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NEW CONCEPT OF GAS MIXTURES FOR WELDING HIGH-STRENGTH STEEL S960 MC

Tomasz WĘGRZYN[1*], Bożena SZCZUCKA-LASOTA[2],
Kinga KUROWSKA-WILCZYŃSKA[3], Adam DORING[4]

[1] Politechnika Śląska; tomasz.wegrzyn@polsl.pl, ORCID: 0000-0003-2296-1032
[2] Politechnika Śląska; bożena.szczucka-lasota@polsl.pl, ORCID: 0000-0003-3312-1864
[3] Politechnika Warszawska; k.kurowska.wilczynska@gmail.com, ORCID: 0000-0001-5114-9401
[4] Wyższa Szkoła Bankowa w Gdańsku; lukasz.wszolek@diagno-test.pl, ORCID: 0000-0001-5114-9401
* Correspondence author

Purpose: Checking the quality of a joint made with a newly developed method.
Design/methodology/approach: A new welding method has been developed in order to obtain a high-quality joint. The properties of the joint were checked by NDT (Non Destructive test) tests and the strength and fatigue strength were tested.
Findings: Now, adding to the shielding gas mixture can improve the quality and properties of the weld.
Research limitations/implications: In the future, it can be suggested to investigate the effect of nitrogen in other gaseous shielding mixtures of the MAG welding process.
Practical implications: The proposed innovation will not cause problems in the production process. Only the shielding gas will be modified without affecting the technological process, management and economic aspects.
Social implications: Modifying the welding method will not affect the environment and production management methods.
Originality/value: What is new is to propose a new solution with its scientific justification. The article is addressed to manufacturers of structures made of HSS and AHSS steels.

Keywords: welding process, S960 MC steel, means of transport, shielding gas mixtures.

1. Introduction

The article presents the results of tests leading to the selection of the correct MAG welding parameters of a thin-walled structure made of S960 MC fine-grained steel. These steels are increasingly used in the construction of means of transport due to their high strength and acceptable relative elongation at the level of 8% (Jaewson et al., 2011; Darabi and Ekula, 2016). The most recognized high-strength steels are the fine-grained steel S 700 MC. The weldability of this steel is quite well recognized (Golański et al., 2018; Skowrońska et al., 2017).

The dominant martensitic structure of the steel is not conducive to good weldability. In order to obtain a proper and high-quality joint, it is necessary to very precisely determine all welding parameters: current, arc voltage, welding speed, beveling method, type of electrode wires and gas mixtures (Silva et al., 2019;, Krupicz et al., 2020). Welding of 960 MC steel is even more complicated compared to 700 MC steel due to the higher carbon and titanium content to strengthen the parent material. However, it is related to the possibility of the formation of additional non-metallic inclusions in the weld, mainly titanium nitrides and carbonitrides (Shwachko, 2000; Mazur and Grela, 2002). Additionally, when welding high-strength steels, as in classic unalloyed steels, the hydrogen content should be controlled (Łabanowski and Fydrych, 2008). When welding HSS steels, cracks often occur both in the weld and in the Heat Affected Zone (HAZ). The reasons for these cracks are usually:

- dominant martensitic structure,
- welding stresses,
- hydrogen interaction.

In order to reduce welding stresses, it is recommended to limit the linear energy during welding to the level of 4.4 kJ/cm, while in order to reduce the hydrogen content in the weld, it is recommended to use preheating.

2. Research materials

For MAG welding of S960 MC steel with a thickness of 1.8 mm, the UNION X90 wire (EN ISO 16834-AG 89 6 M21 Mn4Ni2CrMo) was used and a mixture of 90% Ar-18% CO_2, which was modified by additionally introducing nitrogen with 1% and 2%. In the welding process, it was decided to check the need for drying preheating to a temperature of 80°C.

Table 1 shows the mechanical properties of the S960 MC steel used in the construction of various means of transport.

Table 1.
Tensile strenght of steel S960 MC

YS MPa	UTS, MPa	A5, %
950	1250	8.1

In addition to high strength and yield point, the yield point is considered to be the acceptable value of the relative elongation at the level of 8%. The high temporary tensile strength is related to the higher content of carbon and titanium compared to unalloyed constructional ones, which favors the formation of titanium nitrides and carbonitrides of the TiN, Ti (C, N) type. In unalloyed steels, the content of Ti is introduced at the maximum level of 0.0035%, and in HSS steels, the content of titanium is twenty times greater (Table 2).

Table 2.
Chemical composition of S960 MC

C, %	Si, %	Mn, %	P, %	S, %	Al, %	Nb, %	V, %	Ti, %	Ni, %
0.12	0.25	1.3	0.02	0.01	0.015	0.1	0.05	0.07	1.7

Source: Łabanowski, Fydrych, 2008.

Chemical composition of steel is similar with electrode wire composition (tab. 3).

Table 3.
Wire UNION X90 – chemical composition

UNION	C%	Si%	Mn%	P%	Cr%	Mo%	Ni%	Ti%
X90	0.10	0.8	1.8	0.010	0.35	0.6	2.3	0.005

Source: Skowrońska, Szulc, Chmielewski, Golański, 2017, pp. 104-111.

Before starting to make joints from sheets with a thickness of t = 1.8 mm. no chamfering was performed. The distance between the sheets and the threshold was 0.5 mm.

The welding parameters were as follows:

- diameter of the electrode wire: 1 mm,
- arc voltage: 19 V,
- welding current: 113 A,
- welding speed: was 315 mm/min,
- shielding gas flow: 14 l/min,
- the nature of the weld: single-pass.

The joints were made with a drying pre-heating to the temperature of 80°C and without pre-heating.

3. Metodology

After MAG welding. standard non-destructive testing (NDT) of the joints was carried out:

- VT – visual examination with an eye armed with a magnifying glass at 3 × magnification – the tests were carried out in accordance with the requirements of PN-EN ISO 17638, evaluation criteria according to EN ISO 5817.
- MT- magnetic particle testing – the tests were carried out in accordance with the PN-EN ISO 17638 standard. the tests were assessed in accordance with EN ISO 5817, with a magnetic flaw detector test device type REM-230.

The analysis of the obtained results of non-destructive tests allowed to select joints for destructive tests, which consisted of the temporary tensile strength and fatigue strength tests. The samples were also structurally examined using a light microscope (LM). The tests were carried out in accordance with the PN-EN ISO 9016:2021 standard. It was decided to check the content of diffusible hydrogen and nitrogen in the tested joints. Tests on the content of H in the weld were carried out according to the illustrative glycerin method described in the standard "Determination of the total amount of hydrogen in the weld metal of steel electrodes with acid, rutile or alkaline coating. BN-64/4130 "(BN-64/4130, 2013).

4. Research results and their analysis

Joints were made with the use of three shielding mixtures with different nitrogen content. The joints were made without preheating and with preheating. The results of macroscopic visual tests carried out with the naked eye and the magnetic-powder tests of the resulting connections with the use of various shielding mixtures are presented in Table 4.

Table 4.
Results of non-destructive research

Type of shielding mixture	Welding without preheating	Welding with preheating to 80°C
Ar + 18% CO_2	Cracks in the weld.	No cracks
Ar +18% CO_2 + 1% N_2	No cracks	No cracks
Ar + 18% CO_2 + 2% N_2	Cracks in the weld and in the HAZ	No cracks

It has been found that for proper welding of 2 mm thick sheets of S960 MC steel. preheating prior to welding is recommended. The preheating temperature of 80°C was found to be sufficient as no cracks were observed in these joints in all three tested cases. It was additionally noted that the shielding gas mixture Ar + 18% CO_2 + 1% N_2 allows for obtaining the correct joint also without the use of preheating.

The next stage of the research was to estimate the content of diffusible hydrogen in the weld. Immediately after welding, the content of diffusible hydrogen in the weld was checked. The test results are presented in Table 5.

Table 5.
Diffusing hydrogen content [ml / 100 g of weld metal]

Type of shielding mixture	Welding without preheating	Welding with preheating to 80°C
Ar + 18% CO_2	6.3	4.2
Ar +18% CO_2 + 1% N_2	6.2	4.1
Ar + 18% CO_2 + 2% N_2	6.3	4.2

Based on the results of the tests presented in Table 6 it was found that hydrogen is at the recommended level of 3-5 ml/100 g of the weld metal only when preheating is used. For further destructive tests (structure and mechanical properties) only joints made with preheating at 80°C were taken into account. The dominant structure was martensite and ferrite and carbides, mainly (Ti, Nb) C, carbonitrides (mainly Ti (C, N) and nitrides (mainly TiN). The presence of small amounts of bainite was also found. It should be noted, that the crystal lattice of TiN nitride is identical to the crystal lattice of alpha ferrite, which favours ferrite nucleation during the rapid transformation of austenite under welding conditions. The dominant martensitic structure with ferrite is observed. the average size of ferrite is at a different level. The average size of ferrite grain in the weld for the tested shielding gas mixtures is presented in Table 6.

Table 6.
Average size of ferrite grain in the joint [μm]

Type of shielding mixture during the welding process with preheating to 80°C	Average size of ferrite grain
Ar + 18% CO_2	19
Ar +18% CO_2 + 1% N_2	17
Ar + 18% CO_2 + 2% N_2	21

It was found that the most advantageous mixture is Ar + 18% CO_2 + 1% N_2. It has the greatest influence on ferrite grain refinement which influences the plastic properties of the joint. The next stage of the research was to check the mechanical properties. Table 7 shows the immediate tensile strength of joints made in various sheathing mixtures.

Table 7.
The results of strength tests of a joint made with the use of various shielding gas mixtures

Shielding gas	R_e [MPa]	R_m [MPa]	A_5 [%]
Ar + 18% CO_2	429	678	4.9
Ar +18% CO_2 + 1% N_2	434	703	5.1
Ar + 18% CO_2 + 2% N_2	410	654	4.7

The table data shows that it is possible to obtain high tensile strength of the joint (at the level of 700 MPa) with an acceptable relative elongation (at the level of 5%). This result was obtained only in one case when 1% N_2 was added to the Ar-CO_2 mixture. The strength of joints made in the cover of the remaining mixed gas mixtures (Ar + 18% CO_2, Ar + 18% CO_2 + 2% N_2 is significantly lower and the relative elongation is below 5%. It has been found that a mixture containing 1% nitrogen is the most favourable, justify the fact that nitrogen has a high affinity for titanium and forms nitrides TiN and carbonitrides Ti (N, C), the size and distribution of which is strongly related to the nitrogen content in the weld metal and has an impact on the strengthening of the weld metal, nitrogen in weld metal shielded from three different tested mixtures (Table 8).

Table 8.
The content of nitrogen in the weld metal in the weld metal depending on the type of the shielding mixture used

Shielding gas	Nitrogen content in the weld. ppm
Ar + 18% CO_2	50
Ar +18% CO_2 + 1% N_2	55
Ar + 18% CO_2 + 2% N_2	65

The table data confirmed that the addition of nitrogen to the gas mixture influenced the nitrogen content in the weld. Analysing the results of non-destructive and destructive tests to date, it can be concluded that the nitrogen content in the weld metal should be about 55 ppm. Then, the bending test of all tested joints was carried out. Three measurements were made in the joint bending test from the side of the ridge and from the side of the face (Table 9).

Table 9.
Bend test results for a joint made with various shielding gas mixtures

Shielding gas	Face side	Ridge side
Ar + 18% CO_2	No cracks	No cracks
Ar +18% CO_2 + 1% N_2	No cracks	No cracks
Ar + 18% CO_2 + 2% N_2	No cracks.	Cracks in the weld

There were no cracks in the weld and in the HAZ, both from the side of the ridge and the face, only in the first two tested cases (mixture without nitrogen and mixture with 1% nitrogen). Cracks in the weld were observed only for the joint made in a gas mixture shielding with 2% nitrogen.

5. Conclusion

In the article. it was decided to check the effect of nitrogen added to the shielding mixture in the MAG process when welding high-strength steel S960 MC. For this purpose, joints were made in the Ar + 18% CO_2 shield with the addition of 1% N_2 and 2% N_2, respectively. At the same time, the influence of the use of preheating at the level of 80°C was tested. The hydrogen content in all the test joints was analysed. The results of non-destructive tests and tests for the assessment of hydrogen content in the welds clearly showed that the use of preheating gives better results. In further tests, joints made only with the use of preheating were checked. The tensile strength test and the bending test were performed and the nitrogen content in the tested welds was assessed. Based on all the tests performed, it can be concluded that the gas mixture Ar + 18% CO_2 + 1% N_2 is the most appropriate for the welding of 960 MC steel in the MAG process.

In the tested welds, it was observed that the dominant phase is martensite, which is not conducive to good weldability:

1. Preheating (80°C) is recommended prior to MAG welding of S960 MC.
2. It is possible to obtain the tensile strength of a joint made of 960 MC steel at the level of 700 MPa.

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