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Tomasz WĘGRZYN, Bożena SZCZUCKA-LASOTA*
Silesian University of Technology, Faculty of Transport and Aviation Engineering
Krasińskiego 8, 40-019 Katowice, Poland
Jan PIWNIK
COBRABID Sp. z o. o.
Łucka 15, 00-842 Warsaw, Poland
Adam JUREK
Novar Sp. z o. o.
Towarowa 2, 44-100 Gliwice, Poland
Krzysztof Ireneusz WILCZYŃSKI
COBRABID Sp. z o. o.
Łucka 15, 00-842 Warsaw, Poland
**Corresponding author*. E-mail: bozena.szczucka-lasota@polsl.pl

MIXED WELDING OF THE MOBILE CONSTRUCTION PLATFORM IN THE AUTOMOTIVE INDUSTRY

Summary. This paper examines the possibility to improve mixed weldability of pins to mobile platforms. There is an increasing demand for mixed joints made of hard-weldable steel used in civil engineering and the automotive industry. A good example of this is welding of movable platform elements such as a pin to arm joints. The pin is very often made of yield structural steel S690 QL (1.8928), while the arm of the movable platform is mainly made of DOCOL 1400M steel from the AHSS group (advanced high-strength steel). This kind of joint is not easy to manufacture due to the different chemical compositions and thicknesses of both grades of steel. The difference in the thickness of welded elements creates an additional difficulty. The main aim of this article is to determine the most appropriate welding parameters and select additional materials to obtain the correct joint with good mechanical properties, free from welding defects and incompatibilities. This article examines whether the application of micro-jet cooling technology during the welding process might help to overcome these issues. For the first time, micro-jet cooling was not used to weld these grades of steel. The welding parameters and the micro-jet cooling parameters were investigated.

1. INTRODUCTION

Advanced high-strength steel and high-yield structural steel will play a major role in the construction of smart cities. The use of high-strength steel provides many benefits to organizations such as automotive companies as they combine lightweight with high strength, flexibility and beneficial parameters of fracture mechanics [1]. High-strength steel significantly reduces the weight of products that are made from it, compared with the same products made using other materials [2-3]. For applications in transport, there is an increasing demand for welding of new steel grades, including mixed steel joints that support high structural strength [2-5]. An example of this application is welding of elements of movable platforms. This article examines the possibility of manufacturing a correct mixed weld from various materials of pin to arm of a mobile platform. Advanced high-strength steel

(e.g. DOCOL 1400M steel) is mainly used for the platforms' arms, whereas high-yield structural steel (e.g. S690 QL - 1.8928) is used for the pins [7-10]. High-strength steel has become particularly useful in the automotive industry (Fig. 1) for three important reasons [1]:
- high ultimate tensile strength, up to 1400 MPa,
- high yield stress, up to1200 MPa, and
- elongation, up to 9%.

Fig. 1. Newest generation of steel in a car body structure [13]

Advanced high-strength steel (e.g., DOCOL 1400M steel) and high-yield structural steel (e.g. S690 QL - 1.8928) are used in the construction of various kinds of transport. Recently, these materials have found great use in car body and track frame structures. It is also possible to use these grades of steel in mobile platforms. The aim is to achieve a considerably larger operational range and lifting capacity of mobile platforms. The use of these grades of steel could lead to an increase of the operational range of the arms of mobile platforms and an increase load capacity. Fig. 2 shows an example of mobile platforms with significantly extended lifting arms.

Fig. 2. Mobile platform on a special vehicle [12]

The increase in the use of modern AHSS steel in the automotive industry and also in the construction of modern structures for the needs of smart cities is a result of the possibility of reducing the thickness of body sheets with a simultaneous improvement in the mechanical properties of the structure compared to the use of conventional steel. This article focuses on mixed welding of thin-walled constructions of movable platform arms with a pin of much greater thickness. The thickness of the cylindrical pin is 40 mm, whereas the thickness of the sheet metal used for the platform arm is much smaller and amounts to 1.8 mm. Joints of varying thicknesses and chemical compositions tend to produce cracks in the heat-affected zone as well as in the weld. The aim of this paper is to select the most appropriate welding process parameters to ensure good mechanical properties of the mixed joint made of S690 QL and DOCOL 1400 M steel used in the construction of mobile platforms. In addition to vehicles themselves, the structure of modernized mobile platforms with an expanded operational range also benefits from application of mixed grades of high-strength steel. The use of these new materials requires an understanding of their welding behavior and the need to develop new mixed welding tools and methods that will provide the desired steel properties and fulfill the increasing requirements of the automotive industry [6, 7]. This is the first study to analyze possibilities of using DOCOL 1400M with S690 QL steel welding with micro-jet cooling [8, 11]. A comparison of traditional low-strength and high-strength steel is presented in Fig. 3.

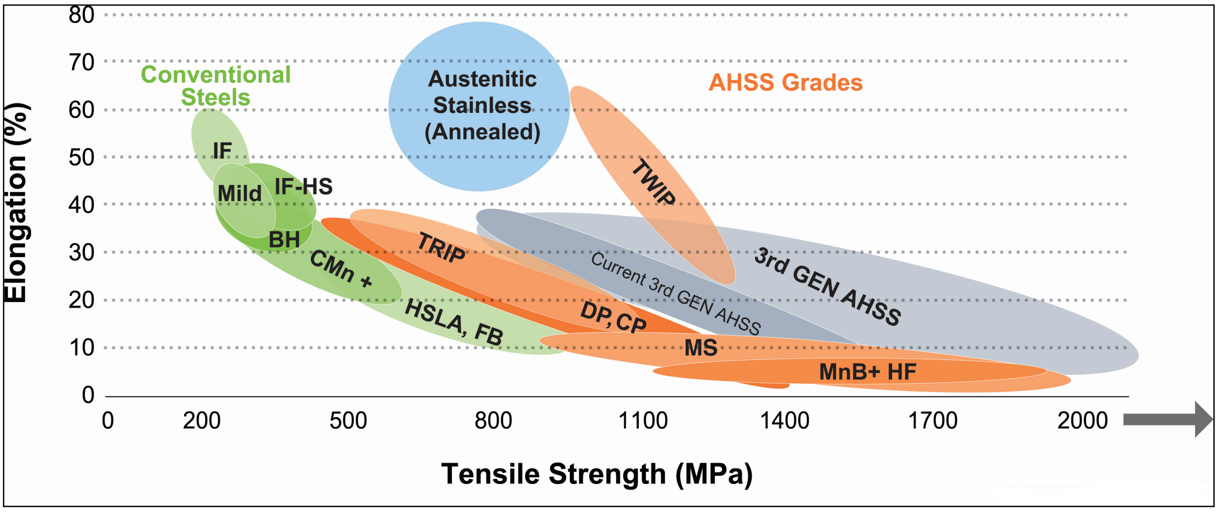

Fig. 3. Steel strength ductility (Ashby map) [9]

The increase in strength corresponds to a reduction of plastic properties of steel, which can degrade the weldability (brittleness of the weld, possibility of cracking).

2. MATERIALS AND METHODS

S690 QL is a high-yield structural steel grade produced in compliance with EN 10025:6:2004. The material is heat treated using the quench and temper process and has good bending and welding properties. S690 QL steel is basically used for crane elements, mobile platforms, pins, etc. The use of S690 QL steel reduces the total weight of a transport vehicle structure. The tensile strength of this steel is high, up to 900 MPa, the yield strength is 700 MPa and the relative elongation is up to 15% [6, 7]. During the welding of this steel, deterioration in the mechanical properties of the joint compared to the parent material can be observed. It is therefore recommended to limit the linear energy during the welding process to 4,5 kJ/cm [8-11].

DOCOL 1400 M steel (from the AHSS group) is characterized by very high strength, up to 1400 MPa, and yield strength of 1150 MPa. DOCOL 1400 M steel has much lower relative elongation of 5%. Typical applications of DOCOL 1400 M steel include mobile platforms' arms, lifting equipment, truck frames, etc [6, 7]. Table 1 presents the mechanical properties of S690 QL and DOCOL 1200M steel used for welded elements of moving platforms (arm and pin).

DOCOL 1400 M steel and S690QL steel are considered difficult to weld due to the appearance of cracks in the weld [12]. Welding of both these steel grades (separately and in mixed joints) produces difficulties due to the presence of a dominant martensitic structure in them [7, 12-13]. Mixed joints create additional complications due to the differences in the chemical composition and varied plastic properties. Table 2 presents the chemical composition of DOCOL 1400 M steel and S690QL steel.

The chemical composition of both grades of steel is not very similar. Only carbon, manganese, phosphorus and sulfur are on the similar level in both materials. S690 QL steel has much higher amounts of Ni and Mo, which is linked to much higher elongation (better plastic properties).

Table 1
Mechanical properties of S690 QL steel and DOCOL 1400 M steel [7]

Steel grade	The yield point YS [MPa]	Tensile strength UTS [MPa]	Relative elongation A_5 [%]
DOCOL 1400M	1150	1400	4
S690 QL	690	900	15

Table 2
Chemical properties of S690 QL steel and DOCOL 1400 M steel [7]

Steel grade	C [%]	Si [%]	Mn [%]	P+S [%]	Ni [%]	Al [%]	Mo [%]	Ti [%]
DOCOL 1400 M	0.17	0.20	1.40	0.012	0.01	0.04	0.05	0.025
S690 QL	0.19	0.8	1.7	0.019	2.1	0.015	0.72	0.05

It was decided to verify the possibility of proper circumferential welding of a thick-walled pin (40 mm height and 40 mm diameter) made of S690 QL steel to a thin-walled arm of a mobile platform (with a thickness of 1.8 mm) made of DOCOL 1400 M steel. It was decided to produce welds using the MAG (Metal Active Gas) process by testing the following gas mixture as a shielding gas mixture: Ar + 18% CO_2 (according to the PN-EN 14175 standard).

The following electrode wire was selected: UNION X96 (EN ISO 16834-A G 89 5 M21 Mn4Ni2,5CrMo). The chemical composition of the wire is presented in Table 3.

Table 3
Electrode wire used in this research - chemical composition [11]

C [%]	Si [%]	Mn [%]	P [%]	Cr [%]	Mo [%]	Ni [%]	Ti [%]
0.12	0.8	1.9	0.010	0.45	0.55	2.5	0.05

The chemical composition of the electrode wire is quite similar to that of the base material. The diameter of the electrode wire was 1.0 mm, the arc voltage was 20 V and the welding current was 113 A. The welding speed was varied twice: 300 mm/min and 350 mm/min. The source of direct current was always connected to (+) on the electrode; the weld (arm-pin) was single-stitched. Before welding, pre-heating to the temperature of 90° C was performed.

In this study, non-destructive testing (NDT) was firstly carried out after pin-arm welding, which included:

- Visual testing (VT) of prepared welded joints was performed using a magnifying glass at the magnification of 3×. The test was performed according to the PN-EN ISO 17638 norm and assessment criteria of the EN ISO 5817.
- Magnetic particle testing (MT) - tests were carried out according to the PN-EN ISO 17638 norm, with assessment performed according to the EN ISO 5817, using a magnetic flaw detector of REM-230 type.
- Radiographic tests - tests were carried out according to the PN EN ISO 15614-1 norm. The radiation source was SMART 200.

For the destructive tests, the following assessments of pin to platform arm welding were performed:

- Examination of the microstructure of specimens digested using Adler's reagent and a light microscope (LM).
- Hardness measurement (HPO 250 hardness tester, HV10 test method).

To further enhance the mechanical properties of joints after MAG welding, micro-jet cooling technology was additionally selected. For the steel structure welding process, the micro-jet cooling parameters were as follows:
- number of cooling nozzles: 1,
- form of cooling medium: Ar,
- pressure of the cooling medium: 0.6 - 0.7 MPa,
- diameter of the micro stream: 60 - 70 μm,
- distance of the micro-jet nozzle from the welded surface: 20 mm, and
- single-stitch weld.

The micrographs of the parent material structure were taken using the CSI JOEL 6340-FEG high-resolution scanning electron microscope by observation of secondary electrons (SEs); the accelerating voltage was 7.5 kV.

Once all of the tests were performed, quality control checks were applied, especially visual tests, tensile strength analysis and structure verification.

3. RESULTS

A mixed butt-type welded joint from S690 QL steel (pin) with a thickness of t_1 = 40 mm and DOCOL 1400 M steel (platform mobile arm) with a thickness of t_2 = 1.8 mm was made. The MAG (135) welding method was used in the down position (PA) according to the EN 15614-1 norm. The element preparation for single-stitched welding is presented in Fig. 4. Initially, the gap between the welded elements in the range of 1 mm to 2 mm, step 0.5 mm, was selected.

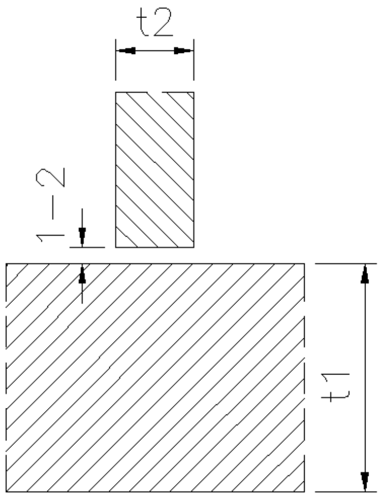

Fig. 4. Preparation of the element for manual welding, thickness t_1=2 mm

Two correctly welded parts of the mobile platform are shown in Fig. 5.

After the welding, the following non-destructive tests (NDT) were carried out: visual (VT), magnetic-particle (MT) and radiographic. The gap between the welded elements' arm-gap (Fig. 2) was found to be in the range of 1 to 2 mm, 0.5 mm step, by various parameters of micro-jet cooling after MAG welding. The optimal gap between elements, welding speed and micro-jet cooling parameters affect the cooling conditions of the weld. The composition of the created mobile platform joint (pin-arm) is presented in Table 4 (welding speed 300 mm/min) and Table 5 (welding speed 350 mm/min).

The data presented in the table show that the gap between elements should be 1.5 mm and argon micro-jet cooling should not be too intensive. The welding speed should rather be 300 mm/min. Welding at this speed (300 mm/min) corresponds to fewer welding defects and non-conformities.

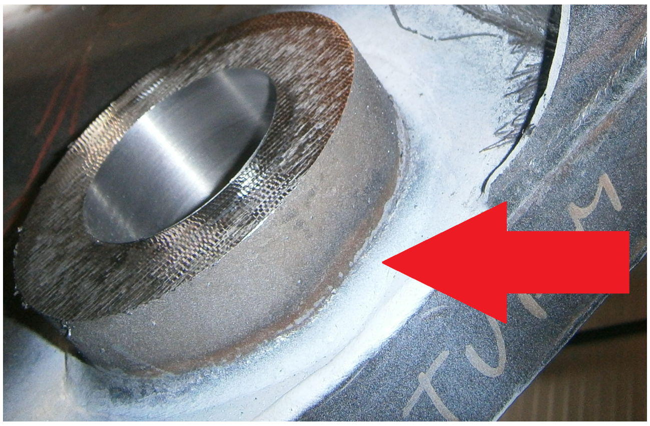

Fig. 5. Prepared weld

Table 4
Assessment of non-destructive testing of the movable platform joint (welding speed: 300 mm/min)

Micro-jet stream pressure [MPa]	Micro-jet stream diameter [μm]	Gap [mm]	Observation
without	without	1	Cracks in the weld and HAZ
0.6	60	1	Cracks in the weld
0.7	60	1	Cracks in the weld
0.6	70	1	Cracks in the weld
0.7	70	1	Cracks in the weld
without	without	1.5	Cracks in the weld and HAZ
0.6	**60**	**1.5**	**No cracks**
0.7	**60**	**1.5**	**No cracks**
0.6	**70**	**1.5**	**No cracks**
0.7	70	1.5	Cracks in the weld
without	without	2	Cracks in the weld and HAZ
0.6	60	2	Cracks in the weld
0.7	60	2	Cracks in the weld
0.6	70	2	Cracks in the weld
0.7	70	2	Cracks in the weld and HAZ

Due to the complicated nature of the joint, only the harness test and metallography observations were carried out. Further joint hardness distribution was also determined. Only samples with positive results from non-destructive tests (NDT) were tested (the gap between elements was only 1.5 mm, welding speed 300 mm/min); micro-jet cooling was always nonintensive. The results are presented in Table 5.

Table 5

Assessment of non-destructive testing of the movable platform joint (welding speed: 350 mm/min)

Micro-jet stream pressure [MPa]	Micro-jet stream diameter [µm]	Gap [mm]	Observation
without	without	1	Cracks in the weld and HAZ
0.6	60	1	Cracks in the weld and HAZ
0.7	60	1	Cracks in the weld
0.6	70	1	Cracks in the weld
0.7	70	1	Cracks in the weld
without	without	1.5	Cracks in the weld and HAZ
0.6	**60**	**1.5**	**No cracks**
0.7	**60**	**1.5**	**No cracks**
0.6	70	1.5	Cracks in the weld
0.7	70	1.5	Cracks in the weld
without	without	2	Cracks in the weld and HAZ
0.6	60	2	Cracks in the weld
0.7	60	2	Cracks in the weld
0.6	70	2	Cracks in the weld and HAZ
0.7	70	2	Cracks in the weld and HAZ

Table 6

Hardness distribution in a mixed joint

Micro-jet stream pressure [MPa]	Micro-jet stream diameter [mm]	DOCOL 1400M	HAZ-1	Weld	HAZ-2	S690 QL
0.6	60	375	399	321	391	258
0.7	60	376	392	313	381	256
0.6	70	374	391	311	380	257

Analyzing the data from Table 5, it can be noted that micro-jet cooling must be used for the MAG welding process. Decreasing the cooling intensity increases the hardness both in the weld and heat-affected zones (pin and arm). Finally, microstructure observations were carried out. The typical structure of the weld is presented in Fig. 6.

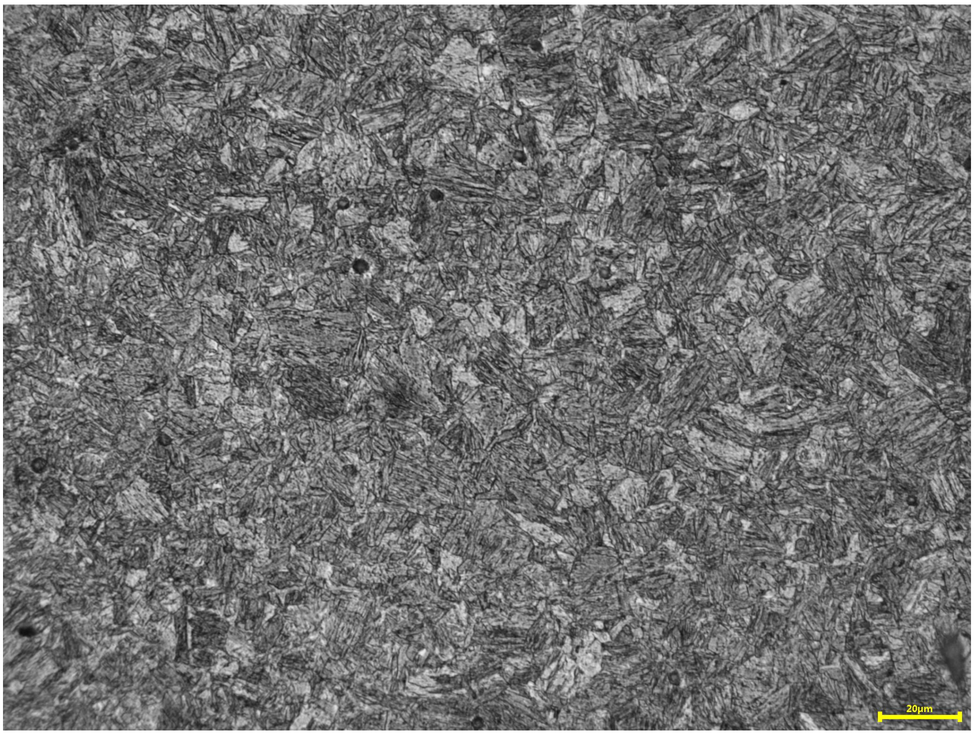

Fig. 6. Microstructure of the joint cross-section without the use of micro-jet cooling

Fig. 6 shows the microstructure of the cross-section of the joint, where the martensitic structure is clearly visible. Welds are free from defects and incompatibilities. The authors of the study [14] obtained similar results for the joining method combined with forced air cooling. The tests and microstructure characterizations presented in [14] revealed that forced air cooling during the joining process can accelerate the cooling process and suppress the coarsening of grains and the dissolution of precipitate phases. Therefore, it was decided to check the weld structure by SEM (scanning electron microscopy). In this grade of steel, the content of Ti is much higher compared to other groups of structural steel. It was assumed that non-metallic inclusions may form in the joint; these inclusions are insoluble.

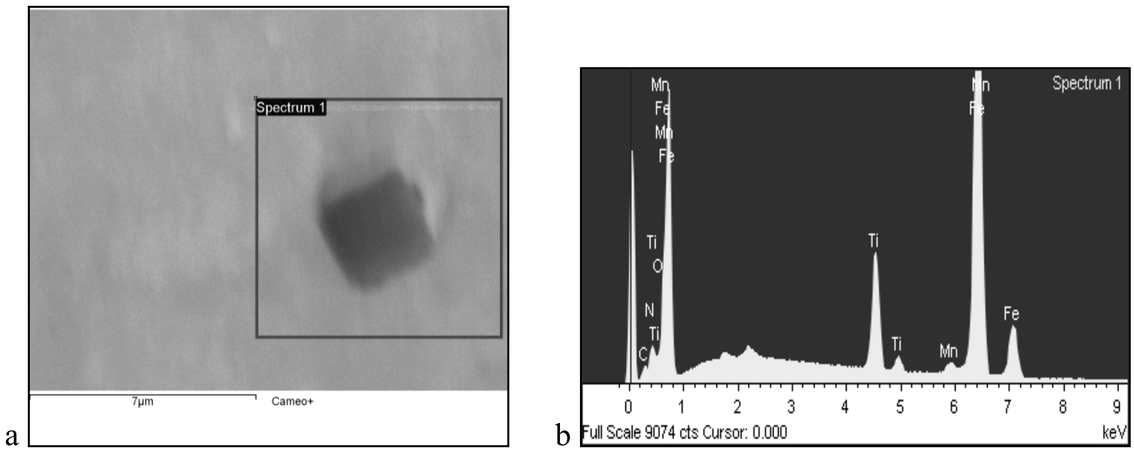

Fig. 7. Microstructure of weld with titanium carbide particles and EDS (energy-dispersive spectroscopy) analysis of the area – the square part in fig. 7a

Table 7

Chemical composition of titanium carbide particles, presented in Fig. 7

	Weight concentration, %	Atom concentration, %
C K	2,22	8,81
N K	2,51	8,53
Ti K	9,78	9,73
Mn K	1,66	1,44
Fe K	83,83	71,49
Total:	100,00	100,00

Titanium with such contents forms non-metallic inclusions (heterogeneous nature), mainly TiO, TiN and TiC. The SEM (scanning electron microscopy) results, showing an example of inclusions obtained in the welding process, are shown in Fig. 7.

The spectrum and chemical composition (Table 7) confirm the existence of titanium carbide in the weld. Only small amounts of inclusions were found. No other inclusions were identified by SEM (scanning electron microscopy) and EDS analyses. Similar effects were observed by Górka in [15].

4. CONCLUSIONS

In civil engineering and transport, there is an increasing demand for the use of mixed joints made of high-yield steel from the AHSS group. It is anticipated that such connectors will be used in creating smart cities. Tested in the article two grades of steel (S690 QL and DOCOL 1400 M) are increasingly used in automotive industry. The possibility of creating mixed joints from these types of steel is presented in this paper. This article presents the selection of some MAG process parameters (welding speed and the gap between elements) and selection of micro-jet cooling parameters in mixed welding of the pin (S690 QL steel) with movable platform arms (DOCOL 1400 M steel). The proper gap between elements (arm and pin) was also tested. Optimally selected gap between elements, welding speed and micro-jet cooling parameters affect the cooling conditions of the weld. This leads to the conclusion that the welding parameters should be selected carefully to avoid cracks and other welding defects and incompatibilities. Positive results of non-destructive and destructive tests confirmed that it is possible to produce the correct weld of arm with pin using MAG welding and micro-jet cooling. Due to the complicated nature of the joint, no other destructive tests, such as impact strength and tensile strength, were performed.

Acknowledgments

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