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Application of Advanced Welding Methods in the Production of Rims for Special Purposes

Abstract: Special rims belong to structural elements determining the safety and service life of vehicles. Because of the fact that welded joints are integral parts of rims, the quality of the former affects the service life of the entire element. In turn, welding, as a special process, is decisive for the quality of joints. Advanced high-performance welding methods (such as laser or hybrid welding) can increase the efficiency and improve the quality of welded joints. The article presents results of technological tests involving the laser and hybrid welding of steel grades DD11 and DD14 (used in the production of rims). The reference technology was MAG welding. The welded joints were subjected to non-destructive and destructive tests. The test results revealed that both laser and hybrid welding enabled the obtainment of joints meeting strength-related requirements. However, the laser welding process led to the lowering of the weld face and the formation of significant weld porosity.

Keywords: Rims, Steel DD11, DD14, MAG welding, Laser welding, Hybrid welding

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Introduction

Economic and climatic changes worldwide have inspired search for special machinery-related solutions characterised by low energy consumption combined with high efficiency. Manufacturers of machinery, equipment and components are expected to produce the lowest possible carbon footprint. Increasingly often, entrepreneurs, in addition to their own initiatives aimed to reduce energy consumption and increase efficiency, expect their suppliers to do the same [1, 2]. The Trelleborg company deals with the design and production of highly specialised solutions concerning the processing of rubber and the manufacturing of components making up specialist engineering solutions (e.g. special-purpose rims manufactured by the Trelleborg Wheel Systems division). Rims for special purposes are used in environments characterised by very demanding operating conditions, necessitating high product reliability [3].

The primary industrial sectors where special-purpose rims are used include the following areas:

- agriculture – tyres and rims for harvesters, tractors and other vehicles used in agriculture,
- forestry – tyres and rims used in forestry,
- mining – tyres and rims used in mines,
- metallurgy – tyres and rims resistant to high temperature,
- transport of materials and structures – tyres and rims for forklifts and transport equipment.

The design of special-purpose rims continues to pose a challenge both for industry as such and for design engineers. Such rims are expected to satisfy rigorous requirements in terms of mechanical properties (of the base material of the rim, in accordance with the PN-EN10111:2009 standard [4]) and the maximum load affecting the rim (expressed in [kg] in accordance with ETRTO – The European Tyre and Rim Technical Organisation).

One of the primary criteria decisive for the design of the rim is its weldability. The development

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of joining processes is aimed at increasing joining efficiency, which, in turn, entails increased process efficiency. Solutions should make it possible to join materials using high-performance methods, significantly improving entrepreneur's competitive edge. Joining processes include fusion welding, pressure welding, brazing, soldering and adhesive bonding [5–7]. Welding technologies continue to be the most important processes enabling the joining of steel structures. The global welding market share is presented in Figure 1. Technologically advanced joining methods such as double-pulse MAG (*Metal Active Gas*) welding, laser welding, hybrid welding or high-performance resistance welding not only enable the obtainment of high product repeatability but also make it possible to increase production efficiency and improve product quality. The market share of above-named technologies continues to grow along with their automation and mechanisation [8].

Reference publications lack comprehensive information concerning the effect of arc linear energy and laser beam energy on the structure and properties of joints made using high-performance technologies (double-pulse MAG welding, laser welding or hybrid welding) and the assessment of the effect of such technologies on the quality and efficiency of the rim manufacturing process.

Each modification of the manufacturing process improving product quality and working conditions, reducing energy consumption and increasing efficiency translates into lower manufacturing costs and higher sales, which, in turn, improves the manufacturer's brand image, increases investors' confidence and readiness for new investments.

The article discusses an attempt to assess the applicability of technologically advanced high-performance and energy-saving joining methods (laser or hybrid welding) in the production of special-purpose rims, aimed to ensure the obtainment of joints characterised by proper structure as well as mechanical and operational properties satisfying customer's requirements in accordance with guidelines formulated by ETRTO (The European Tyre and Rim Technical Organisation).

Test materials

The tests involved the use of low-carbon hot-rolled steels for cold plastic working, i.e. grades DD11 and DD14, in accordance with the PN-EN10111:2009 standard [4]. The above-named steels are used in the production of special-purpose rims. The chemical composition of the test steels (according to the producer's conformity certificate and requirements specified in the PN-EN10111:2009 standard) and their mechanical properties are presented in Table 1.

The comparison concerning the results of chemical composition analysis and mechanical properties of test specimens revealed that the test steels satisfied related requirements for steel grades DD11 and DD14 (in accordance with the PN-EN 10111 standard).

The MAG and hybrid welding processes involved the use of filler metal wire G4Si1 having a diameter of 1.2 mm (ESAB) (in accordance with EN ISO 14341-A: G4Si1) and shielding gas MISON 18 composed of Ar (81.97%), CO_2 (18%) and NO (0.03%) (Table 2).

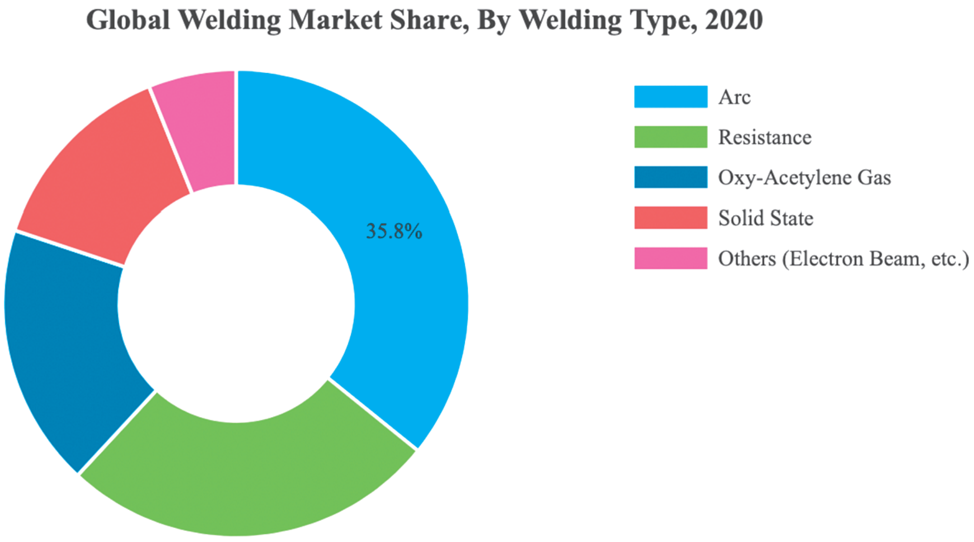


Fig. 1. Global welding market share [8]

Table 1. Chemical composition and mechanical properties of test materials

Chemical composition [% mass]							
Material	**Standard** **Conformity certificate**	**C**	**Si**	**Mn**	**P**	**S**	**Al**
DD11	PN-EN 10111	≤ 0.120	-	≤ 0.600	≤ 0.045	≤ 0.045	-
	0001105031146	0.080	0.018	0.500	0.014	0.011	0.043
DD14	PN-EN 10111	≤ 0.080	-	≤ 0.350	≤ 0.025	≤ 0.025	-
	0001104963495	0.033	0.006	0.190	0.012	0.006	0.032

Mechanical properties				
Material	**Standard** **Conformity certificate**	R_e **[MPa]**	R_m **[MPa]**	A **[%]**
DD11	PN-EN 10111	170–340	≤ 440	≥ 28
	0001105031146	286	399	35.9
DD14	PN-EN 10111	170–290	≤ 380	≥ 36
	0001104963495	236	315	46.5

Table 2. Chemical composition of the filler metal wire and of the shielding gas mixture

	Chemical composition [% mass]			
MAG welding	Filler metal wire	**C**	**Mn**	**Si**
	G4Si1	0.074	1.68	0.95
	Shielding gas	**Ar [%]**	**CO_2 [%]**	**NO [%]**
	Mison 18	81.97	18	0.03

Technological welding tests

The initial test results were used to adjust welding process parameters. The adopted quality-related criterion was quality level B in accordance with the following standards:

- PN-EN ISO 5817:2014-05 [9] – in relation to arc welding,
- PN-EN ISO13919-1:2020 [10] – in relation to laser welding,
- PN-EN ISO 12932 [11] – in relation to hybrid welding.

The technological welding tests involving low-carbon hot-rolled steel grades for cold plastic working, i.e. DD11 and DD14, were performed using the following processes:

- MAG welding,
- laser welding,
- hybrid (laser + MAG) welding.

The MAG welding process was performed in the TWS production plant in Liepaja (Latvia), whereas laser and hybrid welding tests were performed at the Welding Centre of the Upper Silesian Institute of Technology of the Łukasiewicz Research Network in Gliwice. Welding process parameters were adjusted based on authors' own test results [3] and data contained in related reference publications [12].

The MAG welding process was performed using a stand applied for the welding of special-purpose rims of diameters exceeding 20" (Fig. 2) and equipped as follows:

- welding station (Kemec Weld),
- Feed 3004 filler metal wire feeder (ESAB).

The test plates were subjected to square butt weld preparation with the gap between the them amounting to 2 mm. The Autrod 12.64 filler metal wire (grade G4Si1) (ESAB), having a diameter of 1.2 mm and composed of C (0.074%), Mn (1.68%) and Si (0.95%), was fed at a rate of 6.1 m/min. The welding process was shielded by gas mixture M21 (designated as Mison 18). The shielding gas was composed of Ar (81.97%), CO_2 (18%) and NO (0.03%). The shielding gas flow rate amounted to 15 l/min. The average welding current amounted to 327 A, whereas arc voltage amounted to 32.2 V.

The laser welding tests were performed using a welding station (Fig. 3) equipped with a tilting turntable enabling the positioning of elements subjected to welding, a KR30HA 6-axis industrial robot characterised by a positioning accuracy of min. 0.15 mm (KUKA) and a TruDisk 12002 disk laser (Trumpf) equipped with a system of optical fibres having diameters of 200 µm, 300 µm, 400 µm and 600 µm, making it possible

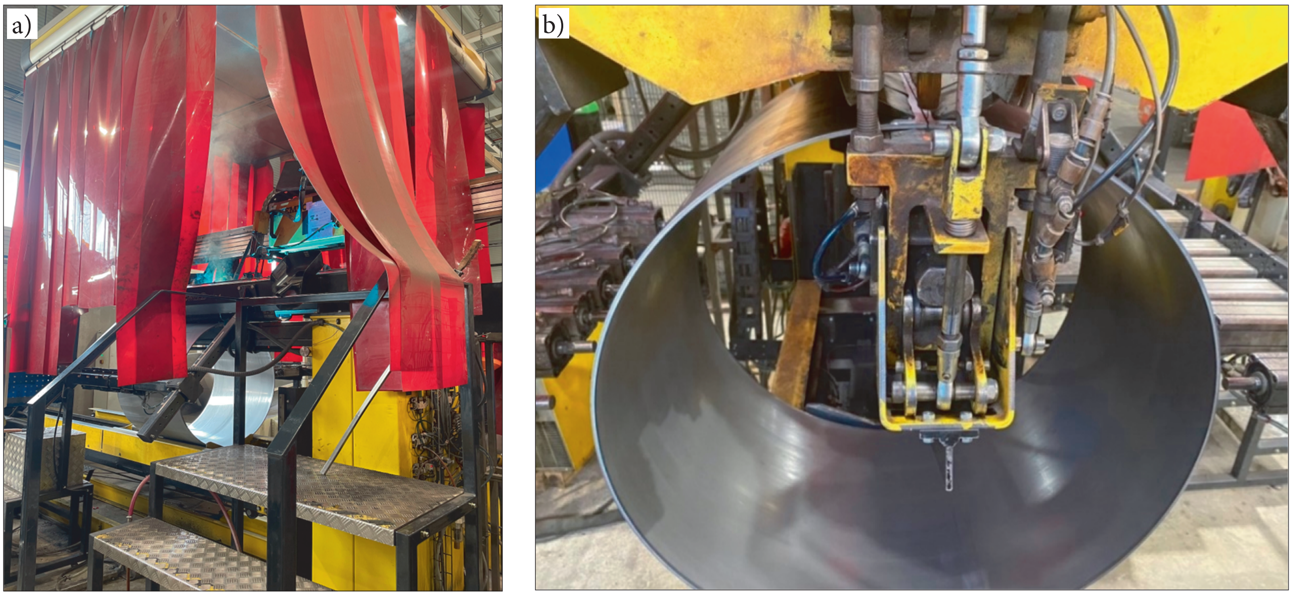


Fig. 2. Station for the welding of special-purpose rims (having a diameter of more than 20”): a) main view, b) gripping clamps with a cylinder to be welded

to connect the resonator with the welding head. The test plates were subjected to square butt weld preparation without a gap. The resonator was connected with the head by means of an optical fibre having a diameter of 300 μm. The welding process was shielded by argon. The shielding gas flow rate amounted to 16 l/min. The laser power amounted to 4.5 kW, whereas the welding rate amounted to 0.8 m/min.

The hybrid welding tests (laser + MAG) were performed using a welding station (Fig. 3) equipped with a KUKA KR30HA industrial robot and a hybrid welding head based on a classical D70 welding head (Trumpf). The arc welding power source (EWM) used in the process featured programmes enabling operation in the synergic mode (Fig. 4b,c). The welding power source control system was integrated (by a computer programme) with the robot controller. The test plates were subjected to square butt weld preparation without a gap. The welding process involved the use of filler metal wire G4Si1 (Autrod 12.51) having a diameter of 1.2 mm (ESAB). The filler metal wire feed rate amounted to 8.5 m/min. The welding process was shielded by mixture M21 (designated as Ferroline C18); the shielding gas flow rate amounted to 16 l/min. The process was performed using a welding current of 270 A, an arc voltage of 26 V, a welding rate of 1.2 m/min and a laser power of 3.5 kW. The distance between the laser beam focus area and the centre of the electric arc wire amounted to 2 mm.

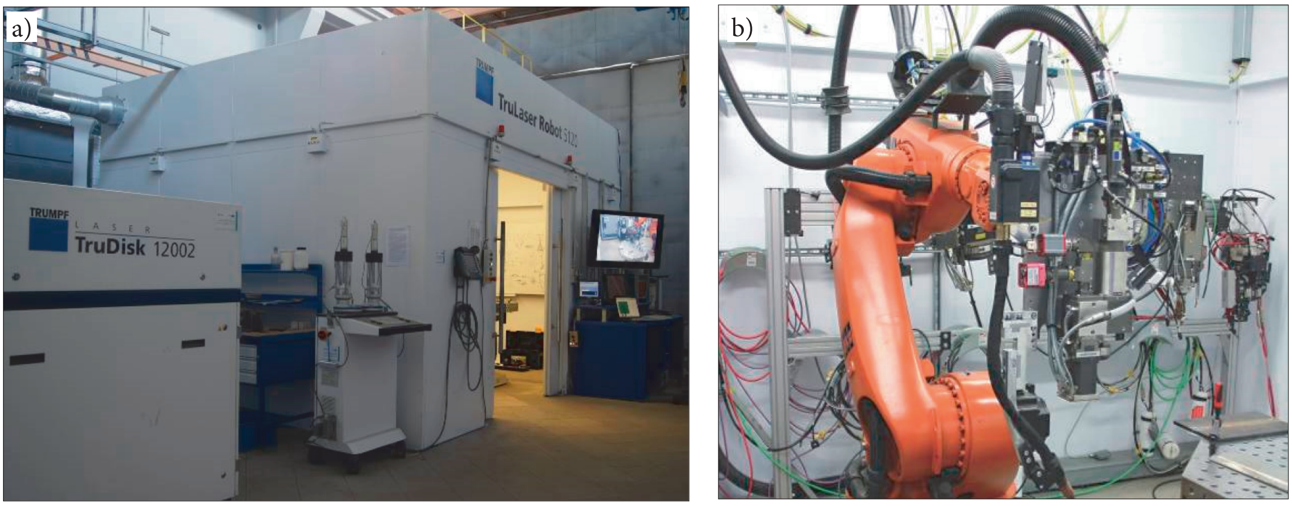
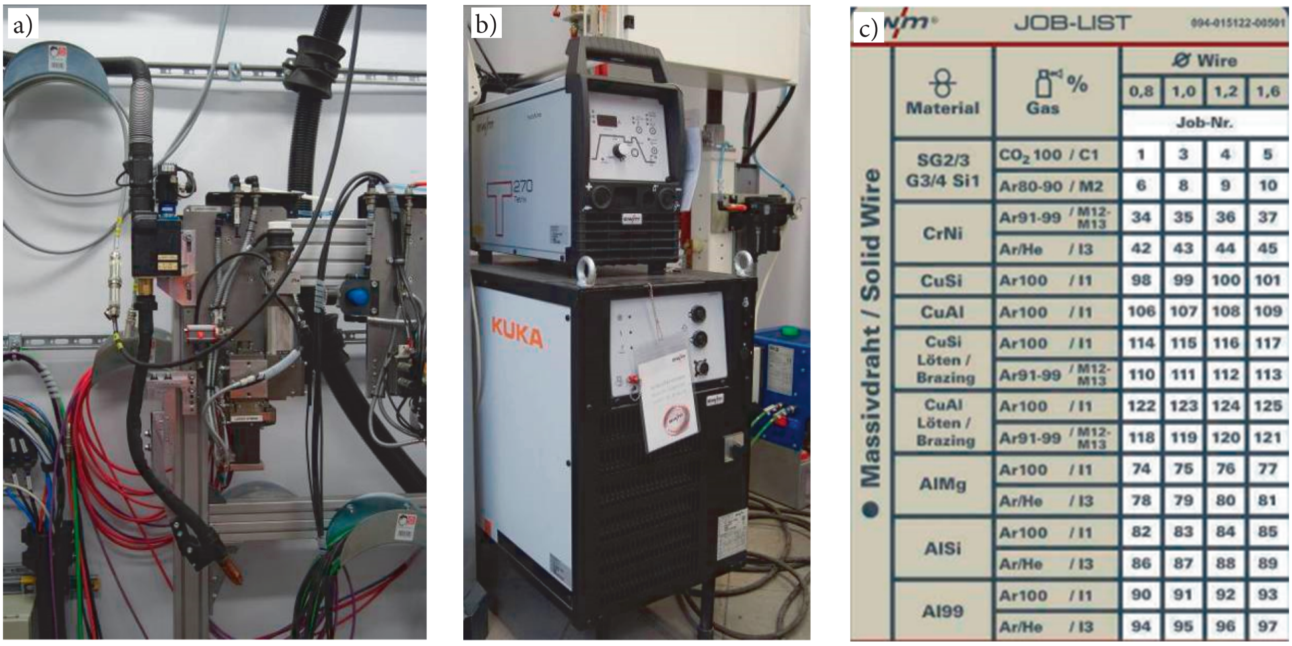


Fig. 3. Robotic laser welding station featuring the TruDisk 12002 disk laser: a) main view, b) laser and hybrid welding head (D70), integrated with the industrial robot



JOB-LIST 094-015122-00501

Massivdraht / Solid Wire

Material	% Gas	Ø Wire			
		0,8	1,0	1,2	1,6
		Job-Nr.			
SG2/3 G3/4 Si1	CO_2 100 / C1	1	3	4	5
	Ar80-90 / M2	6	8	9	10
CrNi	Ar91-99 / M12-M13	34	35	36	37
	Ar/He / I3	42	43	44	45
CuSi	Ar100 / I1	98	99	100	101
CuAl	Ar100 / I1	106	107	108	109
CuSi Löten / Brazing	Ar100 / I1	114	115	116	117
	Ar91-99 / M12-M13	110	111	112	113
CuAl Löten / Brazing	Ar100 / I1	122	123	124	125
	Ar91-99 / M12-M13	118	119	120	121
AlMg	Ar100 / I1	74	75	76	77
	Ar/He / I3	78	79	80	81
AlSi	Ar100 / I1	82	83	84	85
	Ar/He / I3	86	87	88	89
Al99	Ar100 / I1	90	91	92	93
	Ar/He / I3	94	95	96	97

Fig. 4. Laser head for laser and hybrid welding (laser + MIG/MAG) (a); MIG/MAG welding power source (EWM) (b); exemplary list of welding machine programmes in the synergic mode (c)

Testing methodology and test results

The quality of welded joints made of steels DD11 and DD14 was assessed on the basis of non-destructive and destructive test results. The non-destructive tests included visual tests (VT) and radiographic tests (RT). The destructive tests included metallographic tests, (static) tensile tests, bend tests, impact tests and hardness measurements.

The visual tests (VT) of the joints were performed in accordance with the PN-EN ISO 17637 standard [13], whereas the radiographic tests (RT) were performed in accordance with the PN-EN ISO 17636-1: 2013 standard [14]. The assessment criterion adopted during the tests was quality level B (in accordance with related standards [9, 10, and 11]). The results of the visual inspection of the weld face and of the weld root as well as the results of the radiographic tests of the MAG and hybrid-welded joints revealed that the latter satisfied quality level B-related requirements. In turn, the laser-welded joints were characterised by the lowered weld face and weld porosity.

The specimens used in the metallographic tests were sampled in accordance with the PN-EN ISO

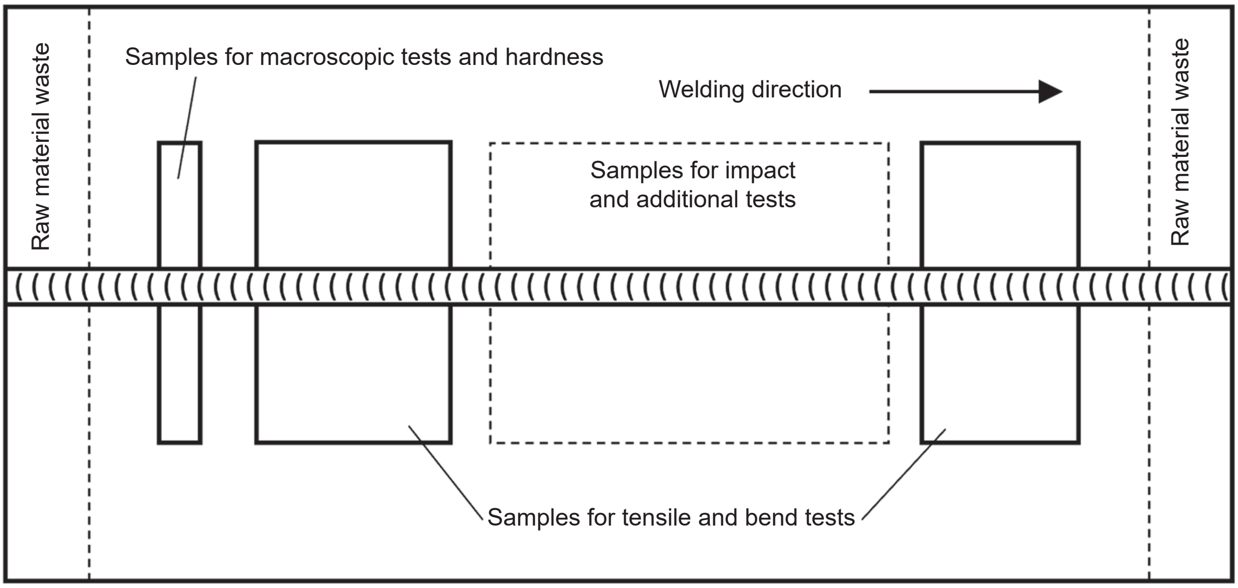


Fig. 5. Area where the specimens were sampled for metallographic and mechanical tests (in accordance with the PN-EN ISO 15614-1:2017 standard [16])

17639-2022-07 standard [15], perpendicularly in relation to the welding direction. The sampled specimens included the weld, the heat affected zone (HAZ) and the base material (Fig. 5). The test specimens were subjected to grinding performed using abrasive paper, the granularity of which was restricted within the range of 80 to 1000. Afterwards, the joints were subjected to etching in 5% Nital (5% solution of HNO_3 in ethanol).

The macroscopic tests were performed in accordance with the PN-EN ISO 17639-07:2022 standard [15]. Images were recorded using a C-70 camera (Olympus), whereas the macrostructure was assessed by the unaided eye, using an SZX9 stereoscopic microscope (Olympus) and a magnification of up to 50×. The test results are presented in Table 3.

The microscopic tests were performed using a GX71metallographic light microscope (Olympus) and magnification restricted within the range of 50x to 500x. The microstructural observations aimed to describe the structure of the welded joints and reveal welding imperfections (if any). The microscopic tests were performed in accordance with the PN-EN ISO 17639-2022-07 standard [15]. The observations were focused on the heat affected zone (HAZ) and the weld (in accordance with the schematic diagram presented in Figure 6). The test results are presented in Table 3.

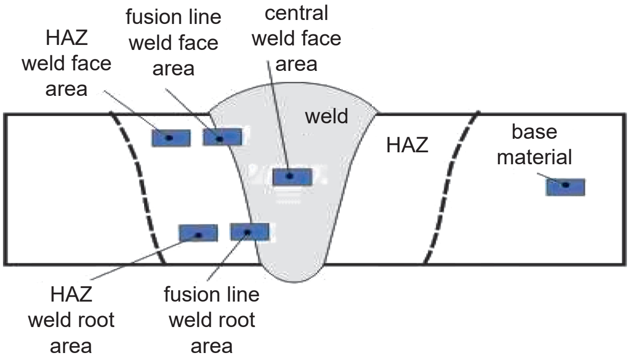
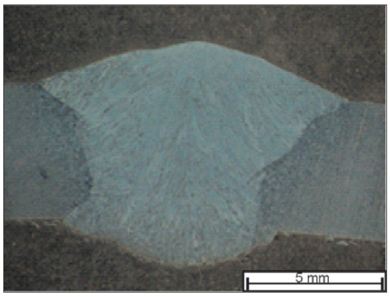
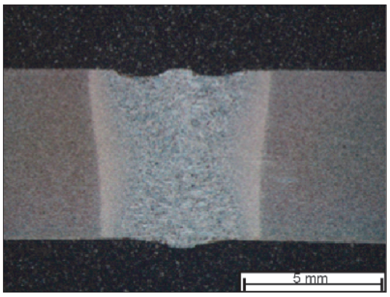
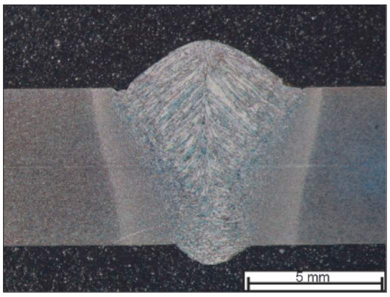
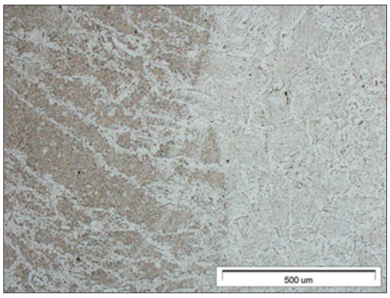
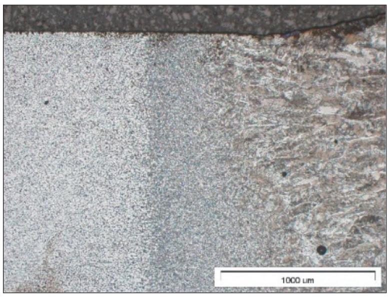
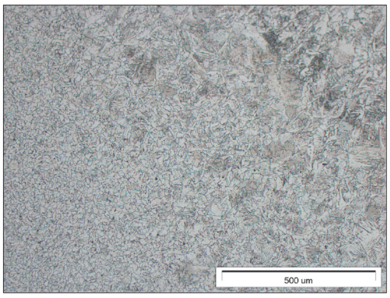
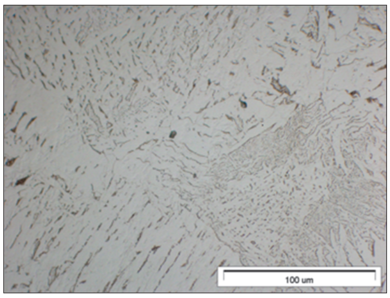
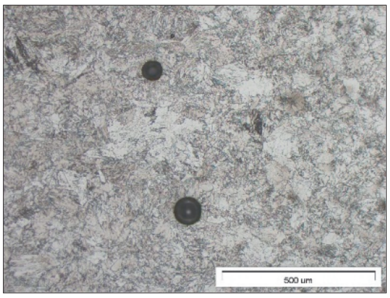
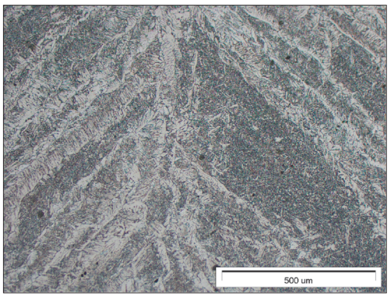


Fig. 6. Areas of the welded joint subjected to microscopic observations [17]

The (static) tensile tests involving the MAG, hybrid and laser-welded butt joints made of steel grades DD11 and DD14 (i.e. 2 specimens sampled from the test joint) were performed in accordance with the PEN ISO 4136:2013-05 standard.

Table 3. Macro and microstructure of the test joints

	MAG-welded joint	**Laser-welded joint**	**Hybrid-welded joint**
Macrostructure			
HAZ microstructure			
Weld microstructure			

The subject of the tests was only tensile strength R_m [12]. The criterion adopted in the test amounted to 170 MPa, i.e. the minimum strength in relation to steels DD11 and DD14. The test was performed using a QC501A2 testing machine. The results of the tensile test are presented in Figure 7.

The analysis of the test results revealed explicitly that all of the test joints, regardless of applied welding methods, satisfied the requirements concerning the base material, i.e. a tensile strength of more than 170 MPa.

The bend tests of the butt joints aimed to verify the plasticity of the joints, identify the flexural (i.e. bend) strength of the test joints and detect the presence of welding imperfections (if any). During the tests, the external surface of the joint was subjected to tension, whereas the internal surface (adjacent to the bending pin) was subjected to compression. The assessment criterion adopted in the tests was the value of the bend angle. When the bend angle amounted to 180° and the surface of the specimen subjected to bending did not reveal the presence of any welding imperfections, a given bend test result was recognised as positive. The performance of the tests necessitated the sampling of two sets of specimens (two specimens per one set). The first two specimens were subjected to the face bend test of butt weld (FBB), whereas the second set of the specimens was subjected to the root bend test of butt weld (RBB). The performance of the above-named tests required the removal of excess weld metal both on the weld face and on the weld root side.

The bend tests, involving the use of a QC-501A2 testing machine, were performed in accordance with the PN-EN ISO 5173:2010/A1:2012E standard [18]. The surfaces of the joints subjected to bending did not contain any cracks, which led to the conclusion that all of the joints were characterised by appropriate plastic formability (the bend angle amounted to 180°).

The hardness measurements of the welded joints involved metallographic specimens (previously subjected to etching) and were performed in accordance with the requirements of the PN-EN ISO 9015-2:2016-04 standard [19]. The Vickers hardness (HV) tests were performed along a measurement line located 2 mm away from the specimen edge. The tests involved the weld, the HAZ and the base material (three indentations made in each area). The schematic diagram showing the arrangement of hardness measurement points is presented in Figure 8. The Vickers hardness tests

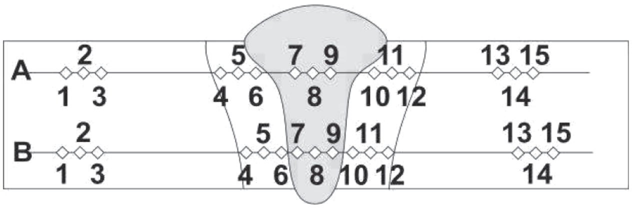


Fig. 8. Arrangement of hardness measurement points in the test joints [19]

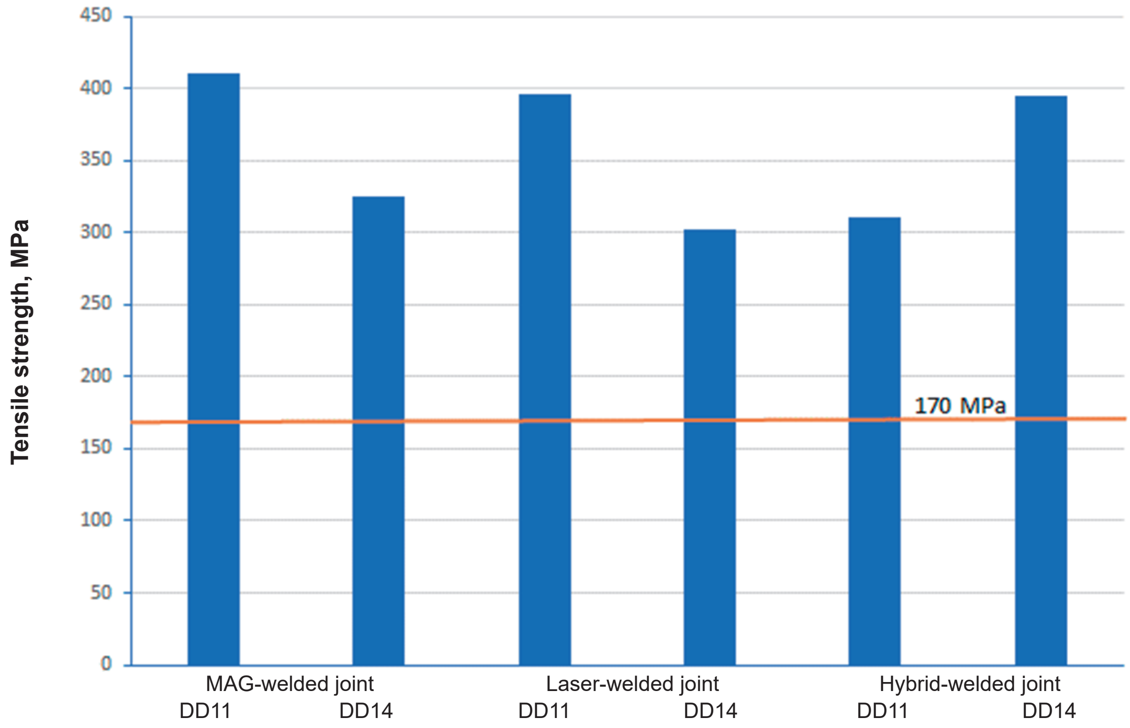


Fig. 7. Results of the static tensile tests of the MAG, laser and hybrid-welded joints made of steels DD11 and DD14

were performed using a Brickers 220 hardness tester. The test results are presented in Figure 9.

The analysis of hardness distribution revealed that the highest hardness values (yet below 200 HV) were identified in the weld made using the MAG process (Fig. 9). Hardening between the zones was not identified and the difference in hardness amounted to less than 100 HV.

The impact tests were performed in accordance with the PN-EN ISO 148-1:2017-02 standard [20], using specimens of reduced cross-section (2.5 mm × 8.0 mm × 55.0 mm) and provided with a V-notch having a depth of 2 mm. The notch was made in the base material, the heat affected zone and in the weld. The impact tests were performed at a temperature of 20°C and that of -40°C. Impact energy was determined using an RKP 450 impact testing machine (ZWICK). The weld-related test results, presented as average values based on three tests concerning each zone of the joint, are presented in Figure 10.

The hardness test results revealed that, in all of the cases, the values of toughness exceeded 150 J/cm^2, which indicated high plastic properties of the joints.

Summary

Increasingly rigorous requirements concerning functional properties of special-purpose rims and related manufacturing (particularly joining) technologies necessitate the search for advanced and innovative welding methods.

The reduction of welding operation time through the implementation and automation of

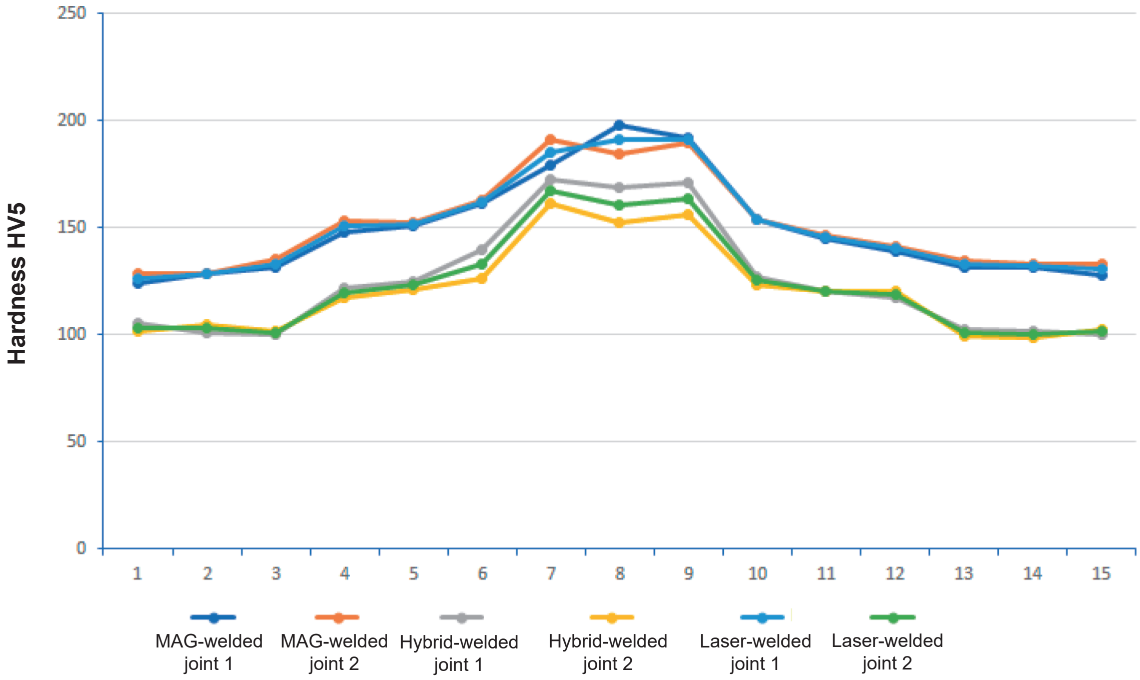


Fig. 9. Hardness distribution in the test joints made of steels DD11 and DD14

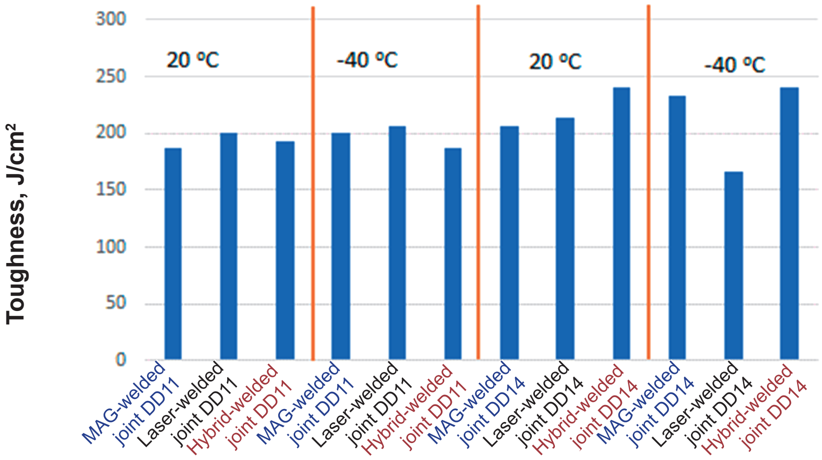


Fig. 10. Weld toughness tested at a temperature of 20°C and -40°C MAG-welded, laser-welded and hybrid-welded joints

high-performance welding methods reduced the cost of transformation (i.e. rim fabrication). Costs of transformation and materials constitute the entire manufacturing cost (including overhead and variable costs). Higher quality translates not only into lower costs but also more favourable functional properties, safe operation and a more attractive brand image.

Presently, one of the most common arc welding methods applied in the production of steel rims is the MAG welding technique. Currently used manufacturing processes enable the obtainment of rims having diameters in excess of 20". However, because of the lack of repeatability combined with a significant number of products containing welding imperfections, the process is costly and time-consuming. Rims having diameters below 20" are welded using the MAG method or flash welding processes. Smaller sizes combined with simpler joining technologies translate into significantly lower number of cracks in joints during the initial shaping of the cylinder.

The repeatability and quality of special-purpose welds, constituting key aspects in terms of technical and customer's requirements, also affect the operational safety of products. The necessity of satisfying related expectations necessitates changes to design, production efficiency and quality (of special-purpose rims). In order to meet the above-named challenge it is necessary to get to know factors affecting the quality of welded joints, which, in turn, should enable the selection and application of new, e.g. laser or hybrid, welding methods.

The analysis of the results obtained in the technological welding tests involving the use of the MAG, laser and hybrid processes during the fabrication of joints made of steels grades DD11 and DD14 revealed that the above-named steels could be joined using technologically-advanced and high-performance laser beam-based welding methods. All of the technologies discussed in the article enabled the obtainment of joints satisfying structural and mechanical requirements concerning special-purpose rims (including strength, bend resistance, hardness and toughness). However, the structural analysis of the laser-welded joints revealed the lowering of the weld face and significant weld porosity. Although the above-named imperfections did not significantly affect the mechanical properties of the joints, yet they could become centres of (e.g. fatigue) cracking, which is unallowed as regards the operation of special-purpose rims. The foregoing led to the conclusion that the most favourable technological solution enabling the obtainment of higher process efficiency was hybrid welding.

All leading producers are interested in high-performance welding technologies enabling the production of steel rims. Although advancements in the implementation of the technologies in the lot production are difficult to assess, each implementation improving efficiency translates into increased sales.

Acknowledgements

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