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Environmental Assessment of the Arc and the Laser Welding of Austenitic Steels

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Abstract: The article presents results of research work enabling the environmental assessment of the arc and the laser welding of corrosion resistant austenitic steel X5CrNi18-10 (1.4301). The steel, characterised by high corrosion resistance, favourable mechanical properties and good weldability enjoys growing popularity in many industrial sectors. The application of welding technologies in industry necessitates the performance of tests aimed to identify conditions guaranteeing safe work and protecting workers' health. Welding and allied technologies belong to the group of processes adversely affecting a work environment. Various welding processes trigger the emission of welding fumes and other pollutants containing numerous substances posing health hazards. The performance of environmental assessment makes it possible to identify and analyse how a given product or a technological process affect the environment. The assessment also enables the comparison of manufacturing processes and technologies in order to indicate those characterised by the lowest environmental impact. The primary ingredients of corrosion resistant steels are chromium and/or nickel. The compounds of the aforesaid chemical elements, present in welding fumes, are rated among substances having a potential or proven carcinogenic effect.

Keywords: austenitic steels, welding, emission of total dust, emission of gases, environmental assessment of the process

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Introduction

Corrosion resistant steels include stainless as well as heat-resistant and high-temperature creep resisting steels [1]. Because of their microstructure, the above-named steels are divided into ferritic, martensitic, austenitic, ferritic-austenitic (duplex) and precipitation-hardened steels [1]. Corrosion resistant steels contain a minimum of 10.5% of chromium as well as a maximum of 1.2% of carbon and alloying elements such as nickel, molybdenum, niobium, titanium and nitrogen [1]. The presence of the aforesaid elements provides protection against weather factors and aggressive chemical compounds. Presently, austenitic steels constitute the largest group of stainless steels [2]. The austenitic structure of steel is related to an appropriately high content of nickel. In turn, the content of chromium provides the above-named steels with high resistance to corrosion

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when exposed to air atmosphere, fresh water, organic acids, nitric acid solutions and basic (alkaline) solutions [3, 4]. The corrosion resistance of various grades of austenitic steels is not identical and depends on their chromium and nickel contents. Other alloying elements, including Mo, Ti, Nb, Si and Cu can also effectively improve the corrosion resistance of austenitic steels under specific work conditions. Because of the above-presented advantages, austenitic steels are used, among other things, in chemical, petrochemical, food, automotive, power and building industries [4].

Austenitic steels are characterised by favourable weldability [2,3,5]. Classical welding methods include manual metal arc welding (MMAW), gas metal arc welding (MIG/MAG), flux-cored arc welding, TIG welding and submerged arc welding, whereas advanced welding methods include laser beam welding, hybrid (laser + arc) welding, plasma arc welding and electron beam welding.

Because of the fact that austenitic stainless steels are increasingly commonly used in welded structures as the base material, it is necessary to perform competent and effective assessment how the joining of the aforesaid steels affects a work environment and external environments. It is also necessary to identify and analyse all the environmental aspects of technological processes including types and amounts of pollutants emitted during joining processes. It is necessary to apply the cleaner production (CP) policy, where the negative environmental impact is limited to a minimum. The objectives of cleaner production are satisfied, among other things, by modifying related technologies and their operating conditions [6]. Cleaner production is a production management system, where measures taken at all manufacturing stages make it possible to prevent or limit a negative environmental impact. As a result, it is possible to reach a higher level of environmentally friendly production defined as the prevention of environmental pollution and climate changes as well as the protection of workers' health. All of the above-named factors constitute major components of sustainable development [7].

Product-related life cycle assessment (*LCA*) constitutes one of the environmental assessment methods used, among other things, to identify and evaluate important environmental aspects as well as to indicate possible improvements of such aspects at various stages of product life and manufacturing processes. In addition, life cycle assessment helps prevent the formation of pollutants or develop and improve a given product or an entire process [8]. Life cycle assessment is not only used to design new products and technologies but also to improve already existing ones, thus reducing their negative environmental impact. An important LCA application includes the possibility of identifying and assessing the environmental impact of a given product during its entire life or that of a technological process at its individual stages [8]. The performance of the complex analysis of environmental impacts and the indication of the most harmful hazards makes it possible to modify processes and reduce their environmental impact. In addition, life cycle assessment enables the comparison of manufacturing processes and technologies and the identification of those characterised by the lowest environmental impact.

Welding and allied processes belong to production processes adversely affecting work and external environments. The emission of welding fumes is responsible for many negative health-related consequences and increases the concentration of airborne particulate matter and gases. Welding fumes (dual-phase condensing aerosols) are the mixture of solid particles and gases [9]. Solid particles are formed through the condensation and oxidation of metal vapours. In accordance with requirements of the International Agency for Research on Cancer (IARC), welding fumes are rated among factors of a proven carcinogenic

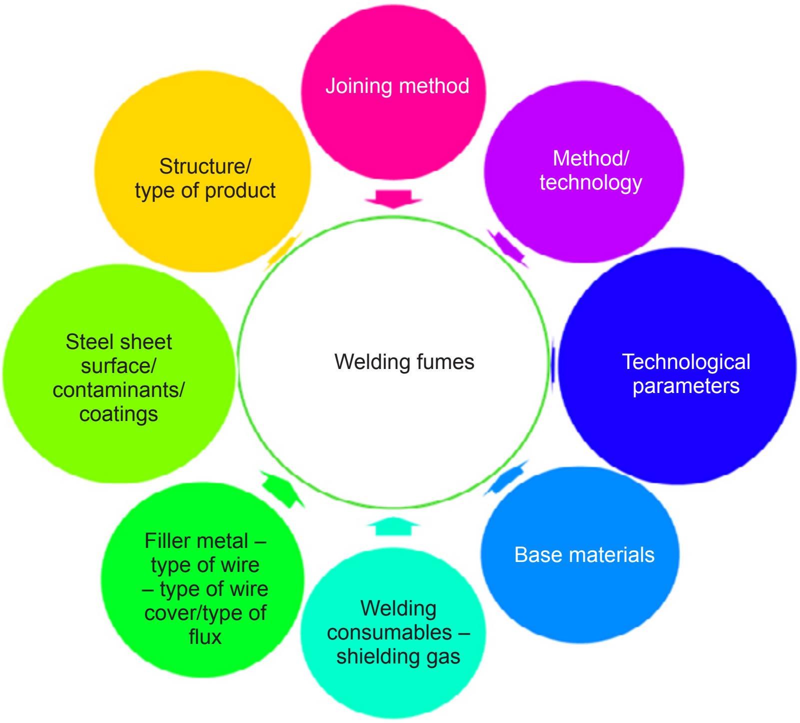


Fig. 1. Factors affecting the volume of welding fumes emitted during joining processes [11]

effect [10]. Gaseous pollutants are primarily nitrogen oxides, carbon monoxide, ozone and various types of hydrocarbons [9]. The volume of generated pollution depends mainly on joining methods, base materials and filler metals as well as on technological process parameters (Fig. 1) [11].

Particularly high health hazards for welders are connected with the welding of austenitic steels as their primary alloying elements are chromium and nickel. The compounds of these elements, present in welding fumes, are rated among substances of a proven or probable carcinogenic effect [12]. In the future, an environmental assessment concerning the welding of austenitic steels will be an important tool enabling the modification of technological conditions accompanying welding processes with respect to work environment protection. The methodology of the environmental assessment of welding processes based on the emission of welding fumes constitutes the first stage of assessment in the cleaner production policy. The environmental assessment discussed in the article was performed using the most popular austenitic steel grade, i.e. steel 1.4301 (X5CrNi18-10), characterised by high corrosion resistance and ductility. The above-named steel grade is resistant to most oxidising acids, foods, sterilising solutions, organic chemical substances, dyes and inorganic chemical substances [13]. Steel 1.4301, also characterised by favourable weldability, is used in the production of household goods (trays, utensils, cooking equipment and dishes, sinks and refrigerators), dairy equipment, brewing equipment, elements of exhaust systems, welded structures as well as in food processing, civil engineering and in the paint and varnish industry [13].

Tests of the emission of welding fumes

The objective of tests concerning the emission of welding fumes (i.e. carbon monoxide and nitrogen oxides), generated during the welding of stainless steel 1.4301 using various welding processes, was to obtain data related to the volume of emission in relation to welding methods, technological parameters and filler metals. Another stage of the tests involved the environmental assessment of various methods used in the welding of austenitic steels based on the technique of environmental management, i.e. life cycle assessment (LCA). One of the goals of the environmental assessment was the identification of factors connected with a given product or process, potentially affecting the environment. The environmental assessment discussed in the article involved the following welding methods:

- 111 – manual metal arc welding (MMA);
- 131 – gas metal arc welding using inert gas and a solid wire electrode (MIG) – standard and low-energy variants (ColdArc, CMT);
- 135 – gas metal arc welding using active gas and a solid wire electrode (MAG) – standard and low-energy variants (ColdArc, CMT);
- 136 – flux-cored MAG welding;
- 141– tungsten inert gas welding (TIG);

- 521 – solid-state laser beam welding (LBW)
- 521 + 131 – hybrid welding – laser + arc (HLAW).

Table 1 presents the chemical composition of the base material, i.e. austenitic steel grade 1.4301, whereas Table 2 presents filler metals and shielding gases used in the tests. The range of technological parameters, for which the emission of pollutants was tested is presented in Table 3.

The tests concerning the volume of welding fumes emitted during the use of various welding methods were performed using test rigs presented in Figure 2. The test rigs were adapted for specific requirements of individual welding methods – MMA welding, TIG welding, mechanised MAG welding, laser beam welding and hybrid welding.

The primary elements of the test rig:

1. Fume chamber – welding process is performed inside the fume chamber. The design of the chamber prevents the release of pollutants outside. The upper part of the chamber is provided with an outlet port featuring a fume filter. The shape and the dimensions of the chamber depend on a welding method.

Table 1. Chemical composition of the base material used in the tests – stainless austenitic steel grade 1.4301 [1]

Steel grade	**Chemical composition [%] in accordance with PN-EN 10088-1**									
	C	**Si**	**Mn**	**P max**	**S**	**N**	**Cr**	**Mo**	**Ni**	**Ti**
X5CrNi18-10 (1.4301)	≤ 0.07	≤ 1.0	≤ 2.0	0.045	≤ 0.015	0.11	17.5 -19.5	-	8.0 -10.5	-

Table 2. Filler metals and shielding gases used in the tests [14-16]

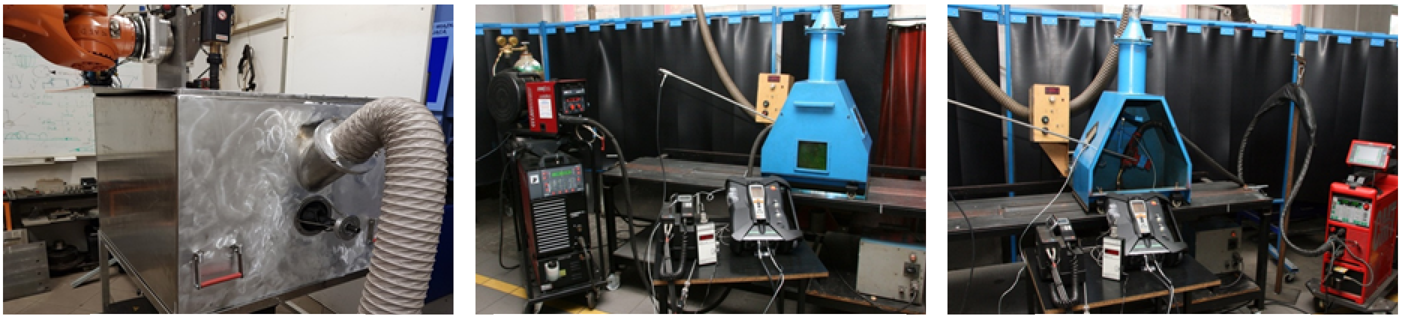
Welding method	**Filler metal**			**Shielding gas**
	Type	**Grade**	**Diameter [mm]**	
MMA (111)	Covered electrodes: rutile coating low-hydrogen coating low-hydrogen coating	E 19 9 R 22 E 19 9 B 22 E 19 9 Nb B 22	4.0 4.0 4.0	–
MIG (131) standard	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	100% Ar
MIG (131) CMT	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	100% Ar
MIG (131) ColdArc	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	100% Ar
MAG (135) standard	solid wire	G 19 9 L Si (308L-Si/ MVR-Si)	1.2	98% Ar + 2% O_2 97% Ar + 3% CO_2
MAG (135) CMT	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	98% Ar + 2% O_2 97.2% Ar + 2.5% CO_2
MAG (135) ColdArc	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	98% Ar + 2% O_2 97.5% Ar + 2.5% CO_2
MAG (136)	metallic flux-cored wire	T 19 9 L M M1 (SAFDUAL SD 650)	1.2	82%Ar + 18% CO_2
TIG (141)	TIG rod	W 19 9 L Si (308L-Si/MVR-Si)	1.6	100% Ar
LBW (521)	-	-	-	100% Ar
HLAW (521+131)	solid wire	G 19 9 L Si (308L-Si/MVR-Si)	1.2	100% Ar

Table 3. Ranges of technological parameters used in the tests concerning the emission of pollutants during the welding of steel grade 1.4301 [14-16]

Welding method	Technological parameters			
	Welding current [A]	Arc voltage [V]	Welding rate [m/min]	Electron beam power [W]
MMA (111)	150	-	-	-
MIG (131) standard	150-300	20-33	-	-
MIG (131) CMT	67-122	10-17	0.35-0.95	-
MIG (131) ColdArc	80-145	15-18.5	0.35-0.95	-
MAG (135) standard	150-300	20-34	-	-
MAG (135) CMT	67-122	10-17	0.35-0.95	-
MAG (135) ColdArc	80-150	15.5-18.5	0.35-0.95	-
MAG (136)	150-250	24-34	-	-
TIG (141)	100-150	18-20	-	-
LBW (521)	-	-	0.5-1.5	2500-6500
HLAW (521+131)	215-305	26-29	0.8-1.5	2500-6500

2. Exhaust system – consists of a fan and a flexible suction hose. The air flow rate ensures the complete capture of pollutants, prevents welding fumes from settling on the chamber walls and does not affect the course of the welding process.
3. Welding equipment
    - Tests concerning the emission of welding fumes accompanying the welding of steel 1.4301 were performed using the following machines:
    - MMA method – PSP-630 welding rectifier,
    - MIG/MAG method – MAGOMIG-401C semiautomatic welding machine,
    - TIG method – KEMPPI PRO 5000 welding machine,
    - MIG/MAG CMT method – TransPulsSynergic 2700/CMT welding machine (Fronius),
    - MIG/MAG ColdArc method – Phoenix 330 ColdArc + Phoenix drive 4L welding machines (EWM Hightec Welding),

a) MMA method b) TIG method c) MIG/MAG method



d) LBW and HLAW methods e) MIG/MAG ColdArc method f) MIG/MAG CMT method

Fig. 2. Test rigs used in measurements concerning the emission of welding fumes in relation to various welding method used to weld stainless steel 1.4301

  - LBW method – TruDisk 12002 industrial solid-state laser (Trumpf),
  - HLAW method – TruDisk 12002 industrial solid-state laser (Trumpf), MIG/MAG arc welding machine - PHOENIX 452 RC PULS KUKA welding power source (EWM Hightec Welding GmbH).

4. Equipment used for measuring the concentration of welding fumes –TESTO 33 / TESTO 350 gas analysers

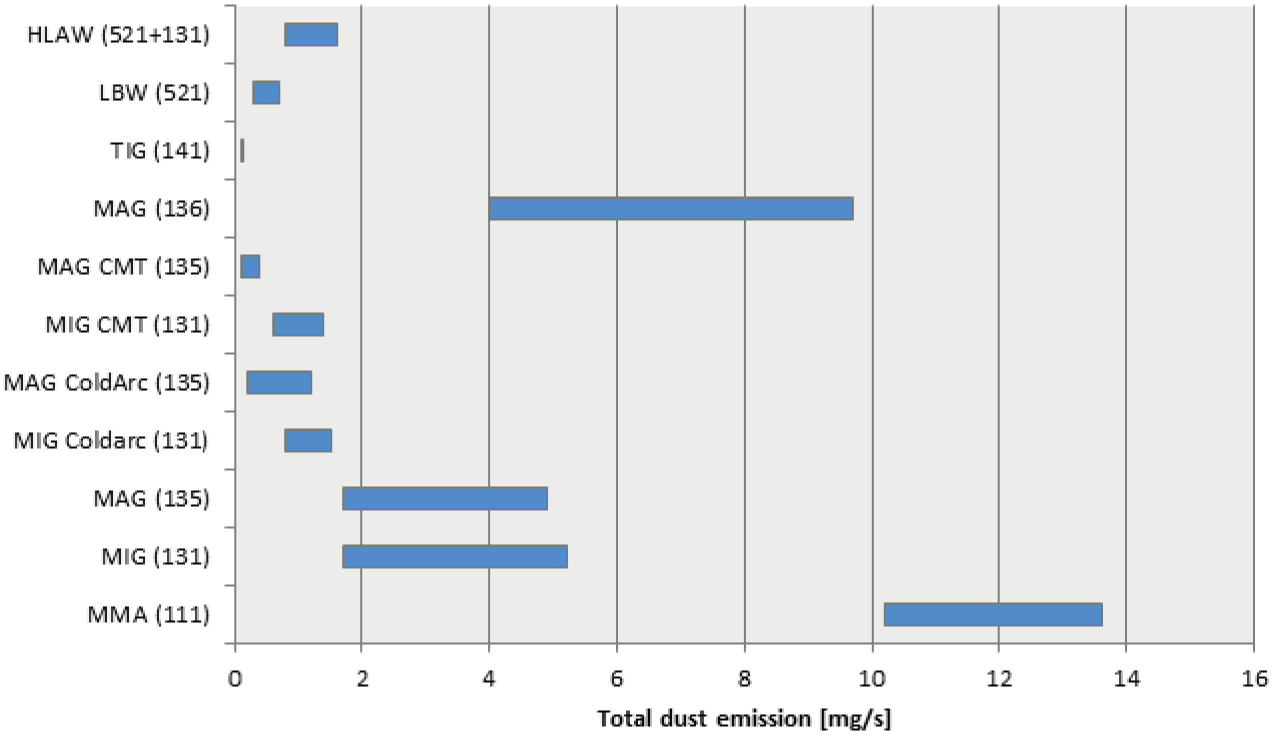
Specimens of welding fumes used in the tests were sampled applying the gravimetric method (based on calculating the difference between filter weights preceding and following the welding process within a previously specified time). The tests concerning the emission of welding fumes were performed using the direct method involving the use of gas analysers as well as gas concentration (NO, NO2, CO) temperature readouts.

Analysis of the emission of welding fumes in relation to various methods used in the welding of austenitic stainless steel

The volume of total inhalable dust and gases – nitrogen oxides (NOx) and carbon monoxide (CO) emitted during the welding of stainless austenitic steel 1.4301 is presented in Figures 3 through 5. The presented volumes take into account ranges of technological parameters used in tests of emission related to individual welding methods (Table 3).

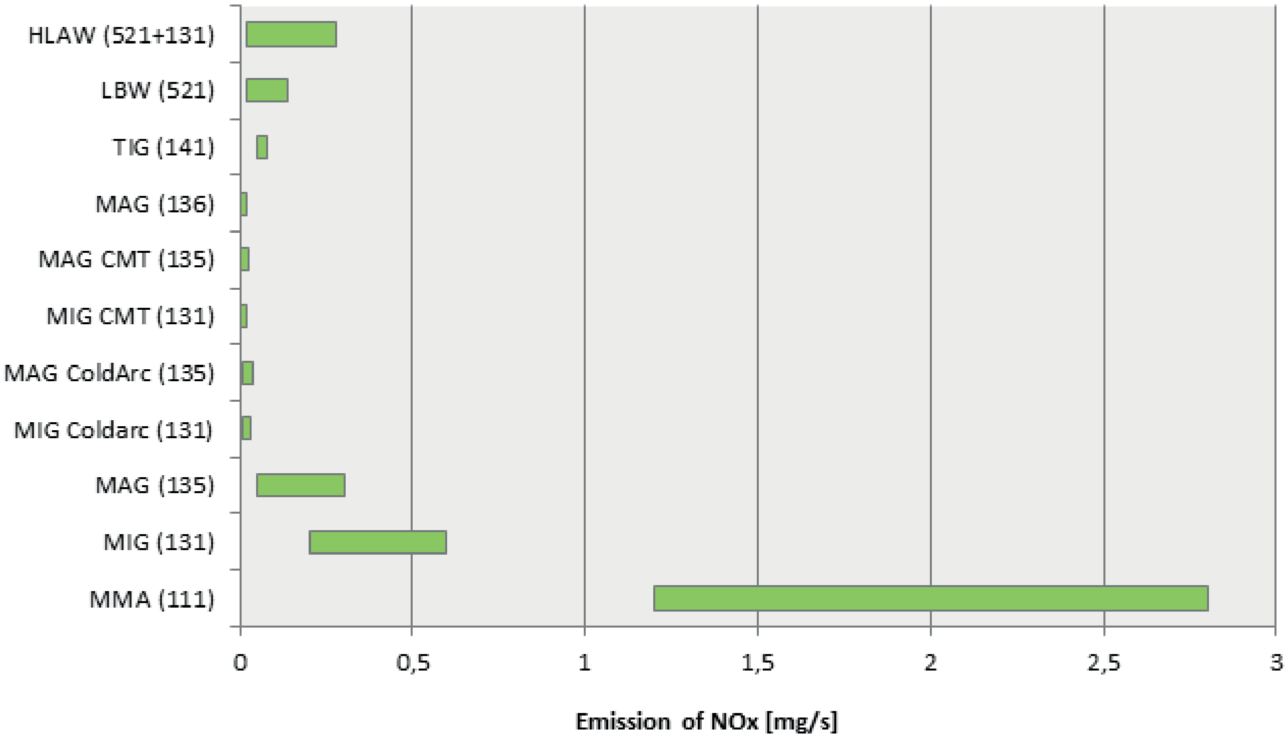
The tests concerning the volume of welding fumes emitted during the welding of steel 1.4301 revealed that the TIG method was characterised by the lowest emission of welding fumes, restricted within the range of 0.11 mg/s to 0.16 mg/s (depending on welding current parameters). In turn, the MMA welding process was characterised by the highest emission of pollutants; in relation to an electrode having a diameter of 4.0 mm, the emission was restricted within the range of 10.17 mg/s to 13.55 mg/s (depending on the type of electrode coating). The MAG welding performed using the metallic flux-cored wire was also characterised by high emission and, depending on technological parameters of the welding process, was restricted within the range of 4.06 mg/s to 9.69 mg/s. In comparison with the flux-cored MAG welding process, the use of the solid wire during MAG welding decreased the emission of total dust by twice. In turn, the use of low energy variants (ColdArc and Cold Metal Transfer (CMT)) of the MIG/MAG welding methods led to the 4-fold reduction of total dust emission in comparison with that accompanying the use of standard MIG/MAG methods. The laser beam welding (LBW) of steel 1.4301 was characterised by low total dust emission, the volume of which, restricted within the range of 0.32 mg/s to 0.74 mg/s, depended on welding rates and laser beam power. The emission accompanying the LBW process was nearly 7 times lower than that accompanying the use of the MIG/MAG methods. The application of the hybrid welding method (HLAW) performed using the filler metal in the form of a solid wire having a diameter of 1.2 mm led to emission restricted within the range of 0.79 mg/s to 1.51 mg/s. The volume of emission accompanying the use of the HLAW process was comparable with that accompanying the use of the low-energy methods.

Similar, to the emission of total dust, the results of the tests concerning the emission of nitrogen oxides revealed that the volume of emission was connected with a method used in the welding of steel 1.4301. The highest emission of NO_x accompanied the MMA welding process and, depending on the type of electrode coating, was restricted within the range of 1.2 mg/s to 2.71 mg/s. The emission of NO_x during the MIG welding process was restricted within the range of 0.24 mg/s to 0.60 mg/s. In turn, as regards the remaining welding methods subjected to analysis, the volume of emission was below 0.3 mg/s, where the lowest emission accompanied the use of the low-energy methods. During the



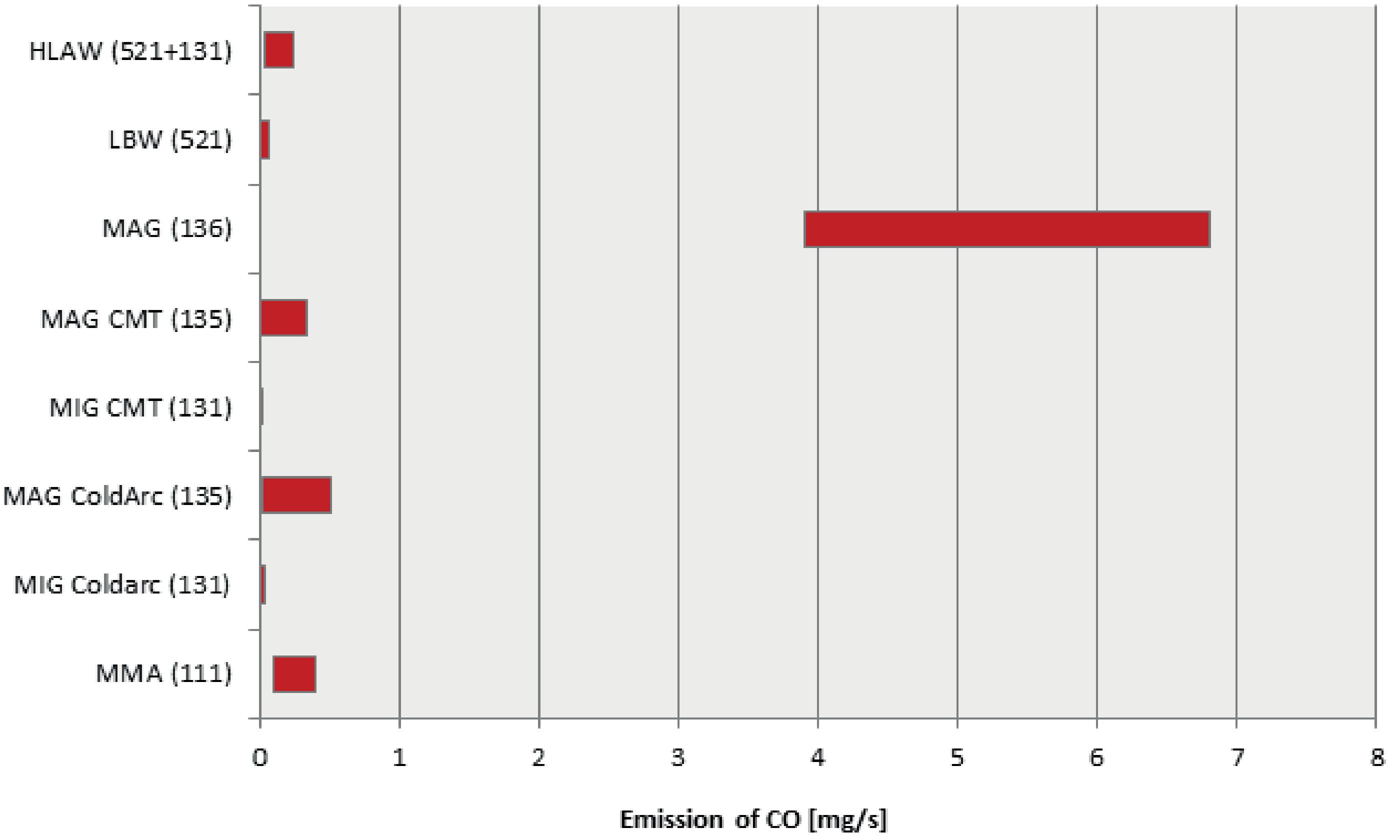
Welding method	Min/max emission of total dust in time [mg/s]	Filler metal	Shielding gas	Technological parameters
HLAW (521 + 131)	0.79	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	2500 W/ 260 A/ 28 V
	1.51			6500 W/ 260 A/ 28 V
LBW (521)	0.32	–	100% Ar	2500 W
	0.74			6500 W
TIG (141)	0.11	TIG rod W 19 9 L Si (308L-Si/MVR-Si)	100% Ar	100 A/ 18 V
	0.16			150 A/ 20 V
MAG (136)	4.06	Flux-cored wire T 19 9 L M M1	82% Ar + 18% CO_2	150 A/ 24 V
	9.69			250 A/ 34 V
MAG CMT (135)	0.14	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	68 A/ 10.5 V
	0.37		97.5% Ar + 2.5% CO_2	122 A/ 17 V
MIG CMT (131)	0.58	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	67 A/ 10.7 V
	1.43			121 A/ 17 V
MAG ColdArc (135)	0.19	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	80 A/ 15.5 V
	1.22		97.5% Ar + 2.5% CO_2	140 A/ 18.5 V
MIG ColdArc (131)	0.84	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	80 A/ 15 V
	1.54			145 A/ 18.5 V
MAG (135)	1.68	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	150 A/ 20 V
	4.86			300 A/ 34 V
MIG (131)	1.76	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	150 A/ 20 V
	5.16			300 A/ 33 V
MMA (111)	10.17	E 19 9 Nb B 22 (low-hydrogen coating)	–	150 A
	13.55	E 19 9 B 22 (low-hydrogen coating)	–	150 A

Fig. 3. Volume of total dust emission during the MMA, MIG, MAG, TIG, laser (LBW) and the hybrid (HLAW) welding of stainless steel 1.4301



Welding method	Min/max NO_x emission in time [mg/s]	Filler metal	Shielding gas	Technological parameters
HLAW (521 + 131)	0,02	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	2500 W/ 260 A/ 28 V
	0,28			6500 W/ 260 A/ 28 V
LBW (521)	0,02	–	100% Ar	2500 W
	0,14			6500 W
TIG (141)	0,05	TIG rod W 19 9 L Si (308L-Si/MVR-Si)	100% Ar	100 A/ 18 V
	0,08			150 A/ 20 V
MAG (136)	0,00	Flux-cored wire T 19 9 L M M1	82% Ar + 18% CO_2	150 A/ 24 V
	0,02			250 A/ 34 V
MAG CMT (135)	0,003	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	97.5% Ar + 2.5% CO_2	122 A/ 17 V
	0,026		98% Ar + 2% O_2	68 A/ 10.5 V
MIG CMT (131)	0,002	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	67 A/ 10.7 V
	0,018			121 A/ 17 V
MAG ColdArc (135)	0,006	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	97.5% Ar + 2.5% CO_2	140 A/ 18.5 V
	0,037		98% Ar + 2% O_2	80 A/ 15.5 V
MIG ColdArc (131)	0,005	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	80 A/ 15 V
	0,031			145 A/ 18.5 V
MAG (135)	0,06	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	150 A/ 20 V
	0,27		97% Ar + 3% CO_2	300 A/ 34 V
MIG (131)	0,24	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	150 A/ 20 V
	0,60			300 A/ 33 V
MMA (111)	1,20	E 19 9 B 22 (low-hydrogen coating)	–	150 A
	2,71	E 19 9 R 22 (rutile coating)	–	150 A

Fig. 4. Volume of nitrogen oxide (NO_x) emission during the MMA, MIG, MAG, TIG, laser (LBW) and the hybrid (HLAW) welding of stainless steel 1.4301



Welding method	Min/max CO emission in time [mg/s]	Filler metal	Shielding gas	Technological parameters
HLAW (521 + 131)	0.03	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	2500 W/ 260 A/ 28 V
	0.25			6500 W/ 260 A/ 28 V
LBW (521)	0.01	–	100% Ar	2500 W
	0.07			6500 W
MAG (136)	3.99	Flux-cored wire T 19 9 L M M1	82% Ar + 18% CO_2	150 A/ 24 V
	6.76			250 A/ 34 V
MAG CMT (135)	0.010	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	68 A/ 10.5 V
	0.337		97.5% Ar + 2.5% CO_2	122 A/ 17 V
MIG CMT (131)	0.004	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	67 A/ 10.7 V
	0.020			121 A/ 17 V
MAG ColdArc (135)	0.016	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	98% Ar + 2% O_2	80 A/ 15.5 V
	0.505		97.5% Ar + 2.5% CO_2	140 A/ 18.5 V
MIG ColdArc (131)	0.005	Solid wire G 19 9 L Si (308L-Si/MVR-Si)	100% Ar	80 A/ 15 V
	0.034			145 A/ 18.5 V
MMA (111)	0.15	E 19 9 B 22 (low-hydrogen coating)	–	150 A
	0.36	E 19 9 R 22 (rutile coating)	–	150 A

Fig. 5. Volume of carbon monoxide (CO) emission during the MMA, MIG, MAG, TIG, laser (LBW) and the hybrid (HLAW) welding of stainless steel 1.4301

laser welding process it was observed that the emission of nitrogen oxides increased in relation to higher values of laser beam power. The LBW process performed using a laser beam power of 6500 W was accompanied by an emission of 0.14 mg/s. Similar to laser welding, during the hybrid (HLAW) welding of steel 1.4301, the emission of nitrogen oxides was related to laser beam power and, additionally, arc welding current parameters.

The comparative analysis concerning the emission of carbon monoxide in relation to various methods used when welding steel 1.4301 was difficult to interpret as there were different sources of CO emission in different welding methods. Carbon monoxide in gas-shielded welding processes was formed as a result of the thermal dissociation of carbon dioxide being a component of the shielding gas. In cases where covered electrodes and flux-cored wires were used as filler metals, the emission of CO resulted from the thermal decomposition of carbon compounds contained in the coating of the electrodes and in the core of the flux-cored wires. In the tests concerning the emission accompanying the flux-cored MAG welding process (136), arc was shielded by a two-component gas mixture (82% Ar + 18% CO_2). As a result, the emission of carbon monoxide (connected with the dissociation of CO_2) was high and restricted within the range of 3.99 mg/s to 6.76 mg/s. In the tests concerning the emission accompanying the low-energy MAG welding processes (i.e. CMT and ColdArc), arc was shielded by two gas mixtures, i.e. 97.5% Ar+ 2.5% CO_2 and 98% Ar + 2% O_2. The emission of carbon monoxide was repeatedly higher in terms of the mixture containing CO_2. During the MMA welding process, carbon monoxide was formed as a result of the thermal decomposition of carbonates being components of the coating; the emission of CO was restricted within the range of 0.15 to 0.36 mg/s. Because the MIG, LBW and HLAW processes were shielded by argon, the only source of carbon monoxide carbon burnt out of the base material. The emission of carbon monoxide in the above-named cases was extremely low.

The tests and detailed analyses concerning the volume of welding fumes emitted when welding stainless austenitic steel 1.4301 revealed that the dominant hazard was the emission of total dust, the volume of which was primarily dependent on a welding method, technological conditions and parameters, filler metals (in the form of covered electrodes), electrode wires and types of shielding gases. The identification of total dust emitted during the welding of austenitic steel as the primary environmental hazard was connected with its carcinogenic effect resulting from the presence of nickel and compounds of hexavalent chromium. Table 4 presents the volume of total dust emitted during the welding of austenitic steel 1.4301 (X5CrNi18-10), i.e. the average value of emission in relation to the entire range of technological parameters subjected to analysis. The analysis of the welding methods involved calculations of the multiplicity of dust emission in relation to the method identified at the safest and least environmentally harmful, i.e. TIG

Table 4. Emission of total dust during the welding of austenitic steel 1.4301; multiplicity factor with reference to the TIG method-related emission

No.	Welding method	E_P – emission of dust in time [mg/s]	Multiplicity factor where E_P TIG =1
1.	MMA (111)	11.90	99.2
2.	MAG (136)	6.85	57.1
3.	MIG (131)	3.45	28.8
4.	MAG (135)	3.30	27.5
5.	HLAW (521 + 131)	1.20	10.0
6.	MIG Coldarc (131)	1.15	9.6
7.	MIG CMT (131)	1.00	8.3
8.	MAG ColdArc (135)	0.70	5.8
9.	LBW (521)	0.50	4.2
10.	MAG CMT (135)	0.25	2.1
11.	TIG (141)	0.12	1.0

welding, where the value adopted for TIG-related emission index amounted to 1.

The emission of total dust accompanying the MMA welding of stainless austenitic steel 1.4301was nearly 100 times higher than that accompanying the use of the TIG method. The emission of total dust accompanying the use of the standard MIG/MAG method was nearly 30 times higher than the emission related to the use of the TIG method. In turn, the emission accompanying the use of the HLAW method was 10 times higher than that recorded relation to the TIG method, whereas the emission accompanying the LBW process was 4 times higher than the emission triggered by the TIG process.

Environmental assessment of the methods used for the welding of austenitic steel 1.4301

The subsequent stage of the research-related tests involved the environmental assessment of methods used in the welding of stainless steel 1.4301 in relation to hazards resulting from the emission of welding fumes. To determine the potential risk it was necessary to apply the formula taking into consideration hazard to workers' health in relation to the volume of emitted pollutants, the presence and types of ventilation systems, types of tasks performed by workers and their distance from the source of total dust emission [17]. The aforementioned formula is the following:

$$PR=(E_P \cdot W_P) \cdot L \cdot R \cdot K_b \qquad [17]$$

where

- PR – potential risk of total dust emission,
- E_P – coefficient concerning the volume of total dust emission, specified as the multiplicity of total dust emission accompanying the use of the TIG method (Table 4),
- W_P – factor identifying the potential effect of a dust component on health,
- L – factor related to a ventilation system,
- R – factor related to the type of a welding process; manual welding/automatic welding stations,
- K_b – factor related to the distance between the worker (head /body) and the source of total dust emission.

The identification of a potential risk included the adoption of the following assumptions:

- in relation to the methods subjected to analysis, only the emission of total dust was taken into consideration; the dominant hazard accompanying the welding of stainless austenitic steel 1.4301 was the emission of total dust, variable WP was designated as 1,
- tests of emission were performed under identical environmental conditions; variable L was designated as 1 – test rig was equipped with a local exhaust,
- simplified formula has the following form:

$$PR=E_P \cdot R \cdot K_b$$

- factor characteristic of a given welding process: R = 1 automated welding, R = 2 manual welding,
- factor related to the distance between the worker and the emission source: K_b = 1 automated welding, K_b = 3 manual welding.

Table 5 presents results of the calculation of potential risks related to total dust emission during the welding of steel 1.4301 performed using various methods.

The interpretation of a potential risk resulting from total dust emission in relation to individual methods used in the welding of austenitic steel 1.4301 and corresponding to the environmental assessment of a given welding method was referred to a five-grade scale of risk assessment [18]. The five-grade scale of risks was the following:

- very low risk – welding methods, where $PR \leq 12$,
- low risk – welding methods, where $12 < PR \leq 35$,
- medium risk – welding methods, where $35 < PR \leq 100$,
- high risk – welding methods, where $100 < PR \leq 200$,
- very high risk – welding methods, where $PR > 200$.

The assessment of risks resulting from total dust emission in relation to the methods used for the welding of austenitic steel 1.4301 is presented in Table 6.

The test results revealed that the use of automated processes was beneficial in terms of reducing the risk resulting from total dust emission as such processes were performed under hermetic conditions and, consequently, the distance between the worker and the source of

Table 5. Potential risk resulting from total dust emission in relation to various methods used in the welding of austenitic steel 1.4301

No.	Welding method	E_P – coefficient related to total dust emission/ comparison with TIG	R –factor related to the welding station (manual/ automatic)	K_b – factor related to the distance between worker's head/body and the source of total dust emission	PR – potential risk
1.	MMA (111)	99.2	2	3	595.2
2.	MAG (136)/ manual	57.1	2	3	342.6
3.	MAG (136)/ automated	57.1	1	1	57.1
4.	MIG (131)/ manual	28.8	2	3	172.8
5.	MIG (131)/ automated	28.8	1	1	28.8
6.	MAG (135)/ manual	27.5	2	3	165.0
7.	MAG (135)/ automated	27.5	1	1	27.5
8.	HLAW (521+131)/ automated	10.0	1	1	10.0
9.	MIG ColdArc (131)/ manual	9.6	2	3	57.6
10.	MIG ColdArc (131)/ automated	9.6	1	1	9.6
11.	MIG CMT (131)/ manual	8.3	2	3	49.8
12.	MIG CMT (131)/ automated	8.3	1	1	8.3
13.	MAG ColdArc (135)/ manual	5.8	2	3	34.8
14.	MAG ColdArc (135)/ automated	5.8	1	1	5.8
15.	LBW (521)/ automated	4.2	1	1	4.2
16.	MAG CMT (135)/ manual	2.1	2	3	12.6
17.	MAG CMT (135)/ automated	2.1	1	1	2.1
18.	TIG (141)/ manual	1.0	2	3	6.0
19.	TIG (141)/ automated	1.0	1	1	1.0

Table 6. Assessment of risks resulting from total dust emission in relation to various methods used in the welding of austenitic steel 1.4301

Risk level	**Welding method**
Very low risk	manual and automated TIG welding automated low-energy MIG/MAG welding (ColdArc and CMT) laser welding and hybrid welding
Low risk	automated standard MIG/MAG welding manual low-energy MAG welding (ColdArc and CMT)
Medium risk	manual low-energy MIG welding (ColdArc and CMT) automated flux-cored MAG welding (136)
High risk	manual MIG welding manual MAG welding
Very high risk	manual flux-cored MAG welding MMA welding

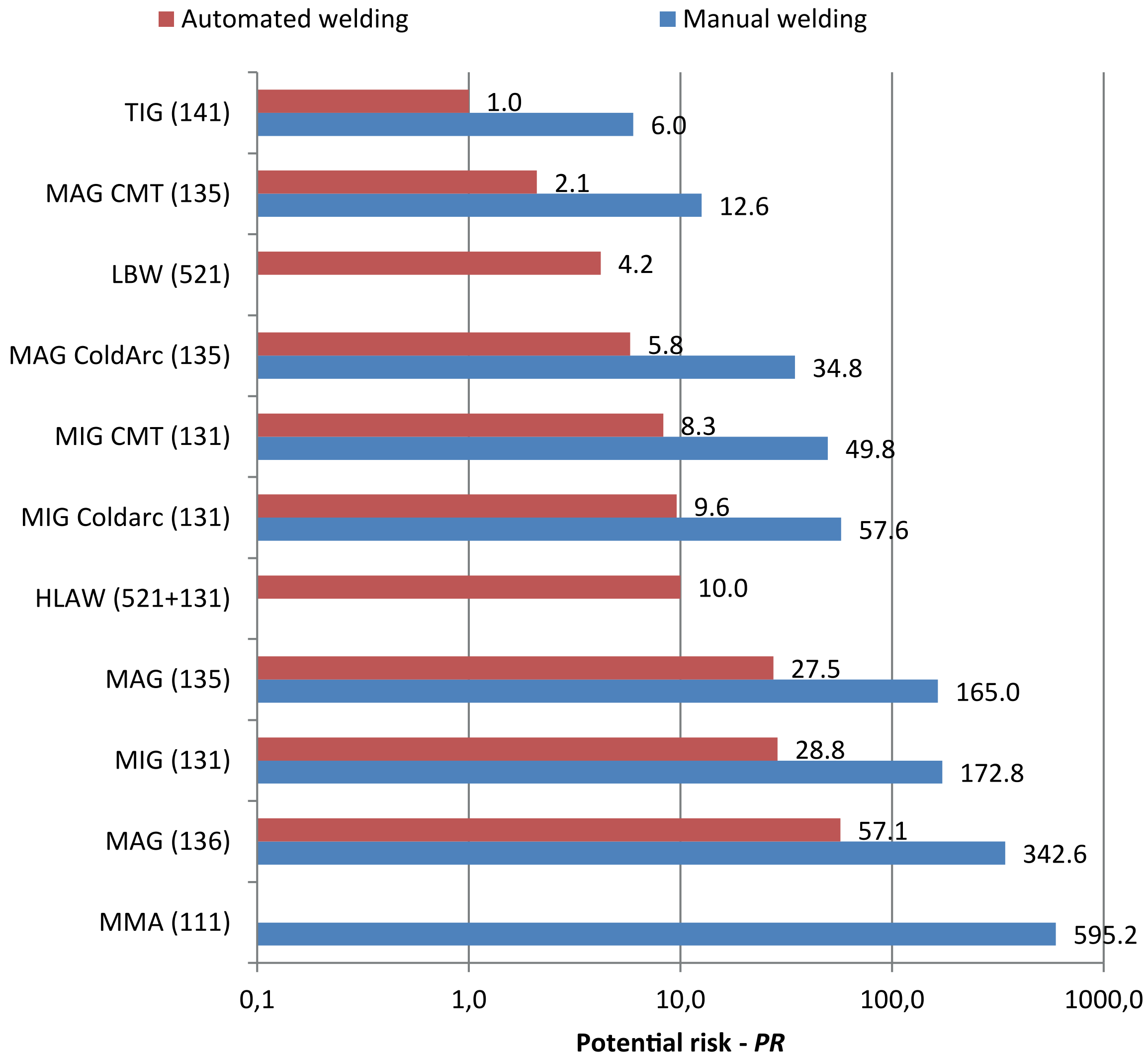


Fig. 6. Potential risk resulting from total dust emission in relation to individual method used in the welding of steel 1.4301

pollution was longer. The comparison of the test results in relation to manual and automatic welding is presented in Figure 6.

The analysis of hazards resulting from the emission of total dust in relation to the manual welding processes revealed that the highest risk accompanied the use of the MMA welding process and was 3.5-fold higher in comparison with that accompanying the use of the standard MIG/MAG welding process, over 10-fold higher in comparison with the risk accompanying the use of the low-energy variants of the MIG welding process and nearly 100 time higher than the risk accompanying the use of the TIG method. In relation to automated welding, the analysis revealed that the highest risk accompanied the flux-cored MAG welding process (136) and was 2-fold higher than the risk accompanying solid wire MIG/MAG welding processes, nearly 6-fold higher than the use of the hybrid welding process (HLAW) and low-energy MIG method variants, nearly 14 times higher than the risk accompanying laser beam welding (LBW) and 57 times higher than the risk accompanying the use of the TIG welding process.

Summary and conclusions

The use of welding technologies in various industries necessitates the investigation and identification of conditions ensuring safe work and protecting workers' health. The growing awareness of welding process-related hazards (known both to employers and employees) as well as increasingly high requirements concerning the competence of HSE personnel and that of environmental protection services necessitate the performance of tests enabling the assessment of factors affecting the volume and types of pollution generated during welding processes.

The improvement of welding technologies is not only connected with advancement of welding process efficiency but also with the reduction of welding fume emission. As a result, research-related tests aim to identify possibilities of reducing health hazards accompanying welding processes through the selection of proper materials and the adjustment of technological parameters. The qualitative and quantitative emission of welding fumes results directly from welding processes, technological conditions as well as chemical compositions of base materials and filler metals.

The above-presented environmental assessment concerning the methods used in the welding of austenitic steel was based on the analysis of the volume of welding fume emission and the assumption that the dominant hazard affecting work safety and the natural environment during the welding of stainless austenitic steels was the emission of total dust.

The results obtained in the tests justified the formulation of the following conclusions:

1. The choice of a given welding method significantly affected the volume of pollutants emitted during the welding process.
2. The technological and material conditions connected with the use of a given welding method affected the volume of welding fume emission during the welding of steel 1.4301 used in the tests.
3. The TIG welding of austenitic steel 1.4301 was accompanied by the lowest emission, whereas the highest emission accompanied the use of the MMA welding process.
4. The criteria adopted to compare risks resulting from total dust emission included the volume of total dust emitted during the welding process, the type of a welding station and the distance between the worker and the source of total dust emission.
5. The tests concerning the manual welding of austenitic steel 1.4301 revealed that the highest risk accompanied the use of the MMA welding process and was 3.5-fold higher in comparison with that accompanying the use of the standard MIG/MAG welding process, over 10-fold higher in comparison with the risk that accompanying the use of the low-energy variants of the MIG welding process and nearly 100 times higher than the risk accompanying the use of the TIG method.
6. In relation to automated welding, the analysis revealed that the highest risk accompanied the use of the flux-cored MAG welding process (136) and was 2-fold higher than the risk accompanying the use of the solid wire MIG/MAG welding processes, nearly 6-fold higher than the risk accompanying the use of the hybrid welding method (HLAW) and the low-energy variants of the MIG method, nearly 14 times higher than the risk accompanying the use of the laser beam welding process (LBW) and 57 times higher than the risk accompanying the use of the TIG welding process

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