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Bożena SZCZUCKA-LASOTA[1], **Klaudiusz GOŁOMBEK**[2], **Tomasz WĘGRZYN**[3]*,
Bogusław ŁAZARZ[4], **Krzysztof LUKASZKOWICZ**[5], **Abilio PEREIRA SILVA**[6],
Romana ANTCZAK-JARZĄBSKA[7]

DOCOL 1100M WELDING IN THE CONSTRUCTION OF ELECTRIC MEANS OF TRANSPORT

Summary. Advanced high-strength steels are important for the automotive sector. Metal active gas (MAG) is the most popular method for joining grades of steel. The goal of the paper is to analyze the mechanical properties of the MAG welding joint made of high-strength DOCOL 1100M intended for the construction of electric vehicles. The manuscript shows a basic understanding of the properties of DOCOL joints. This type of material is characterized by a martensitic microstructure, which makes it difficult to make a proper joint. The tensile strength, metallographic structure, and type of non-metallic inclusions were analyzed as a function of the oxygen amount in the protective gas mixture. Investigations of oxide non-metallic inclusions were carried out using scanning electron microscopy. This article attempts to obtain high joint strength of the electric vehicle structure by controlling the average size of non-metallic inclusions in the weld, which is influenced by shielding gas in the MAG welding process. The solution has application potential for the automotive industry, especially for electric vehicles.

1. INTRODUCTION

While some low-alloy sheet steels are produced routinely in high volumes for vehicle construction today, there have been significant advances in the usage of AHSS (Advanced High Strenth Steel) in the transport industry. The recent developments in the design, metallurgy, processing, and applications of weld construction from automotive steels are the reason for their increasingly wider use. This article discusses automotive steels, such as DOCOL steel, that are currently in the early stages of research. Steel is characterized by low density and a high modulus of strength, which drive future car body development, especially for new vehicles such as electric cars.

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[1] Silesian University of Technology, Faculty of Transport and Aviation Engineering; Krasińskiego 8, 40-019 Katowice, Poland; e-mail: bozena.szczucka-lasota@polsl.pl; orcid.org/0000-0003-3312-1864
[2] Silesian University of Technology, Faculty of Mechanical Engineering; Konarskiego 18a, 44-100 Gliwice, Poland; e-mail: klaudiusz.golombek@polsl.pl; orcid.org/0000-0001-5188-1950
[3] Silesian University of Technology, Faculty of Transport and Aviation Engineering; Krasińskiego 8, 40-019 Katowice, Poland; e-mail: tomasz.wegrzyn@polsl.pl; orcid.org/0000-0003-2296-1032
[4] Silesian University of Technology, Faculty of Transport and Aviation Engineering; Krasińskiego 8, 40-019 Katowice, Poland; e-mail: boguslaw.lazarz@polsl.pl; orcid.org/0000-0003-3513-8117
[5] Silesian University of Technology, Faculty of Mechanical Engineering; Konarskiego 18a, 44-100 Gliwice, Poland; e-mail: Krzysztof.lukaszkowicz@polsl.pl; orcid.org/0000-0003-1511-9066
[6] University da Beira Interior; Convent de Antonio, 6200-001 Covilhã, Portugal; e-mail: abilio@ubi.pt; orcid.org/0000-0002-2100-7223
[7] WSB Merito University Gdansk; Grunvvaldzka 2 B, 80-216 Gdańsk, Poland; e-mail: rantczak@wsb.gda.pl; orcid.org/0000-0002-6853-2041
* Corresponding author. E-mail: tomasz.wegrzyn@polsl.pl

Metal active welding (MAG) is a popular process due to the versatility of the method and the simplicity of the equipment used. This is the dominant method used in the construction and repair of cars and the repair of various types of means of transport [1]. Progress in the automotive industry is created using modern materials and types of connections. It is currently believed that the structure of modern vehicles will require the use of new types of high-strength steel [2-4]. The usage of high-strength materials will significantly reduce the mass of vehicles, which is very important, especially in the construction of electric vehicles and hybrid electric vehicles. More and more durable steel grades are used to build modern vehicles. AHSS materials guarantee very high tensile strength and good fatigue properties [5-6]. High-strength steel is used to make battery mounts, bumper elements, and seat structures [1]. AHSS welding is difficult. An example of this is the newly developed DOCOL 1100M steel with a dominant martensitic structure. Thicker sheets are recommended to be welded with preheating and controlled linear energy. A high Ti content is used in AHSS steels, which exceeds the Ti content in unalloyed steels by more than 12 times and accelerates the formation of some non-metallic inclusions such as oxides, nitrides, and carbides [7-10]. The addition of titanium (Ti) in these steels is justified because titanium inclusions increase the tensile strength. We decided to perform test connections in order to check the possibility of the strength elevation of the connection and bringing the strength of the joint closer to the strength of the base material. It was decided to implement this idea using metallurgical methods, which involve determining the most favorable sizes of non-metallic inclusions, mainly of oxide nature, strengthening the weld metal [4]. Metallurgical issues and the fact that the tensile strength of the welds is lower than the base material have not yet been resolved. This is a research gap indicating why this topic needs to be researched.

2. MATERIAL AND RESEARCH METHODOLOGY

DOCOL 1100 M butt welds with a narrow thickness (of 1.8 mm) were made. The MAG process in the PA position was selected per the hints of the EN 15614--1 norm. In this weld position, welders put metal pieces right below the torch.

The preparation of the material before welding (single bead) is shown in Fig. 1. The total dimensions of the sample were 1.8 mm × 200 mm × 300 mm.

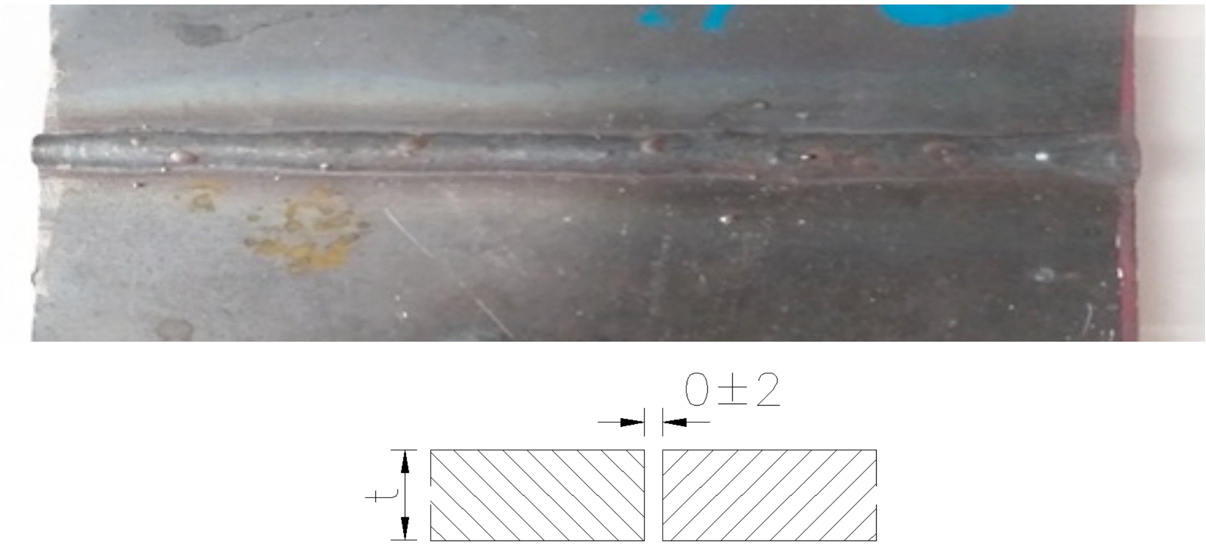

Fig. 1. Preparation of samples for MAG welding, thickness t = 1.8 mm

We decided to produce test welds using various shielding gas mixtures and in the MAG process containing variable CO_2 contents. Four different shielding gases were selected:

- Ar and 8% CO_2,
- Ar and 13% CO_2,

- Ar and 18% CO_2,
- Ar and 23% CO_2.

The most popular gas mixture in welding processes is a mixture containing Ar - 18% CO_2 (PN-EN 14175 standard). The authors decided to check whether this is the most appropriate mixture and examine its impact on the quality of the joints in relation to other tested protective mixtures. The specimen was welded using Union X 90 wire (EN - ISO 16834--A). The chemical composition of Union X 90 wire and DOCOL 1100M steel is present in Table 1.

Table 1 shows that the compositions of the materials are not very similar because the materials differ slightly in the content of certain elements (Ti, Mo, Ni, Cr, and Si). The steel contains a higher Ti content than welding wires to ensure the highest possible tensile of the material. This fact may translate into the formation of various titanium inclusions, especially such as TiO, TiN, TiC, and Ti(C, N). Cr is added instead of Ti to increase the strength of the weld. The electrode wire, on the other hand, has a much higher Mo and Ni content, which increases the ductility of the joint. This protects the joint from welding cracks and reduces the likelihood of their formation.

Table 1

Composition [wt. %] of Union X 90 electrode wire
and DOCOL 1100M steel

Material [%]	C	Mn	Si	Cr	Ni	Mo	Ti	Al
UNION X 90	0.10	1.81	0.81	0.035	2.55	0.61	0.001	0.02
DOCOL 1100M	0.11	1.69	0.19	0.07	0.16	0.12	0.025	0.02

The connectors were made with a direct current source. Shielding argon gas mixtures with various CO_2 contents were used in the tests. This is the most important part of experimental research. The main process parameters are shown in Table 2.

Table 2

Welding parameters of DOCOL 1100M

Shielding gas	Diameter of wire [mm]	Current [A]	Voltage [V]	Polarity	Process speed [mm/min]
Argon + CO_2	1.0	116	20.5	DC "+" on the electrode	330

Table 2 indicates that a DC source was selected for welding with "+" polarity on the electrode. Typical parameters for welding thin-walled steel structures were used.

After welding, we decided to carry out primary tests to get the proper quality of the tested joints. Non-destructive testing (NDT) was conducted in the first experiments used for initial selection.

The following activities were carried out as part of this part of the research:

- visual tests of welds were taken based on the EN ISO 17638 and assessment norm EN ISO 5817,
- magnetic tests of welds were done with the PN-EN ISO 17638 and criteria from EN ISO 5817 using a REM-230 detector.

In the second experimental part, destructive tests were carried out, which consisted of:

- conducting a tensile test of welded EN ISO/6892-1:2020.
- the hardness of welded joints -EN ISO/9015-1:2011 and EN ISO/6507-1:2018-05. These were measurements of HV -Vickers Hardness. In Chapter 3, Table 4 shows the average of five measurements in a given zone (for the parent material and heat affected zone and also weld).
- examination of a structure etched with Nital.
- examination of non-metallic inclusions on scanning microscope.

3. DISCUSSION

The research focused on various amounts of CO_2 in the argon shielding mixture on the quality of the joint made of DOCOL 1100M steel. The designation of the samples and the results of a non-destructive test are given in Table 3.

Table 3

Non-destructive testing results

Sample, symbol	Shielding gas	Observation
Y8	Ar - 8% CO_2	No welding defects or inconsistencies
Y13	Ar - 13% CO_2	No welding defects or inconsistencies
Y18	Ar - 18% CO_2	No welding defects or inconsistencies
Y23	Ar - 23% CO_2	Minor cracks in the HAZ

For further testing, we decided to take into account only samples with the symbols Y8, Y13, and Y18, for which welding incompatibilities were not found. Welding defects in the form of microcracks were found in sample Y23. Table 3 shows that too much CO_2 addition in the protective Ar - CO_2 mixture is unfavorable. Too much oxygen in the shielding gas most likely resulted in the growth of ceramic inclusions in the weld. This view is consistent with the research results presented in 11-12.

The next part of the investigation was to take hardness measurements. Only samples that had no defects after NDT were chosen. Durability focused on all the important areas of the joint: HAZ, weld (fusion zone), and parent (base) material (Table 4).

Table 4

Hardness of the joint

Sample, symbol	Parent material	HAZ	WELD
Y8	318	341	297
Y13	318	337	301
Y18	318	343	296

The data show that HAZ and the parent material material have the highest hardness, while the weld has the lowest. The hardness of all tested joints is comparable. The tested shielding gases (Y8, Y13, and Y18) did not influence the values. The results (Table 4) show that the hardness of the weld and parent metal are at the same level in all cases (Y8, Y13, and Y18).

The highest weld hardness was achieved for joint Y13. Further, a tensile strength assessment was carried out on the INSTRON 3369 machine (Table 5).

Table 5

Tensile strength of the weld

Symbol	YS [MPa]	Tensile strength, UTS [MPa]
Y8	502 ± 8	701 ± 10
Y13	515 ± 12	718 ± 14
Y18	510 ± 10	703 ± 12

All tested joints (Y8, Y13, and Y18) yielded positive results. The sample with the symbol Y13 had the highest tensile strength. This shows that the addition of CO_2 is very necessary in the argon shielding mixture, there is an optimal CO_2 content that allows for obtaining the most favorable plastic properties. In the next part of the research, we checked the metallographic structure of the joint with the highest tensile strength made under the protection of the Ar - 13% CO_2 mixture (sample Y13) and carried out observations using a light and scanning microscope.

Fig. 2 shows the structure of HAZ and the weld for the Y13 joint.

Fig. 3 presents the microstructure of the joint. In addition to the dominant martensitic phase, ferrite (marked in white) and numerous non-metallic inclusions of various sizes and shapes are visible. Based on the nature of the non-metallic inclusions, it can be assumed that they are titanium oxides. In order to more precisely analyze the structure of the joint and identify inclusions strengthening the solution, we performed examinations using a scanning microscope. The test results are presented in Fig. 3.

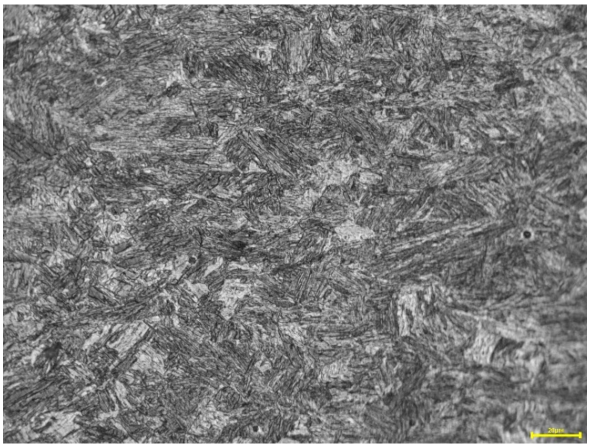

Fig. 2. Joint with the symbol Y13, martensitic structure, fine-grained ferrite, and non-metallic inclusions

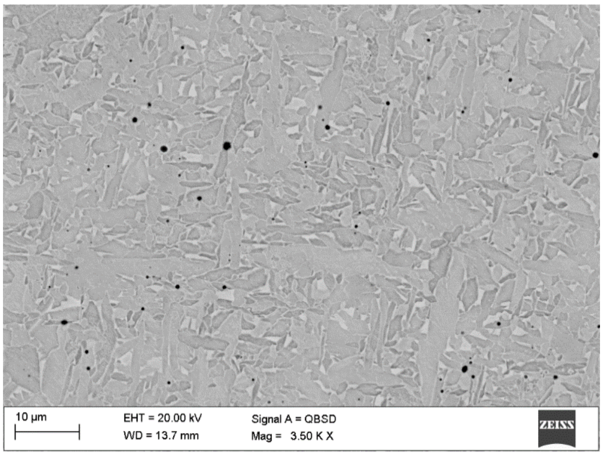

Fig. 3. The structure of the joint determined by scanning electron microscopy (SEM)

From the analysis of the spectral spectrum, it can be concluded that the non-metallic inclusions present in the joint correspond to TiO-type oxides (Fig. 4). The oxides are evenly distributed and not spread. In contact with TiO inclusions, ferrite easily nucleates because TiO has a lattice parameter similar to that of ferrite.

Based on structural examinations using SEM, we found that ceramic inclusions in the weld consist of such elements as Ti and O, which correspond to titanium oxide type, as well as Fe, Mn, Si, Cr, Mo, and C, which come from the warp. In order to confirm the presence of titanium oxides in the microstructure, we performed the surface distribution of the elements using an EDX spectrometer (Fig. 5). The size of titanium oxides ranged from 0.5-3 μm.

In order to confirm the phase composition of DOCOL 1100M steel, we carried out tests using the EBSD technique. It was confirmed that DOCOL 1100M steel in the base material area was characterized by a ferritic structure (Fig. 6c) with a grain size in the range of about 5-15 μm (Fig. 6) with visible subgrain boundaries, and a fine-grained martensitic structure of about 2-4 μm was found in the welded zone (Fig. 7). Based on the results of inverse polar figures (Figs. 6e and 7e), no texture was identified in the structure.

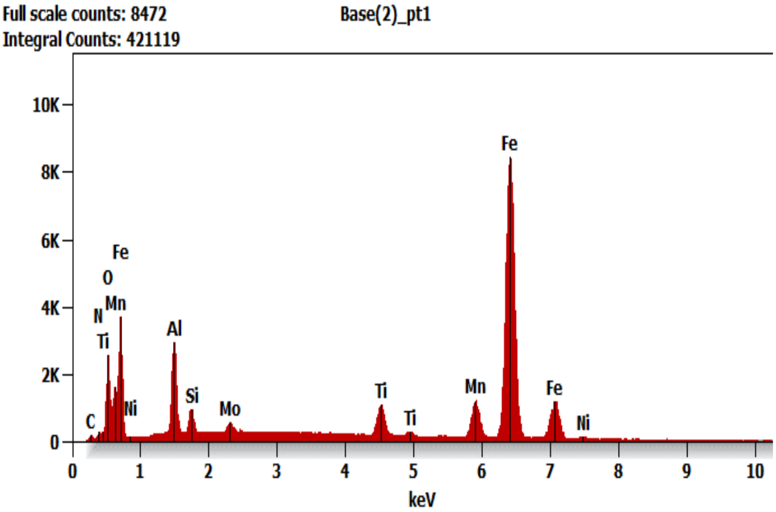

Fig. 4. X-ray microanalysis. Oxide inclusions

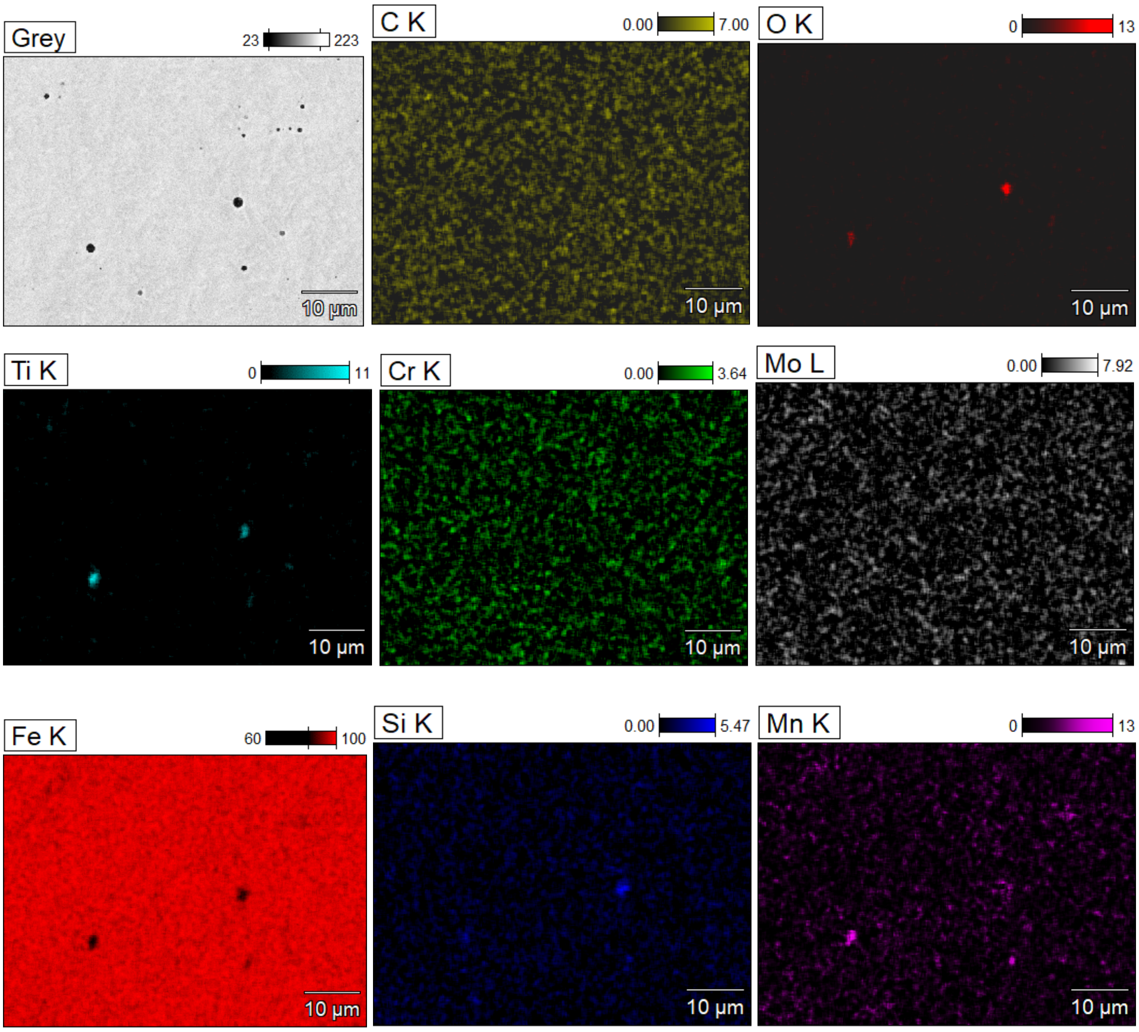

Fig. 5. Element distribution in the joint microstructure of the DOCOL 1100M steel, SEM

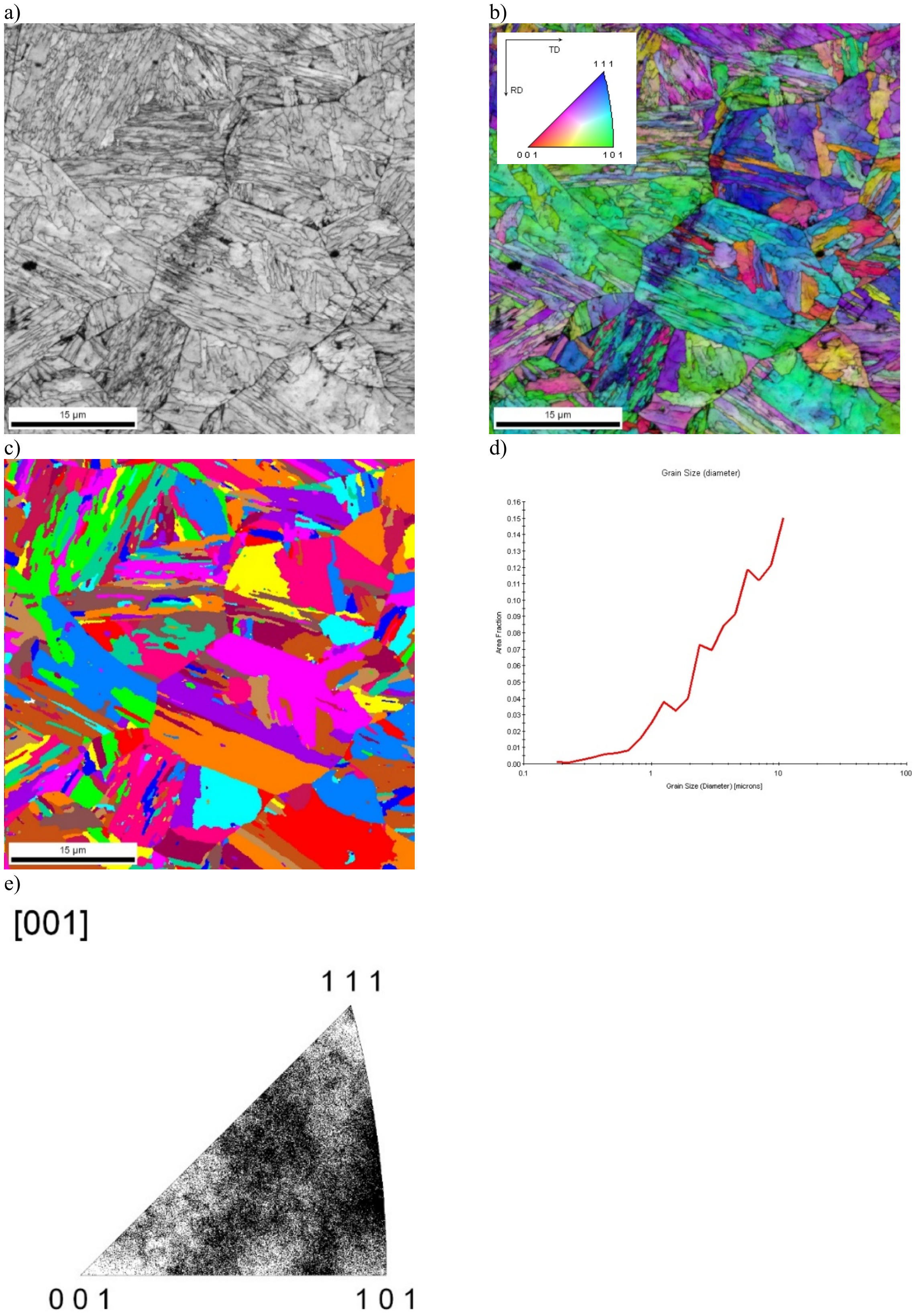

Fig. 6. Microstructure of a base material DOCOL 1100M: a) image quality, b) inverse pole figure map (IPF), c) image of grains, and d) distribution of grain size, EBSD

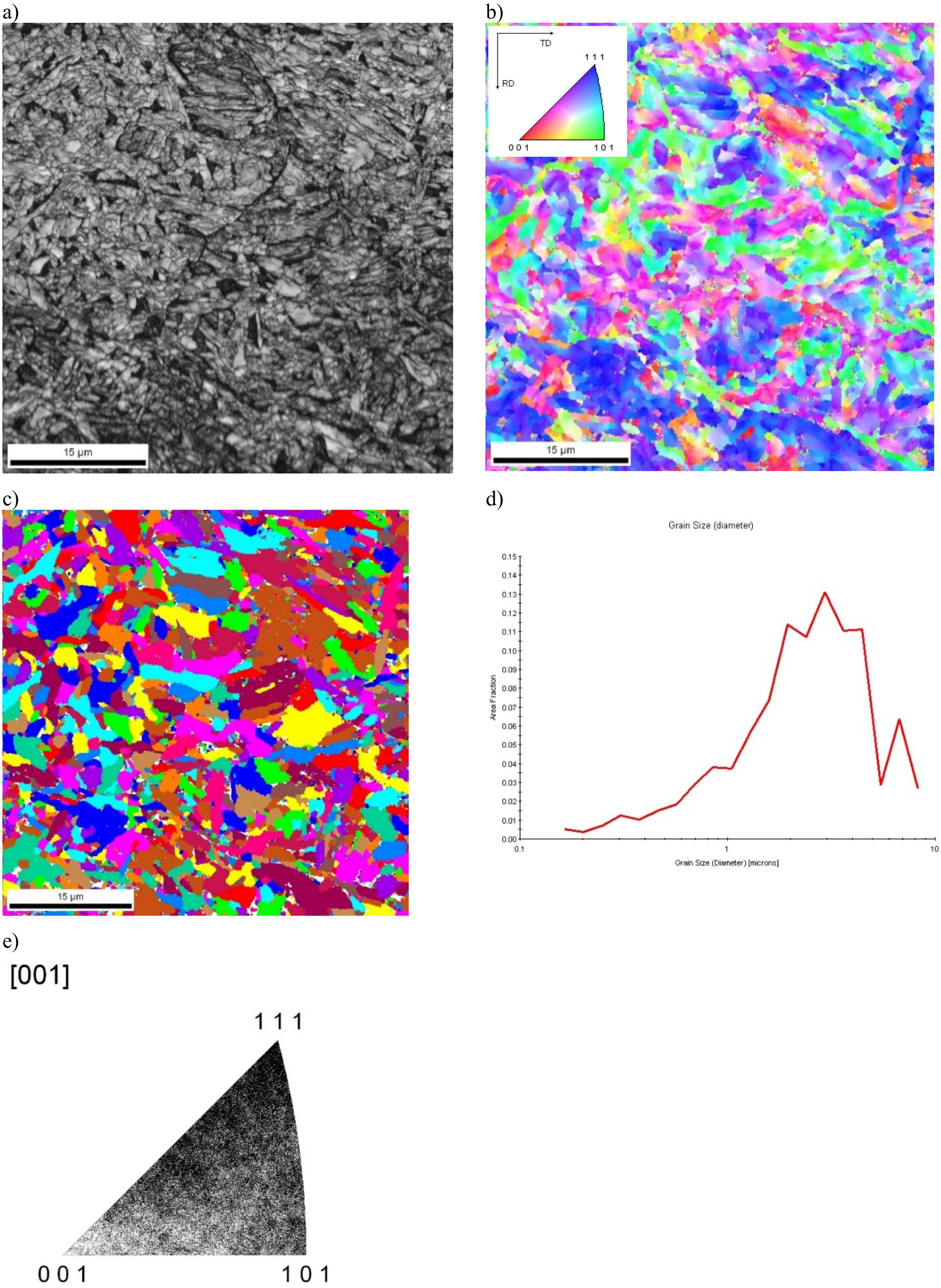

Fig. 7. Microstructure of welded material DOCOL 1100M: a) image quality, b) inverse pole figure map (IPF), c) image of grains, and d) distribution of grain size, EBSD

High-strength steels play a very important role in creating and forming motor vehicles, especially electric ones. HSS steels and AHSS steels have been specially designed to meet the needs of the automotive industry. In classic vehicles, and especially in electric vehicles, the supporting structure must be light and high-strength, have good plastic properties, and be highly weldable. According to the literature, this type of welds are used in various applications in the automotive sector, but it is not easy to meet these difficult requirements. The authors decided to improve the mechanical properties by introducing oxide inclusions of small dimensions and favorable shape into the weld, which can strengthen the weld like a quasi-composite material. The results show that we improved only the tensile strength and obtained the proper joints without welding incompatibilities. The fact that the base material contains a large amount of titanium (10 times more than in classic unalloyed steels) and that the most favorable conditions for the nucleation of titanium inclusions containing oxygen, carbon, and nitrogen were created. The oxygen concentration in the weld, which is a result of the choice of the proper shielding gas in the MAG process, is of great importance. The oxygen concentration determined the formation of inclusions and the mechanical properties of joints.

4. CONCLUSIONS

Light and high-strength structures are extremely important in the design of electric vehicles. Their travel range depends primarily on weather conditions and the weight of the vehicle. HSS steels and AHSS steels have a martensitic structure, which gives them very high strength but makes it difficult to create a joint with good plastic properties. High-strength steels (including the DOCOL 1100M steel, described as a representative of this material group) are obtained under different metallurgical conditions (cold rolling) than the weld, which is a cast material. Therefore, the structure of the joint changes, and it is almost twice as strong as the base material. Specialized and very accurate examinations of non-metallic inclusions under a scanning microscope played a special role in this research. The study confirmed the relationship between oxygen content in the shielding gas and the obtained material microstructure. The joint microstructure with non-metallic inclusion determined the properties of the tested connections. The article examined four joints made of high-strength DOCOL 1100M steel made in a shield of four different shielding gases, which were mixtures of argon with various CO_2 contents. Non-destructive tests showed that too low a CO_2 content in the mixture leads to minor defects and welding inconsistencies in the form of small cracks. Hardness tests showed that the preferred shielding mixture is the Ar - 13% CO_2. Similarly, tensile strength tests showed that the best mechanical properties are provided by the Ar - 13% CO_2 mixture; also, argon shielding mixtures containing 8% CO_2 and 18% CO_2 allow correct joints to be obtained but with worse mechanical properties. The final part of the procedure was the observation of the Y13 joint under a light and scanning microscope (made in the shielding gas Ar - 13% CO_2 mixture). The Y13 joint was dominated by a martensitic structure with a small presence of fine-grained ferrite and non-metallic inclusions. The form, distribution, and chemical composition of the inclusions influenced the mechanical properties of the joint.

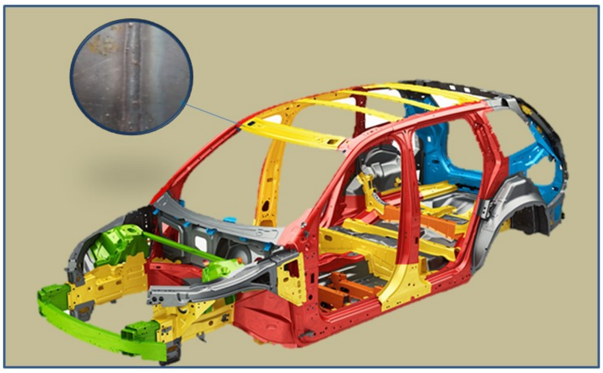

Fig. 8. Macrostructure of the welded material of DOCOL 1100M and the potential application in vehicle body

Therefore, favorable metallurgical conditions were established to obtain a joint with improved mechanical properties, which makes the structures created in the described model suitable for use in the automotive industry.

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