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AHSS STEEL WELDING WITH MICRO-JET COOLING IN MOBILE PLATFORMS

Summary. This paper focuses on the weldability of advanced high-strength steels (AHSS), commonly used by the automotive industry and civil engineering. These steels have found application in the construction of mobile platforms mounted on vehicles. AHSS significantly outperform other materials when it comes to performance flexibility and mass reduction potential. This article verifies whether the application of micro-jet cooling technology during the welding process might help to overcome these issues. The aim of this article is to choose welding parameters in the process with micro-jet cooling to obtain the best mechanical properties of the welded structure (elongation). The best welding parameters for these difficult-to-weld constructions are presented in detail.

1. INTRODUCTION

The use of advanced high-strength steels (AHSS) provides many benefits to civil engineering constructions and automotive structures as they combine light-weight with high strength and flexibility. AHSS is a type of alloy steel that provides much better mechanical properties than low-alloy steel [1]. AHSS steels mainly have a low carbon content between 0.05 and 0.25% to retain good formability and proper weldability. Other alloying elements include up to 2.3% manganese (3 times more than in low-alloy steels), 0.2% Si (2 times less than in low-alloy steel), 0.06% Al (2 times more than in low-alloy steels) and small amounts of Nb and Ti. Very often V, Cu, Cr and Ni are added instead of Ti and Nb [2]. Niobium, titanium, vanadium and copper are added for strengthening purposes. These elements are intended to modify the microstructure of the weld metal deposit. Because of their higher strength and toughness, AHSS steels usually require 25 to 30% more power in the forming process in comparison with low-alloy steels [3]. These steels are also characterized by a low sulfur content (0.01% S), which increases the impact toughness of steel and weld [4]. Zirconium, calcium and rare-earth elements are added for sulfide-inclusion shape control, which increases formability [4]. Copper, silicon, nickel, chromium and phosphorus are added to increase corrosion resistance. It was noted that the increased phosphorus content (0.01% P) has an effect on corrosion resistance [5]. AHSS steel is mainly used in civil engineering structures and the automotive industry such as in car bodies, truck frames, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of stress or need a good strength-to-weight ratio. AHSS steel structures are usually 25% lighter than carbon steel with the same strength [6, 7].

Vehicles, car components, civil engineering structures as well as other products require safety and increased durability of critical elements [8]. AHSS significantly reduce the weight of products compared to the same products made with other steels [8]. Modern mobile platforms are actually made from AHSS steels [9]. High strengths might be achieved through the application of AHSS steels during the manufacturing processes. The use of these new materials requires an understanding of their properties after welding and a necessity to develop new welding tools and methods that will provide the desired steel properties and match the increasing requirements of the industry [10]. AHSS steels are not easy to weld because of the high amounts of martensite [11, 12]. The aim of this paper is to analyze AHSS welding possibilities with micro-jet cooling and select the most favorable welding parameters of welded joints with the desired properties. Recently, micro-jet technology has been developing [13,14]. Welding with micro-jet for low-alloy steels and aluminum alloys gives good results with a noticeable effect on the structure and mechanical properties of weld metal deposit [13, 14]. Micro-jet cooling in welding has been best recognized for low-alloy steels [15, 16]. In this paper, we analyzed the possibilities of AHSS steel welding with micro-jet cooling for the first time.

2. ADVANCED HIGH-STRENGTH STEELS

Conventional low- to high-strength steels have rather simple microstructures, with low carbon contents and nominal alloying elements. They include IF (interstitial free), BH (bake hardened) and HSLA (high-strength low-alloy) and their yield strength equals less than 550 MPa. In comparison, AHSS are a lot more complex, with multiphase ferritic-bainitic, martensitic microstructures that improve their strength and ductility. AHSS also have unique properties, welding requirements as well as advantages, disadvantages and possible applications associated with their use. The comparison of traditional low-strength and high-strength steels is presented in Fig. 1.

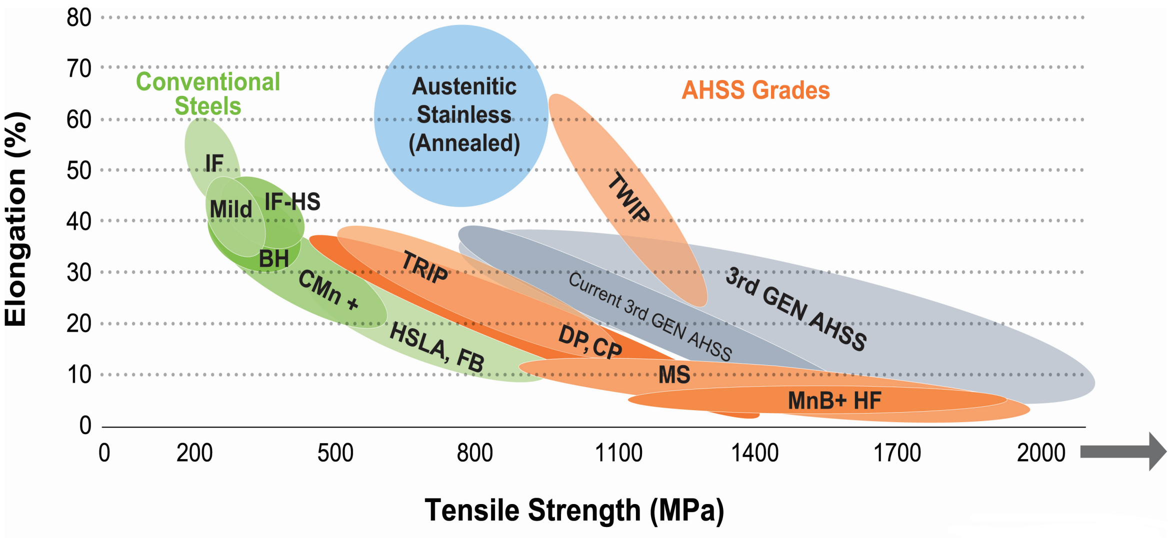

Fig. 1. Steel strength ductility (Ashby map) [6]

AHSS steels as a result of their properties are usually perceived as difficult to work with. The main challenge that constructors face when welding steels from this group is that the produced joint is not as strong as the parent material. Moreover, the heat-affected zone (HAZ) is prone to welding cracks even when preheated to the maximum temperature of 120° C as a result of the martensitic structure and material's high hardness.

Tables 1 and 2 present the mechanical properties and chemical composition of some of the AHSS steels used for the construction of mobile platforms mounted on vehicles.

Table 1
Mechanical properties of AHSS steels most commonly used for the construction of mobile platforms mounted on vehicles

Steel type	Plasticity limit YS, [MPa]		Limit of plasticity after heat treatment [MPa]	Tensile strength UTS, [MPa]		Elongation R80 %	Min bending radius for the angle 90°
	min	max	min	min	max	min	
Docol 900M	700	-	900	900	1100	3	3.0 x width
Docol 1200M	950	-	1150	1200	1400	3	3.0 x width
Docol 1400M	1150	-	1350	1400	1600	3	3.0 x width
Docol 1500M	1200	-	-	1500	1700	3	3.0 x width

Table 2
Chemical composition of AHSS steels most commonly used for the construction of mobile platforms mounted on vehicles

Steel type	C%	Si%	Mn%	P%	S%	Al%	Nb%	Ti%
Docol 900M	0.05	0.20	2.00	0.010	0.002	0.040	0.009	0.008
Docol 1200M	0.11	0.20	1.70	0.010	0.002	0.040	0.015	0.025
Docol 1400M	0.17	0.20	1.40	0.010	0.002	0.040	0.015	0.025
Docol 1500M	0.21	0.20	1.10	0.010	0.002	0.040	0.015	0.025

3. MATERIALS AND METHODS

To improve the weldability of AHSS steels and joints formed from these, it was decided to use shielding gases or their mixtures during the tests. The MAG (Metal Active Gas) welding process commonly uses CO_2 or a mixture of Ar and CO_2, whereas the TIG (Tungsten Inert Gas) welding process relies on pure argon. Application of shielding gases provides the best effects, especially in case of welding of thin-walled elements.

To further enhance the mechanical properties of joints produced from AHSS steel, MAG welding with the addition of the micro-jet cooling technology was selected. For the steel structure welding process, the following micro-jet cooling parameters are implemented:

- quantity of cooling nozzles: 1-9
- form of cooling medium: Ar, He, N_2, various gas mixtures of Ar,
- pressure of the cooling medium: 0.3 - 0.7 MPa,
- diameter of micro stream: 40 - 80 μm,
- distance of the micro-jet nozzle from the welded surface: 20 - 40 mm.

The tests were performed using AHSS DOCOL 1200M martensitic steel because of its high strength properties. Actually, it is a material recommended for the manufacture of mobile platforms mounted on vehicles.

The achievement of the following results was expected: increased weld strength, better relative elongation and elevated content of acicular ferrite and martensite without separation of bainite. To obtain these results, it was decided to apply the MAG welding technique in combination with micro-jet cooling on the face side of the weld.

For the tests, the following elements were selected: electrode wires, shielding gases and micro-jet cooling parameters. The appropriate selection ensured the most beneficial effects and an optimal connection of the selected material:

- two types of shielding gases: CO_2 and a mixture of 82% Ar + 18% CO_2;
- two electrode wires (tab. 3):

1. EN ISO 16834-A G 89 6 M21 Mn4Ni2CrMo - UNION X90
2. EN ISO 16834-A G 89 5 M21 Mn4Ni2,5CrMo - UNION X96

Table 3

Chemical composition of electrode wires

Steel type	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%
UNION X90	0.10	0.81	1.8	0.01	0.007	0.040	0.61	2.31
UNION X90	0.11	0.78	1.9	0.01	0.009	0.035	0.57	2.23

Welding parameters for both electrode wires and both gas mixtures were equal:

- electrode wire diameter: 1.0 mm,
- arc voltage: 19 V,
- welding current: 115 A,
- welding speed: 300 mm/min,
- source of a direct current (+) at the electrode,
- single-stitch weld.

Micro-jet cooling parameters were also identical:

- micro-jet gas: argon
- stream diameter: 60 μm and 70 μm
- gas pressure: 0.6 MPa and 0.7 MPa.

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

4. RESULTS

The first welding test of mobile platform elements was accomplished without the use of micro-jet cooling. Fig. 2 presents the welding process. The method of preparing sheets for welding is shown in Fig. 3.

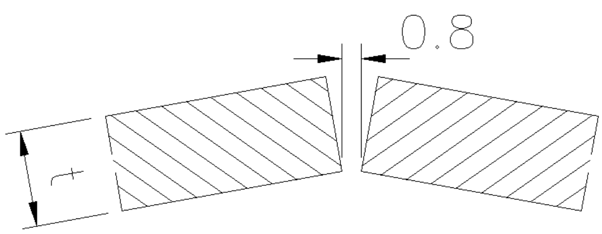

Fig. 2. Preparation of the element for manual welding, thickness t = 1.8 mm

On analyzing the array data, it can be seen that the results of welding DOCOL 1200M steel only with a ceramic backing are not satisfactory. It was decided to make DOCOL 1200M steel joints with the use of micro-jet cooling. The consecutive tests adopted the following parameters:
- mixture of shielding gases CO_2 and 82% Ar + 18% CO_2,
- both electrode wires (UNION X90 and UNION X96),
- ceramic backing and
- argon micro-jet cooling.

The results of the investigations are presented in Tables 5–8.

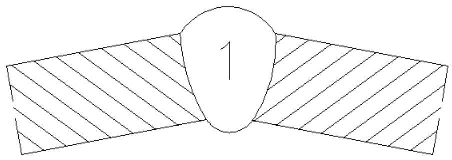

Fig. 3. The prepared weld

To enhance the welding process, a ceramic backing was also used. Table 4 presents the results obtained.

Table 4

Joints produced with the use of ceramic backing

Gas / wire	UNION X90	UNION X96
CO_2	Cracks in the HAZ and in the weld	Cracks in the HAZ and in the weld
82% Ar + 18 % CO_2	Cracks in the HAZ	Cracks in the HAZ

Table 5

Joints produced with shielding gas CO_2, wire UNION X 90 and the use of micro-jet cooling

Parameters/ results	Micro-jet gas pressure: 0.6 MPa	Micro-jet gas pressure: 0.7 MPa
Micro-jet stream diameter: 60 μm	Cracks in the HAZ and in the weld	Cracks in the HAZ
Micro-jet stream diameter: 70 μm	Cracks in the HAZ	Cracks in the HAZ and in the weld

The analysis of the array data (tables 6, 7) shows that not very intense micro-jet cooling and noneffective micro-jet cooling enable the elimination of cracks in the weld, but not in HAZ. The complete elimination of cracks will occur after the replacement of the shielding gas from CO_2 with the Ar–CO_2 mixture (tab. 7, 8).

On analyzing the data in Tables 5-6, it can be seen that micro-jet cooling does not eliminate cracks when using an oxidizing gas such as CO_2. The correct shielding gas is the Ar–CO_2 mix, but this is not enough to obtain the correct welds. It is necessary to use micro-jet cooling with not very intense micro-jet cooling parameters. After welding with two tested wires (UNION X 90 and UNION X 96), no cracks in welds were obtained when the micro-jet cooling parameters were as follows: micro-jet stream diameter 60 µm and micro-jet gas pressure 0.7 MPa or micro-jet stream diameter 70 µm and micro-jet gas pressure 0.6 MPa (tab. 7, 8).

Table 6

Joints produced with shielding gas CO_2, wire UNION X 96 and the use of micro-jet cooling

Parameters/ results	Micro-jet gas pressure: 0.6 MPa	Micro-jet gas pressure: 0.7 MPa
Micro-jet stream diameter: 60 µm	Cracks in the HAZ and in the weld	Cracks in the HAZ
Micro-jet stream diameter: 70 µm	Cracks in the HAZ	Cracks in the HAZ

Table 7

Joints produced with shielding gas 82% Ar + 18 % CO_2,
wire UNION X 90 and the use of micro-jet cooling

Parameters/ results	Micro-jet gas pressure: 0.6 MPa	Micro-jet gas pressure: 0.7 MPa
Micro-jet stream diameter: 60 µm	Cracks in the HAZ	No cracks
Micro-jet stream diameter: 70 µm	No cracks	Cracks in the HAZ

Table 8

Joints produced with shielding gas 82% Ar + 18 % CO_2,
wire UNION X 96 and the use of micro-jet cooling

Parameters/ results	Micro-jet gas pressure: 0.6 MPa	Micro-jet gas pressure: 0.7 MPa
Micro-jet stream diameter: 60 µm	Cracks in the HAZ	No cracks
Micro-jet stream diameter: 70 µm	No cracks	Cracks in the HAZ

As previously suggested, the use of micro-jet cooling enhanced the welding process, generating much better results. The technique provided joints of better quality, without any visible bumps, which was noted during the visual tests. The results are shown in Fig. 4.

After the visual assessment, the strength tests (average of 3 measurements, according to standards: EN ISO 4136:2013-05.) were carried out. The INSTRON 3369 testing machine was selected for this purpose. Various analyses were performed:

- strength of DOCOL 1200M steel after MAG welding (shielding gas mixture 82% Ar + 18% CO_2, wire UNION X90 and UNION X96) without the use of micro-jet cooling,

- strength of DOCOL 1200M steel after MAG welding (shielding gas mixture 82% Ar + 18% CO_2, wire UNION X90 and UNION X96) with the use of micro-jet cooling.

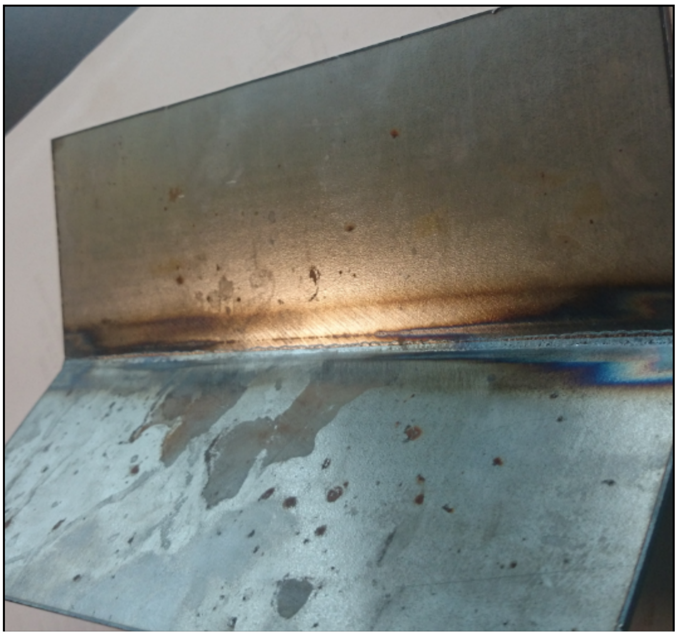

Fig. 4. Visual condition of the joints produced with the use of micro-jet cooling

The results are presented in Tables 9–10. Application of micro-jet cooling during the welding process slightly improved YS and UTS values. The biggest advantage of using micro-jet is the elimination of cracks and significant increase of the elongation.

Table 9

Strength tests' results after welding
(shielding gas mixture 82% Ar + 18% CO_2, wire UNION X90)

Micro-jet parameters	Yield point, YS, [MPa]	Tensile strength, UTS, [MPa]	A5
without	451	765	5.0
70 μm / 0.6 MPa	455	771	5.7
60 μm / 0.7 MPa	459	774	5.8

Finally, the microstructure analysis (Fig. 5) of weld after micro-jet cooling (micro-jet cooling parameters were as follows: micro-jet stream diameter 60 μm and micro-jet gas pressure 0.7) was carried out. Fig. 6 presents the microstructure of the cross-section of the joint after DOCOL M6 steel welding (shielding gas mixture 82% Ar + 18% CO_2, wire UNION X90), where the martensitic structure is clearly visible.

Fig. 5 presents the metallographic structure for AHSS weld with martensite and fine-grained ferrite. This type of structure enables better plastic properties with a relative elongation at the level of almost 6%, which helps to eliminate cracks in the connection and in the heat-affected zone.

Table 10

Strength tests' results after welding
(shielding gas mixture 82% Ar + 18% CO_2, wire UNION X96)

Micro-jet parameters	Yield point, YS, [MPa]	Tensile strength, UTS, [MPa]	A5
without	466	783	4.9
70 μm / 0.6 MPa	471	794	5.6
60 μm / 0.7 MPa	476	791	5.7

Fig. 5. Microstructure of the weld (joint cross-section with the use of micro-jet cooling); the scalebar is 50 μm.

5. CONCLUSION

Manufacturers of mobile platforms mounted on vehicles are constantly challenged with new requirements in terms of improved safety, fuel economy and environmental standards as well as increasing demand for new welding technologies that help to reduce their mass, and expand their operating range and lifting capacity. To meet these goals, the automotive industry is seeking new materials such as AHSS steels. AHSS provides high strength, increased durability and good quality at a low cost, maintaining its formability during the production process at the same time. AHSS steels are not easy to weld, however, and constructors are seeking innovative solutions and techniques that would improve their weldability, tensile strength and relative elongation. Researchers are constantly analysing steels from the AHSS group to better understand their properties and tailor technology used for the production of elements made of these materials. AHSS has been in use by the automotive industry for many years now, but with additional research, manufacturers will be able to apply these material in more applications.

This article shows how the use of micro-jet cooling during the welding process helps to produce joints of much better quality. Further studies are required, however, to assess the exact welding parameters, such as type of micro-jest gas, for each steel type used in the construction of mobile platforms. The welding possibilities of Docol steel with various parameters were analysed (various shielding gases and various electrode wires). Four different micro-jet cooling parameters were tested.

The best properties of the weld structure were obtained by welding with the following micro-jet parameters:

- micro-jet gas mixture: 82% Ar + 18% CO_2;
- 60 μm (diameter stream);
- gas pressure 0.7 MPa.

Correct micro-jet cooling parameters have been established, which allow obtaining an increased elongation joint and eliminate cracks.

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