_2-0.6% N_2	Union X90	330	cracks in weld
P10	Ar-18% CO_2-0.6% N_2	Union X90	430	lack of incompatibilities
P11	Ar-18% CO_2-0.6% N_2	Union X96	330	cracks in weld
P12	Ar-18% CO_2-0.6% N_2	Union X96	430	cracks in weld

The table data shows that the quality of welds is affected by the welding process speed and type of the shielding gases. The biggest nitrogen addition (0.6%) to the shielding gas mixture is unfavourable. It was noticed that high quality welds were obtained when a micro nitrogen amount of 0.3% was introduced to the standard gas mixture (samples P5, P6, P7, P8). For destructive testing, only those joints that passed the NDT inspection were taken into account (samples: P2, P4, P5, P6, P7, P8, P10).

Next, the bending test was carried out. The bending test was realized only for the joints in which no incompabilities were observed. The test specimens were prepared with a dimension of 8 mm × 30 mm. A standard mandrel with a diameter of 90 mm was used in the experiment Bending angle was 180°. The results of bending tests are given in the Tab. 5.

The bending test gave mainly positive results. In the bending test, a crack was noticed only in one case, when the joint was made with UNION X 96 electrode wire (sample P4).

Further impact toughness tests were carried out. It was decided to take into impact toughness test those samples which no incompabilities were found (samples: P2, P5, P6, P7, P8, P10).

The Charpy-V impact toughness could be treated as a verry important welding tests as it give information about the plastic properties of the weld.

Tab. 5

Bending test results

Sample	Gas	Wire	Speed, mm/min	DMW observations
P2	Ar-18% CO_2	Union X90	430	lack of incompabilities
P4	Ar-18% CO_2	Union X96	430	cracks
P5	Ar-18% CO_2-0.3% N_2	Union X90	330	lack of incompabilities
P6	Ar-18% CO_2-0.3% N_2	Union X90	430	lack of incompabilities

P7	Ar-18% CO_2-0.3% N_2	Union X96	330	lack of incompabilities
P8	Ar-18% CO_2-0.3% N_2	Union X96	430	lack of incompabilities
P10	Ar-18% CO_2-0.6% N_2	Union X90	430	lack of incompabilities

The joint is treated to have positive plastic properties when the impact toughness has value of minimum 47 J at the lower temperatures. Impact toughness tests were realized at temperature of -20°C, that corresponds with second class of toughness (Table 6).

Tab. 6

Impact toughness test results

Sample	Gas	Wire	Speed, mm/min	KV (at -20° C), J
P2	Ar-18% CO_2	Union X90	430	44
P5	Ar-18% CO_2-0.3% N_2	Union X90	330	55
P6	Ar-18% CO_2-0.3% N_2	Union X90	430	62
P7	Ar-18% CO_2-0.3% N_2	Union X96	330	53
P8	Ar-18% CO_2-0.3% N_2	Union X96	430	48
P10	Ar-18% CO_2-0.6% N_2	Union X90	430	38

Tests have proven that many factors have an important influence on the quality of joints. It was easy to observe that the composition of electrode wire, the composition of gas mixture and the welding speed have influence on the mechanical properties of the weld. The best properties of the joints were always obtained when: nitrogen was added to the standard shielding gas mixture at the level of 0.3%.

The best result was taken (for sample P6) when the electrode wire was UNION X90 (with a lower carbon content) and when the welding speed was elevated up to 430 mm/min. The next part of the research was the tensile strength analysis. Tensile strength results were prepared only for samples that had positive impact toughness (2- class). The results are shown in Table 7.

The tests have confirmed that many factors have an important impact on the quality of joints. In all the obtained cases (P5, P6, P7, P8), the UTS was above 600 MPa, which can be considered a success in atypical mixed joints. The best properties of the dissimilar metal welds (DMW) were always obtained when: nitrogen was added to the standard shielding gas mixture at the level of 0.3%. The best result was taken (for sample P8) when the electrode wire was UNION X96 (with a higher carbon content) and when the welding process speed was

430 mm/min. The next part of the research was the fatigue analysis. Two samples were tested: for which the highest impact strength (P6) was obtained, and the one for which the highest strength was obtained. The flats were used with loading represented by a cyclic displacement signal in the form of sinusoidal function with frequency of 10 Hz and R equal to -1. The loading stage was carried out to determine the stress at which, after obtaining 2×106 cycles, no failure would occur. Values of the fatigue limit were ranged between 180 MPa and 250 MPa. The fatigue test results are given in Table 8.

Tab. 7

Tensile strength results

Sample	Gas	Wire	Speed, mm/min	UTS, MPa
P5	Ar-18% CO_2-0.3% N_2	Union X90	330	610
P6	Ar-18% CO_2-0.3% N_2	Union X90	430	617
P7	Ar-18% CO_2-0.3% N_2	Union X96	330	633
P8	Ar-18% CO_2-0.3% N_2	Union X96	430	649

Tab. 8

Fatigue limit of the tested joints

Specimen	Stress, MPa
P6	235
P8	226

The fatigue test has confirmed that many factors have an important influence on the quality of joints. The research indicates that the fatigue strength is at a similar level. It can therefore be concluded that both the welding parameters for the P6 sample (UNIX 90 wire) and the welding parameters for the P8 sample (UNIX 96 wire) give the best results. In both cases, a shielding gas plays an important role, in which a nitrogen content of 0.3% is added. All tests showed that better results were obtained with a welding speed of 430 mm/min. The last step of the investigation was to observe the structure of the joint (Fig. 4).

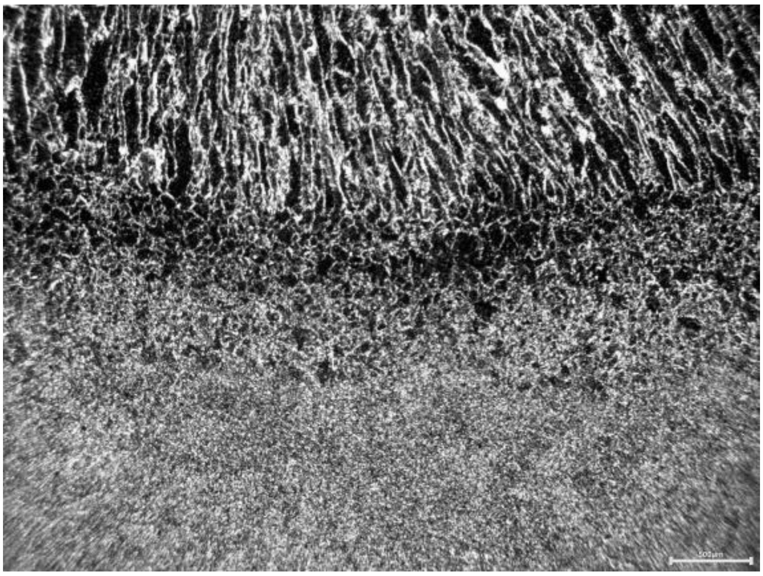

Fig. 4. The structure of dissimilar metal welds (sample P6)

The dominant martensitic structure of Hardox 450 steel is shown in the lower part of the Fig. 4. and the dominant ferritic-pearlitic structure of S355J2 steel is visible in the upper part of the Fig. 4. A very nice fusion line was obtained, which proves that the process parameters were really well selected.

4. CONCLUSION

The article sets out to establish the dissimilar welding parameters for constructions of excavator elements using Hardox450 steel and S355J2 steel. Hardox steel is treated as an important material in the automotive sector because of wear resistance to abrasive wear and its high tensile strength. For economic reasons, there is a need to weld Hardox steels with non-alloy steels. Such joints are found in the elements of excavators. Dissimilar metal welds (DMW) found great application in the construction of vehicles. In the article, it was decided to check the innovative use of shielding gas mixtures with micro-nitrogen additives for welding Hardox 450 steel with S355 unalloyed steel. Test joints were made using 3 different shielding gas mixtures containing Ar -18% CO_2 and Ar -18% CO_2 -0.3% N_2 and Ar -18% CO_2 -0.6% N_2. In addition, the influence of two different electrode wires and two different welding speeds on the quality of welds was simultaneously tested. NDT tests were performed, followed by destructive tests. Each joint examination narrowed down the number of combinations of various parameters, leading to finding the most appropriate solution. Bending tests, impact tests, strength tests and fatigue tests were performed. Research shows that the amount of 0.3% N_2 in the shielding gas mixture is very desirable. This increases the tensile strength and allows for better impact toughness compared to the classic Ar-CO_2 gas mixture.

The use of wire with a lower carbon amount allows for slightly better impact strength, but at the same time a slightly lower tensile strength. Welded joints made with both electrode wires (Unix 90 and UNIX 96) are characterized by comparable fatigue strength. Better results were obtained with increased welding speed (430 mm/min instead of 330 mm/min). The correctness of well-chosen welding parameters is confirmed by the metallographic structure.

The main conclusions could be drawn based on the research study:

1. It is possible to weld correctly joints made of two different grades (dissimilar welding) of Hardox steel and a low-alloy steel.
2. The tensile strength of dissimilar welded excavator elements is on the level of 600 MPa.
3. The welding wire UNION X90 and the complex gas mixture of 80% Ar-18% CO_2-0.3% N_2 provide the most preferred properties of a tested dissimilar weld.
4. Bending tests, microstructure testing, and non-destructive tests have confirmed the possibility of accurate dissimilar welding of the excavator components.

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Received 05.01.2024; accepted in revised form 30.04.2024