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EXAMINATION OF MECHANICAL PROPERTIES OF WELDS OF DOCOL 1200M TOWARD APPLICATION IN COMPONENTS OF SPECIAL VEHICLES

Summary. The paper focuses on modern martensitic steel (Docol 1200M) and its joint manufactured by means of welding process supported by micro-jet cooling for special vehicles' structures. Docol 1200M is a type of material denoted as AHSS (A- advanced; H - high; S – strength; S - steel) with important material characteristics, which allows the potential to reduce the weight of the construction of transport means. The paper verifies if the use of micro-jet cooling after MAG welding process could help to maintain initial mechanical parameters of special vehicles' components. The quality of the joining process was checked by nondestructive and destructive tests. Results from tensile tests have enabled capturing the stress-strain curve as well as mechanical parameters and comparison with data of the parent material. Fatigue properties of the weld are described in terms of the fatigue limit and fatigue diagram, presenting fatigue limit as a key mechanical parameter with respect to the application of the joint examined. Testing the fatigue strength of a new steel grade for special vehicles' structures in the innovative MAG process at micro-jet cooling was treated as the main goal of the study.

1. INTRODUCTION

The application of high-strength low-carbon steel is well established in the automotive and oil sector. Various types of vehicle components such as brake discs [2], coupling zones, towing booms [8], safety cages and crush zones [13, 14], and others are being improved. This is done by introducing new structural solutions [14, 15] and application of modern materials [15, 16], taking advanced high-strength steel (AHSS) [17, 18] such as low carbon martensitic DOCOL steels [14, 16] and steels with increased yield point [8].

Docol 1200M steel as AHSS material has become a particularly attractive material in the production of components for special vehicles with respect to the following reasons [1]:
- high UTS (ultimate tensile strength),
- high YS (yield stress), and
- acceptable plastic properties (impact toughness and elongation).

The genesis of the development of research on AHSS steels results from the need to increase the strength and stiffness of key vehicle components that affect passenger safety. The transformation of the residual austenite into fragmented martensitic structure during the deformation of steel causes an absorption of kinetic energy, which is important in the case of road collisions [3, 4].

AHSS steels owe their strength to a combination of various structures such as bainite, ferrite, martensite, and residual austenite. AHSS steels remain ductile despite the presence of martensite and bainite in them [5]. The use of AHSS steel reduces the weight of structures and lowers energy consumption for vehicle production. High-strength steels could be certainly used in manufacturing various types of cars, as well as in the production of lifting equipment, machine and towing booms [8] (Fig. 1a), transhipment equipment for sea transport, construction machinery, and railroad truck frames. Features of AHSS steels cause an increase in their share, especially in the production of means of transport (including mobile platforms), where their weight can be reduced by up to 25% [4]. The growing demand for modern high-strength steels in the automotive industry results from the possibility of reducing the thickness of the sheets, guaranteeing the mechanical properties found in the constructions made of conventional steel. Moreover, updating the exhaust emission standards in motor special vehicles requires the introduction of additional elements to the vehicle to increase its curb weight. This is related to, among other things, the obligatory installation of various elements in vehicles. As a result, the weight of the vehicle increases by up to about 250 kg in the case of heavy-good vehicles. Materials from AHSS grades have found application in mobile-platform production. The aim is for the operational range to be bigger and the lifting capacity of mobile platforms. Examples of mobile platforms are shown in Fig. 1.

(a) (b)

Fig. 1. Application of advanced high-strength steel: (a) a region of towing boom used for coupling vehicles, (b) mobile platform on a special vehicle [12]

This article for the first time analyzed rules and parameters of Docol 1200M steel (from AHSS group) welding with micro-jet cooling [8]. A composition of Docol 1200M steel is presented in Tab.1.

By analyzing Table 1, it can be seen that this steel is characterized by an increased content of Ti and Al compared with other structural steels. This has an influence on high strength of that material (Tab. 2.)

With respect to engineering point of view, a relationship between the mechanical parameters is important to assess the quality of the steel and its welding because the proportion enables to indicate a size of shape region at the stress that reaches the yield point up to ultimate tensile strength. In this approach, an elongation plays a significant role because the parameter is directly related to ductility, enabling to avoid brittle cracking [7]. Generally, all DOCOL steels are not considered to be well weldable owing to martensite in microstructure even after the typical welding process, which directly results in a low resistance on impact and crack growing taking macro- and micro-scale. It indicates the tension cycles may lead to fracturing the welded steel earlier than in parent material [8, 9]. Therefore, attempts have been made to increase these properties thanks to the use of micro-jet cooling [10, 11]. For this reason, it was decided to check the application of micro-jet cooling, which may affect the structure of a joint and its plastic properties (Fig. 1).

Table 1

Main alloy elements of Docol 1200M

Steel grade	C%	Mn%	Si%	S%	P%	Al%	Nb%	Ti%	C/Mn
Docol 1200M	0.11	01.7	0.2	0.002	0.01	0.04	0.016	0.025	0.06

Table 2

Mechanical properties of Docol 1200M steel

Steel type	Yield stress (YS) [MPa]		Yield stress after thermal curing [MPa]	Ultimate tensile strenght (UTS) [MPa]		Elongation A_{80} [%]
Docol 1200M	Min 900	Max 950	1150	Min 1150	Max 1250	3-4

Fig. 2. Welding station with cooling injector

Micro-jet cooling has proven itself during low-alloy. The use of micro-jet cooling resulted in a fragmented structure which guarantees better mechanical properties. In the presented injector, the number of micro-nozzles can be adjusted in the range 1-9, and the diameter of the micro-stream in the range 50-80 μm. The use of micro-jet cooling during welding of low-alloy steel resulted in an increase of acicular ferrite in weld by 10%, which significantly increased the impact toughness of the joint at low temperatures. This has a significant impact on the safety of the structure [11].

2. MATERIALS AND METHODS

With respect to the taken application expressed by the mobile platform, the Docol 1200M steel and its weld was selected to be examined in static and fatigue tests. Mechanical parameters of the material determined in monotonic tension were strongly related to the high-quality requirements of manufacturers (Figs 3, 4). Nevertheless, the tensile curve of the tested material manifested a short region of the steel hardening, indicating on the rapid occurrence of fracture at stress exceeding the yield stress by the values of 70 MPa, only (Fig. 4).

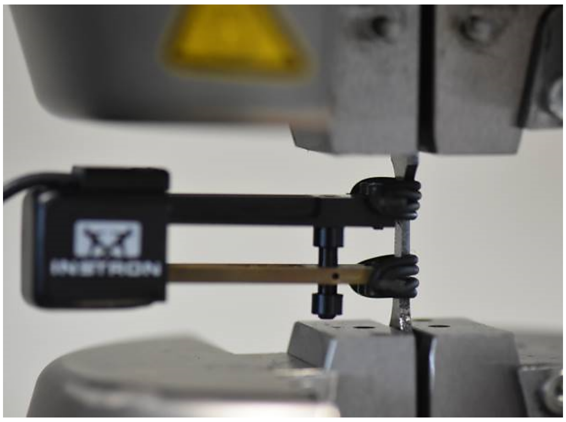


Fig. 3. Flat specimen with extensometer before tensile test

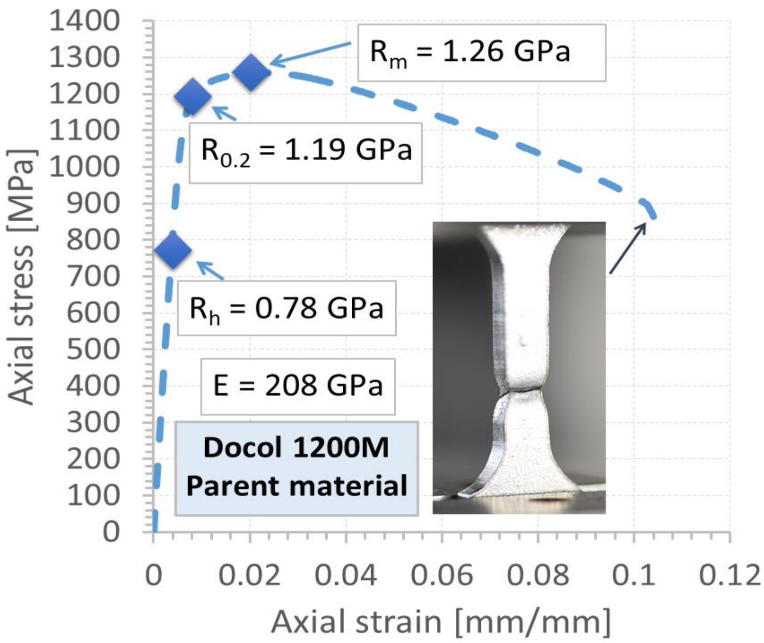


Fig. 4. Tensile characteristic with mechanical parameters and its fracture zone of the Docol 1200M, $R_m/R_{0.2}$ = 1.05, where: E – Young modulus, R_h – Hook limit, $R_{0.2}$ – conventional yield point, R_m – ultimate tensile strength

Docol 1200M high-strength steel is characterized by dominant martensite microstructure, the presence of which makes welding difficult. The HAZ (Heat-Affected Zone) is prone to welding cracks even with preheating to 100° C as a result of martensite presence and elevated hardness.

It is easy to deduce from the Tab. 1 that the high strength of the Docol 1200M steel results from the presence of steel strengthening elements (C, Mn, Si, Al, Nb, Ti), and the low relative elongation results from the lack of such elements as Cr and Mo in these steel grades.

Weldability of Docol 1200M steel was tested using MAG (Metal Active Gas) process and micro-jet cooling. A sheet of 3-mm thickness was welded.

Following filler materials were chosen:

- wire UNION X90 according to standards: EN ISO 16834-A; (composition: C 0.1%, Mn 1.8%, Si 0.7%, Cr 0.3%, Mo 0.65%, and Ni 2.4%) and
- shielding argon gas mixture (18% CO_2).

MAG welding (single-stitch weld) parameters were as follows:

- wire diameter: 1.0 mm,
- voltage: 19 V,

- source of a direct current (+) electrode,
- current: 119 A, and
- speed: 330 mm/min.

Parameters of m-j (micro-jet) cooling were slightly varied:
- one jet (nozzle),
- gas: argon only,
- diameter of the stream: 60 μm and 70 μm, and
- pressure of the argon (micro-jet gas): 0.4 MPa; 0.5 MPa; 0.6 MPa, and 0.7 MPa.

After welding, a quality control was applied:
- visual inspection,
- analysis of mechanical parameters,
- tensile curve,
- hardness test, and
- microstructure verification.

Assessment of a quality of joining manufactured using the micro-jet cooling technique was conducted using tensile and fatigue tests. All experiments were carried on the 8874 Instron testing machine using flat and hourglass mini-specimens. The nominal thickness of specimens was equal to 1.8 mm and thickness in the middle of measuring cross-sections takes 4 mm.

Fatigue tests were conducted on hourglass specimens having weld in the middle of a measuring zone. The force signal in a cyclic form of a sinusoidal function at the frequency of 5 Hz was employed for conducting the fatigue tests. The values of maximum stress were on the level of 700 MPa, 650 MPa, 600 MPa, 500 MPa, 550 MPa, and 500 MPa. The tests were performed up to specimen fracture or the number of cycles following fatigue limit, i.e. 2×10^6 cycles.

3. RESULTS

Welding test of mobile platform elements was done without and without using micro-jet (m-j) cooling system. Fig. 5 shows the details for preparation of the elements for the welding process.

After MAG welding, some non-destructive tests were carried out: visual and magnetic-particle (VT and MT). The gap (Fig. 5) was carefully changed and verified in a range of 1 to 3 mm, with step of 0.5 mm step using various parameters of the process. The results of the non-destructive tests (NDT) are presented in Table 3.

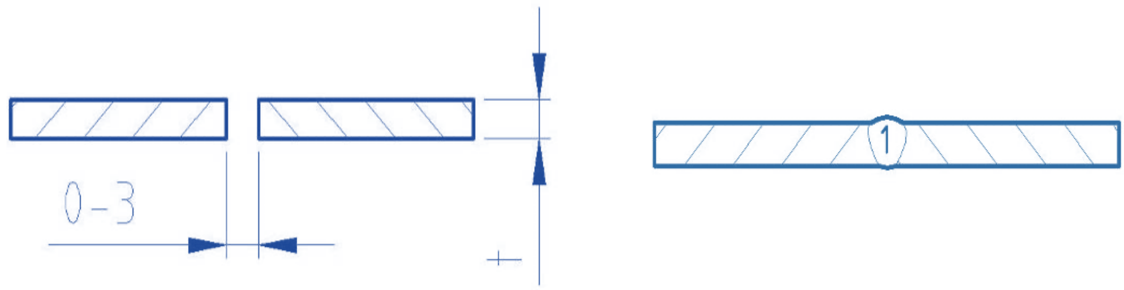


Fig. 5. Details for preparation of the elements for MAG welding with micro-jet (m-j) cooling, thickness t = 3 mm

After welding without micro-jet cooling, cracks occurred very often (results of NDT). One of the methods of crack elimination could be probably preheating at 120° C, but this also does not always give good results. Preheating was not tested in this research, because the authors have concentrated on the aspect of m-j cooling. Moreover, the use of the m-j cooling, which is not sufficiently effective (small micro-jet gas pressure), does not allow us to eliminate cracks in the weld. The table data show that the gap between elements should be equal to 1.5 mm. Important is, that in the same time m-j cooling could not be very intensive. Micro-jet stream pressure 0.6 MPa is recommended. M-j stream diameter could be in the range of 60 μm to 70 μm. It has also been observed that increasing the micro-jet cooling intensity deteriorates the joint quality (gas pressure equal to 0.7 MPa). Analyzing the average number of cracks, it can be seen that the worst effects are obtained when there is no or very intense m-j cooling. The observation of the number of cracks is representative and enables to obtain preliminary information about the influence of m-j cooling parameters on the quality of the welds.

Table 3

Assessment of the movable platform welded joint by means of NDT

m-j pressure [MPa]	m-j diameter [μm]	gap [mm]	number of cracks
-	-	1-3	3-4
0.4	60	1-3	3-4
0.4	70	1-3	2-3
0.5	60	1-3	1-2
0.5	70	1-3	1-2
0.6	60	1.5	No cracks
0.6	70	1.5	No cracks
0.7	60	1.5	2-3
0.7	70	1.5	3-4
With micro-jet cooling (all tested parameters)		2-3	Always cracks in the weld

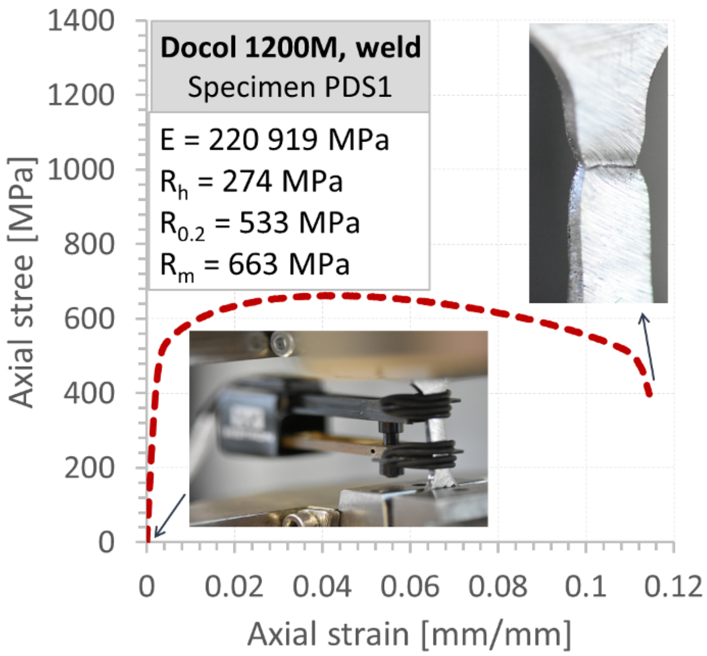


Fig. 6. Tensile characteristic and mechanical parameters of the weld to Docol 1200M $R_m/R_{0.2} = 1.24$

The weld joining at the MAG technique with argon micro-jet cooling obtained smaller values of proportional limit (PL), yield stress (YS), and ultimate tensile strength (UTS) than in the case of the parent material. The beneficial features of the region are ductility that is not sensitive to the welding process, and the proportion of ultimate tensile strength to yield stress has captured the value of 1.23 (Fig. 6).

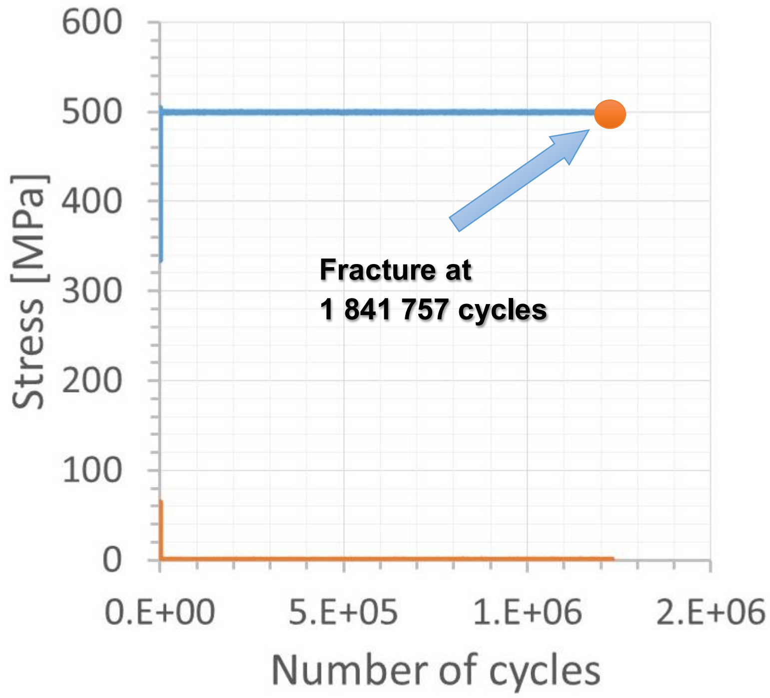
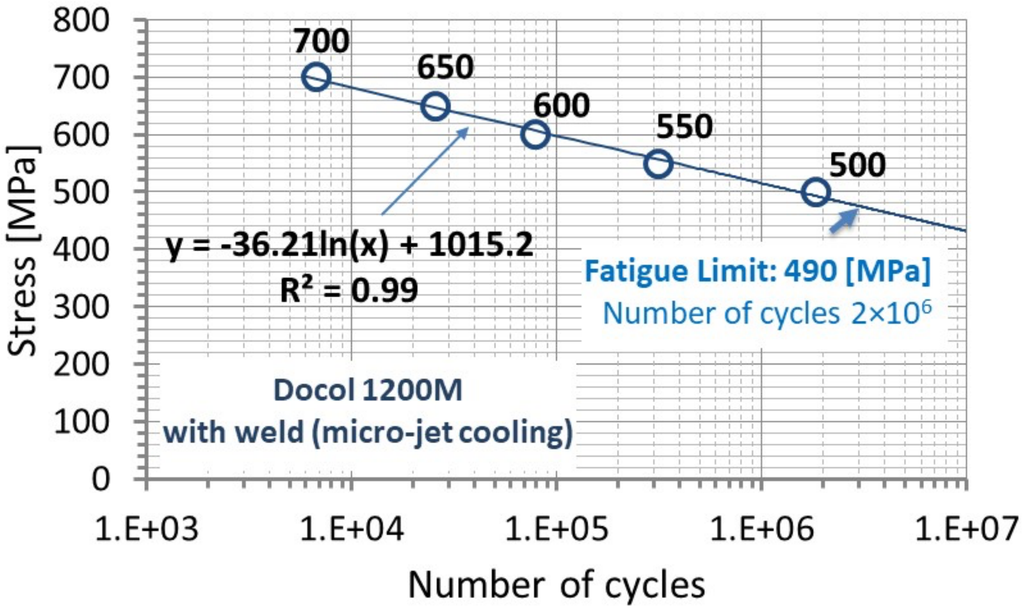


Fig. 7. Minimal and maximal values of cyclic stress in the form of sinusoidal function at amplitude of 500 MPa for the weld of the Docol 1200M with micro-jet cooling

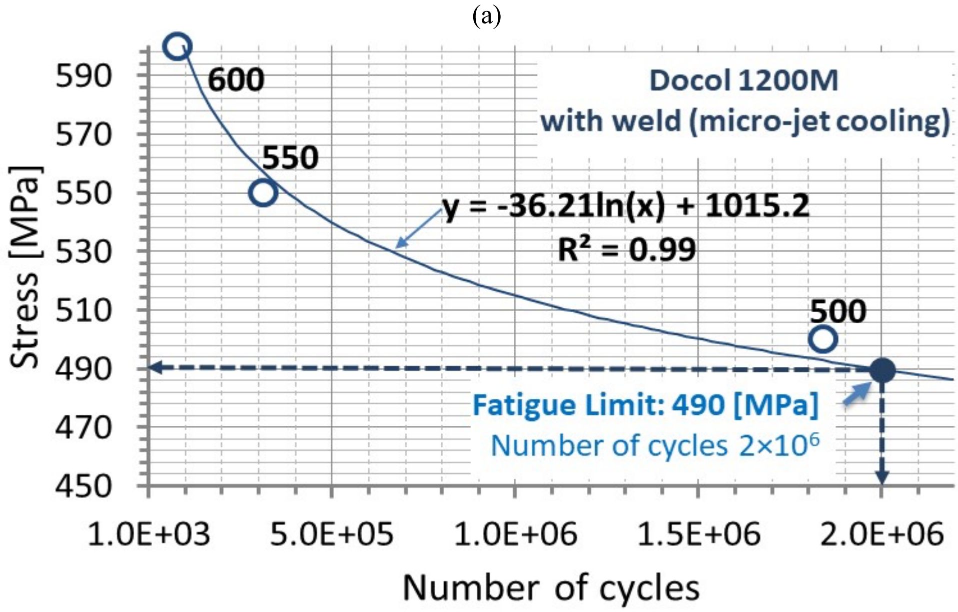
The use of micro-jet cooling in the MAG welding improved both values: YS and UTS. The YS value of welded joint was on the level of 500 MPa, and the UTS value was of 650 MPa. The high value of the relative elongation on the level of 12% (higher than the parent material on the level of 9%) is noteworthy, which proves the correctness of the welding process.

Fatigue tests were conducted on hourglass specimens. The weld was located in the middle of a measuring section. The maximum values of axial stress were from the range from 700 MPa up to 500 MPa using the five levels determined by 50 MPa at R = 0. The tests were conducted up to fracture or the i.e. 2×10^6 loading cycles connected with the fatigue limit. The force signal of a sinusoidal function at the frequency of 5 Hz was employed (Fig. 7). The frequency value was determined with respect to specimen thickness and response of the servo-hydraulic testing machine (8874 INSTRON) under stress signal used for examining the material at cyclic loading. As it can be calculated, the values of time connected with the number of cycles up to fracture have reached the following values: 0.5 h (700 MPa); 1.8 h (650 MPa); 4.4 h (600 MPa); 21.7 h (550 MPa); and 127.9 h (500 MPa). All fatigue tests were conducted continuously, avoiding effects owing to holding the experiments. Besides collecting the loading course at the selected number of cycles, the minimum and maximum values of the signal were recorded for evaluating the quality of the test with respect to the further analysis of results (Fig. 7). The figure shows that with the assumed stress of 500 MPa, 2×10^6 loading cycles were not obtained, i.e., the weld fracture occurred directly at 1 841 757 cycles. This result was taken into account as very close to the value of the fatigue limit of the weld tested. Therefore, the next stage of the investigations was focused on following the value of stress related to the limited number of cycles, i.e., 2×10^6 at no fracturing. This was conducted after analysis of the distribution of the experimental data, which follows a course at $R^2 = 0.99$ (Fig. 8).

Results on Fig. 8, presented in the form of a logarithmic scale on the 0x axis (Fig. 8a) as well as an asymptotic relationship (Fig. 8b) have allowed us to indicated the stress of 490 MPa, which corresponds to the loading cycles of 2×10^6 (Fig. 8b). Therefore, this value of stress was chosen for the fatigue limit of the tested welds. This kind of data is not presented in material certificates on base metal as well as welds; therefore, the captured result is crucial for mechanics of materials (strength analysis), welding technology (quality of weld), and durability approaches (prediction of fatigue resistance). Moreover, in comparison with the value of yield stress and ultimate tensile strength of the weld, the relationship between these mechanical parameters can be proposed in the following form: fatigue limit (FL) = 0.8·yield stress (YS) and fatigue limit (FL) = 0.7·ultimate tensile strength (UTS). It can be directly used by designing and modelling groups, which calculate values of stress and compare it with strength rules. This proves a very positive role of m-j cooling on the weldability of DOCOL 1200M steel.



(a)



(b)

Fig. 8. Fatigue characteristic (a) and section of the (a) showing the value of fatigue limit of the weld to Docol 1200M steel with micro-jet cooling, values of stress levels: from 700 MPa to 500 MPa

Finally, microscope observations were carried out – Fig. 9, where presents the microstructure that is rather favorable, with a martensite and fine-grained ferrite. This type of region expresses better plastic properties than parent material, taking the relative elongation at the level of 11%, which helps to eliminate crack occurrence in the connection and in the heat-affected zone (Fig. 10).

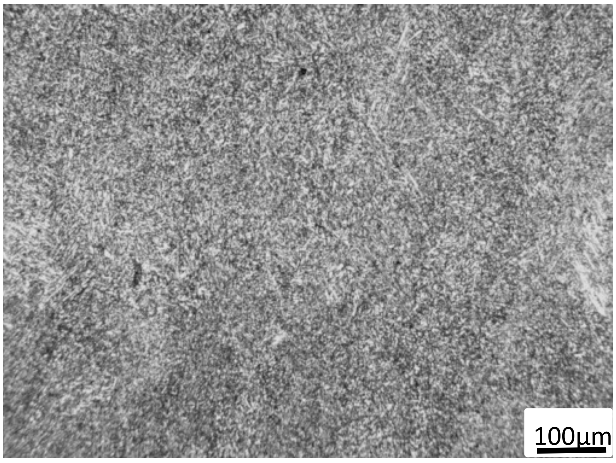


Fig. 9. Structure of the cross-section MAG weld with the use of m-j cooling

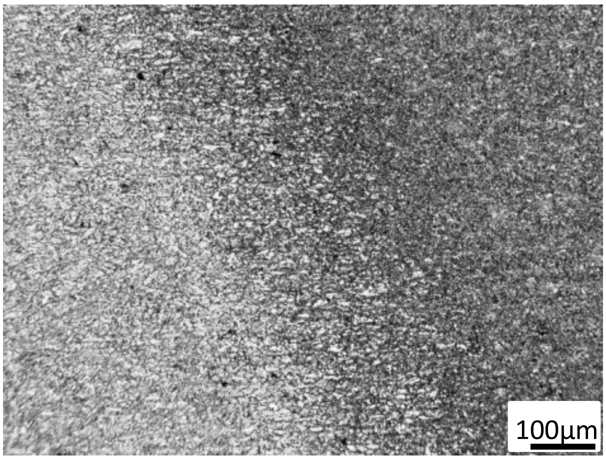


Fig. 10. Structure of the fusion line. On the left is presented base material, on the right HAZ

Fig. 10 illustrates a clear fusion line, heat-affected zone, and base material. The martensitic structure dominates in both zones. Fig. 10 further shows that the joint is made of the correct quality. This corresponds very well to the hardness measurement results (Fig. 11, Tab. 4).

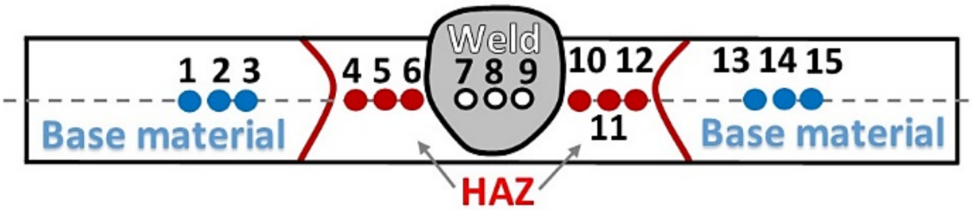


Fig. 11. A scheme of the hardness measurements for the welded joint manufactured at the micro-jet cooling

Table 4

Results of Vickers hardness (HV30) in the indicated points (from Fig. 11) of the MAG weld with m-j cooling

Base material			HAZ			Weld			HAZ			Base material		
Point number														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hardness value [MPa]														
343	341	342	362	362	364	328	329	330	365	362	361	344	341	340

Analyzing the hardness distribution, a comparable hardness value can be found in all tested regions: the base material, the HAZ, and the weld. This confirms that the welding process is very carefully selected. In the joint without micro-jet cooling, a greater scatter of hardness results was observed (Tab 5).

Table 5

Results of Vickers hardness (HV30) in the indicated points (from Fig. 11) of the weld without the micro-jet cooling

Base material			HAZ			Weld			HAZ			Base material		
Point number														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hardness value [MPa]														
341	342	344	367	368	370	323	325	326	369	366	367	343	340	342

4. CONCLUSIONS

The weldability of the Docol 1200M steel used in the construction of special vehicles was checked. Conventional MAG and innovative MAG processes with m-j cooling were tested and compared. Destructive and non-destructive tests were performed. Joints made with the standard MAG process showed welding defects and incompatibilities. Main parameters of the MAG process and micro-jet cooling parameters were determined, after which there were no defects in the welds manufactured.

The distance between 3-mm thin elements selected to joining shows that the gap between them should be equal to 1.5 mm. It was recommended that m-j cooling should not be very intensive. Micro-jet stream pressure should be on the level of 60 MPa, and stream diameter should be in range 0.6 to 0.7 μm. In opposite to the ductility, the yield stress and ultimate tensile strength were sensitive to the welding process.

The joints made with the MAG process and micro-jet cooling withstand the fatigue limit of 490 MPa enabling to reach 2×10^6 cycles at least. This proves a very positive role of the m-j cooling on the weldability of DOCOL 1200M steel.

Mechanical data of the micro-jet cooling Docol 1200M weld enables to indicate loading conditions that do not lead to any permanent deformation and fatigue damages. It is met if a value of tensile stress does not exceed 270 MPa (proportional limit) and 490 MPa (the fatigue limit at tension cycles), respectively.

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