SCIENTIFIC
AND DIDACTIC EQUIPMENT

Thermodynamic conditions when welding fine-grained S960 MC steel

BOŻENA SZCZUCKA-LASOTA[1], TOMASZ WĘGRZYN[2], JAN PIWNIK[3], ADAM JUREK[4], JERZY KALWAS[5], KRZYSZTOF I.WILCZYŃSKI[6]

[1,2]SILESIAN UNIVERSITY OF TECHNOLOGY, [3]ROAD AND BRIDGE RESEARCH INSTITUTE, WARSAW, [4]NOVAR SP. Z O.O. GLIWICE, [3,5,6]COBRABID Sp. z o.o.

Keywords: civil engineering, transport, means of transport, thermodynamic conditions

ABSTRACT:

There is a growing demand for welding of high-strength steels with low weldability used in civil engineering and transportation. Fine-grained steels are an important structural material in the construction of means of transport due to their high tensile strength of 1250 MPa. The purpose of this article was to select thermodynamic parameters in the MAG welding process of low weldability S960 MC steel.
Fine-grained steels are characterised by high tensile strength and yield stress. Joints made of these steels are difficult to weld due to the dominant martensitic structure and complex procedure related to the necessity to reduce the hydrogen content in the weld metal. It was decided to check the role of preheating and interpass layer temperature on the correctness of the MAG joint of the structure with a thickness of 8 mm. The impact resistance of the joint was also checked and the content of diffused hydrogen in the weld metal was evaluated.

Warunki termodynamiczne podczas spawania drobnoziarnistej stali S960 MC

Słowa kluczowe: inżynieria lądowa, transport, środki transportu, warunki termodynamiczne

STRESZCZENIE:

Nieustannie wzrasta zapotrzebowanie na spajanie trudnospawalnych stali wysokowytrzymałych stosowanych w inżynierii lądowej i w transporcie. Ważnym materiałem konstrukcyjnym w budowie środków transportu są stale drobnoziarniste z uwagi na ich dużą wytrzymałość na rozciąganie na poziomie 1250 MPa. Celem niniejszego artykułu było dobranie parametrów termodynamicznych w procesie spawania MAG trudnospawalnej stali S960 MC.
Stale drobnoziarniste, charakteryzują się wysoką wytrzymałością na rozciąganie i granicą plastyczności. Złącza z tych stali są trudnospawalne ze względu na dominującą strukturę martenzytyczną i skomplikowaną procedurę związaną z koniecznością ograniczenia zawartości wodoru w stopiwie. Postanowiono sprawdzić rolę podgrzewania wstępnego i temperatury warstw międzyściegowych na poprawność wykonanego złącza MAG konstrukcji o grubości 8 mm. Sprawdzono udarność złącza i oszacowano zawartość wodoru dyfundującego w stopiwie.

1. INTRODUCTION

The results of the tests performed to select thermodynamic parameters of welding of the structure made of high-strength fine-grained S960 MC steel are presented. These steels are proposed to be used in the construction of means of transport due to their high strength. In this case a relative elongation of 8% is acceptable [1–6]. Unfortunately, such a structure facilitates the occurrence of welding cracks caused, among others, by hydrogen impact [7–11].

The reduction of hydrogen content in the weld is achieved by applying preheating up to 100°C. At the same time there is a view that preheating above 200°C is unfavourable as it leads to the expansion of the heat affected zone [12–19]. The impact of hydrogen on cracking of steel welds and the method of calculating the amount of diffused hydrogen are described comprehensively in the literature [20–29].

These issues have been the subject of the tests since there is very little information on hydrogen-induced cracking of welded joints made of high-strength fine-grained steels.

2. TEST MATERIALS

For MAG welding of 8 mm thick S960 MC steel a UNION X90 welding electrode was used (EN ISO 16834-A G 89 6 M21 Mn4Ni2CrMo), and a mixture of 90% Ar – 2% O_2 was used as the shielding gas. The purpose of the research works was to obtain a correct joint made of S960 MC steel from sheets with a thickness of 8 mm, intended for the construction of means of transport. The welding process was carried out under different thermodynamic welding conditions, such as preheating and variable interpass layer temperatures.

Table 1 presents the mechanical properties of S960 MC steel used for the construction of means of transport.

Table 1 Mechanical properties of S960 MC steel [6]

Yield stress YS, MPa	Tensile strength UTS, MPa	Relative elongation A5 %
950	1250	8.1

A high yield stress of 950 MPa and an acceptable relative elongation of 8% deserve attention. This is related to higher carbon and titanium content as compared to non-alloy structural steels. In C-Mn non-alloy steels the Ti content is introduced at a maximum level of 0.003%, and in high-strength fine-grained steels the titanium content is twenty times higher (Table 2). There is a view that dispersive curing of the weld metal is performed using titanium compounds (TiN, TiO type).

Table 2 Chemical composition of S960 MC steel [6]

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

The chemical composition of the electrode is different from the chemical composition of the welded steel (Table 3).

Table 3 UNION X90 welding electrode —
chemical composition [10]

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

Attention is paid to the addition of chromium in the welding electrode (which increases the strength of the joint) and to the addition of molybdenum (which increases the plastic properties of the joint, especially the impact resistance of the joint at negative temperatures). Prior to the execution of the joints made of sheets with a thickness t = 8 mm, V-type chamfering was performed. The chamfering angle was 60°, and the distance between the sheets and the threshold was 1.5 mm. Welding parameters were as follows: UNION X90 welding electrode diameter was 1.0 mm. Arc voltage and welding current for the first layer and for the remaining layers were different. Current and voltage values were changed to avoid welding defects such as incomplete fusion. The velocity of laying of individual interpass layers was similar: 330–340 mm/min.

The weld was of a seven-pass type. The subsequent layers were welded with increased current and voltage parameters (for deeper fusion and to avoid welding defects) which are presented in Table 4.

Table 4 Welding parameters of subsequent layers of S960 MC steel joint

Layer number (from the root side)	Arc voltage, V	Current intensity, A	Welding velocity, mm/min
first	18	114	330
layers 2–7	21	230	340

Joints were made without preheating and with preheating up to 120°C. Additionally, the interpass temperature of the joint was determined during laying out of layers 2–7 (100°C, 150°C, 170°C, 200°C).

3. TEST METHODS

After MAG welding, the following non-destructive tests (NDT) were carried out:

- Visual testing (VT);
- Magnetic particle inspection (MT).

The analysis of the obtained results of non-destructive tests allowed joints to be selected for impact tests at temperatures of -30°C and -40°C. Metallographic structure of the welds under a light microscope (LM) was examined. The diffused hydrogen content in the weld was measured. The tests were performed according to the indicative glycerine method described in BN-64/4130.

4. TEST RESULTS AND ANALYSIS

The results of the NDT tests are presented in Table 5.

Differences in the evaluation of the joints made with different thermodynamic parameters were observed (application of preheating, different interpass temperatures). The results of macroscopic visual inspections carried out with the unaided eye and magnetic particle inspection of the joints are presented in Table 5.

Table 5 Results of non-destructive testing

Welding without preheating	Welding with preheating up to 120°C, interpass temperature:			
	100° C	150° C	170° C	200° C
Cracks in: welds, HAZ	Cracks in: welds, HAZ	No cracks	No cracks	Cracks in welds

It was found that for proper welding of 8 mm thick plates made of S960 MC steel, preheating is absolutely necessary before welding. It was considered that the preheating temperature of 120°C is sufficient as no cracks were observed in these joints. At the same time, it was noted that the interpass temperature of the joint should be within the range of 150–170°C. In joints made with preheating up to 120°C and with an interpass temperature of 200°C cracks in welds occurred due to another reason (significant expansion of the heat affected zone).

The content of dispersing hydrogen in the weld was checked immediately after welding. It remained low, but at the same time a significant expansion of the heat affected zone was observed with an increase in interpass temperature. The results of the tests are presented in Table 6.

Table 6 Diffused hydrogen in the weld

Type of sample	Diffused hydrogen content, ml/100 g of weld metal
Without preheating	6.4
Interpass layer temp. 100°C	5.8
Interpass layer temp. 150°C	4.0
Interpass layer temp. 170°C	3.8
Interpass layer temp. 200°C	3.4

Based on the test results presented in Table 6, it was found that the hydrogen content is at the level of 3–5 ml/100 g of weld metal only if at the same time:

- preheating is applied;
- the interpass temperature is set at 150–170°C.

For further destructive tests (structure and impact resistance), only joints made with preheating at 120°C and simultaneous provision of the correct interpass temperature were taken into account. Martensite was the dominant structure and small amounts of bainite and fine ferrite were found. The results of the impact test are the average of 3 tests (Table 7).

Table 7 S960 MC steel joint impact resistance (preheating 120°C, interpass temperature 150°C or 170°C)

Interpass temp.	KV at -30°C [J]	KV at -40°C [J]
150°C	49	37
170°C	47	33

Table 7 data indicates that it is possible to comply with the 3rd impact resistance class (impact energy is above the threshold value of 47 J at -30°C). No impact resistance above 47 J was obtained at -40°C, which proves that the requirements for the 4th impact resistance class are not met. Slightly better impact strength is achieved by the joint made with preheating up to 120°C and maintaining the interpass temperature of 150°C.

4. SUMMARY AND CONCLUSIONS

After determining the thermodynamic conditions of the MAG welding process for fine-grained S960 MC steel, a correct joint with good mechanical properties with low hydrogen content in the weld metal was obtained. This joint meets the requirements for the 3rd impact resistance class.

Thermodynamic welding parameters for thick-walled structures made of fine-grained S960 MC steel were selected.

The following conclusions were drawn up:

1. Preheating (120°C) should be applied prior to MAG welding of S960 MC steel;
2. It is important to control the interpass temperature which should be 150–170°C;
3. Preheating and properly selected temperature of the interpass layers will allow the hydrogen content in the weld to be reduced below 5 ml/100 g of the weld metal, which guarantees 3rd impact resistance class.
4. The interpass temperature above 200°C is unfavourable and leads to the expansion of the heat affected zone.

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Credits:
The article is related to the implementation of the COST, CA 18223 project
PhD Eng, Bożena Szczucka-Lasota, professor of the Silesian University of Technology
PhD Eng, prof. Tomasz Węgrzyn (Silesian University of Technology)
PhD Eng, prof. Jan Piwnik (COBRABiD Sp. z o.o.)
MSc Eng, Adam Jurek (Novar)
MSc Eng, Jerzy Kalwas (COBRABiD Sp. z o.o.)
MSc Eng, Krzysztof Ireneusz Wilczyński (COBRABiD Sp. z o.o.)