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The Assessment of the Effect of Technological Conditions of the Laser and Hybrid Welding of Corrosion-Resistant Steels on Welding Fume Emission

Abstract: Corrosion-resistant steels are used in many industrial sectors, including the food, chemical, petrochemical, power engineering and the building engineering industry. Welding processes constitute the main method enabling the joining of corrosion-resistant steels. Typically, corrosion-resistant steels are joined using manual metal arc welding, gas-shielded metal arc welding (MIG/MAG), flux-cored arc welding, TIG welding and submerged arc welding processes. In turn, advanced welding processes include laser beam, hybrid (laser + arc), plasma arc and electron beam welding methods. The growing popularity of laser methods in enterprises has necessitated the determination of the effect of technological conditions on the emission of welding fume, i.e. the dominant risk factor when welding corrosion-resistant steels. In 2017, welding fume (formed through the condensation and oxidation of metal vapours) was rated among factors of proven carcinogenic effect (in accordance with the requirements of the International Agency for Research on Cancer (IARC).

Keywords: laser welding, hybrid welding, MIG, MAG, TIG

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Introduction

The use of welding technologies in various industries entails the necessity of testing and identifying the HSE-related conditions. Welding and allied technologies belong to a group of manufacturing processes adversely affecting the work environment. Various joining processes entail the emission of dust and gaseous pollutants containing substances hazardous to workers' health.

Particularly dangerous for welders' health are corrosion-resistant austenitic steels as their primary alloying components are chromium and nickel. The compounds of the above-named chemical elements (present in welding fume) are rated among substances of either proven or probable carcinogenic effect [1, 2].

Previously, tests concerning the emission of pollutants were primarily concerned with arc welding and braze welding as well as resistance welding, yet the growing applicability of laser beam-based techniques has necessitated the extension of the scope of investigation. Apart from laser beam welding, another process utilising the laser beam is hybrid laser arc welding (HLAW), consisting in the simultaneous use of two heat sources, i.e. laser radiation and electric arc.

Figure 1 presents the shares of various welding processes in industry.

Laser and hybrid welding processes might seem not to pose a threat to workers' health as laser/hybrid welding stations are fully hermetic, automated and, usually, integrated with an exhaust system [4]. However, the significant growth of the number of companies using laser beam welding processes forced the adaptation of work stations and ventilation systems to manufactured elements. In order to avoid irregularities in design calculations (e.g.

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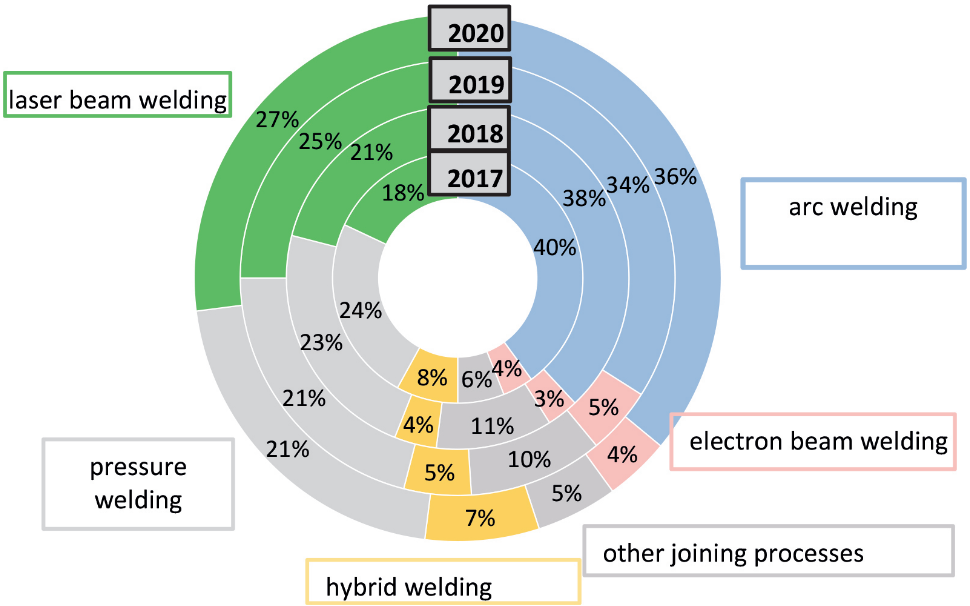

Fig. 1. Various welding technologies used in industry in the years 2017–2020 (own elaboration based on [3])

concerning exhaust ventilation systems) and optimise costs it is necessary to possess emission-related knowledge already at the planning stage [5].

The improvement of welding techniques is not only connected with improved process efficiency but also with reduced welding fume emission. The foregoing requires investigation focused on search for the reduction of welding-related health hazards through the selection of appropriate materials and technological process conditions. The qualitative and quantitative emission of welding fume results from the joining process, technological conditions as well as the chemical composition of the base material and that of the filler metal (if used in a given process) [6]. Technological process conditions significantly affect the emission of pollutants. The modification of process conditions makes it possible to improve the process as regards the reduction of welding fume emission, including carcinogenic elements and compounds.

Total dust emission tests

The tests discussed in the article aimed to identify the volume of welding fume emitted during the laser welding and hybrid welding (laser + MIG – HLAW – Hybrid Laser Arc Welding) of corrosion-resistant austenitic steel X5CrNi18-10 (1.4301) and, afterwards, to determine the effect of material and technological conditions on the emission of total dust. The tests also involved the identification of the correlation concerning process parameters of the laser beam welding (laser beam power and welding rate) and hybrid welding (laser beam power, filler metal feed rate and welding rate) of austenitic steel and the emission of total dust. The determination of the above-named parameters should help identify paths enabling the reduction of environmental impact resulting from the use of such processes in various sectors of industry. The tests also included the comparative analysis of laser beam and hybrid welding processes with respect to dust emission.

The detailed range of material and technological parameters concerning the emission of dust pollutants is presented in Table 1.

The tests concerning the emission of total dust generated during hybrid welding were performed in relation to three laser beam power values as well as various filler metal wire feed rates and welding rates. The tests were conducted in the AL (arc-laser) configuration, with the arc welding torch

Table 1. Material and technological welding process parameters in the tests of dust pollutant emission [7]

Welding method	Base material	Filler metal wire/ diameter	Shielding gas	Technological process parameters		
				P [W]	Vdr [m/min]	Vsp [m/min]
hybrid welding	**X5CrNi18-10 (1.4301)**	308 L Si/ 1.2 mm	Ar	2500–6500	6.5–10.5	0.8–1.5
laser beam welding (key-hole, melt-in)		–		2500–6500	–	0.5–1.5

located in front of the laser beam (the so-called drag arc welding) [8].

The tests concerning the laser beam process involved both the key-hole welding and melt-in welding techniques in relation to three values of laser beam power and various welding rates. During the melt-in welding process, the defocusing of the laser beam amounted to 20 mm.

The melt-in laser beam welding process was performed using a radiation power density of approximately 10^4–10^5 W/cm^2. The obtained level of power density was sufficient to create a weld pool, yet the absorption of beam energy took place only in the thin surface layer of the material. Subsequent layers were heated as a result of material thermal conductivity [9]. The laser beam welding process performed using the key-hole (deep penetration) technique is characterised by the intense evaporation (instead of melting) of the material being welded after exceeding a radiation power density of approximately 10^6 W/cm^2. The pressure of metal vapour stream is sufficiently high for a capillary ("key-hole) to form in the weld pool. During the welding process, the capillary moves along the interface of elements being welded. Metal melts at the front of the capillary and solidifies at its rear part. During the key-hole laser beam welding process, heat is transferred to the material across the entire depth of the capillary and not from the surface (as is the case with the melt-in technique; Fig. 2) [9].

The emission of welding fume accompanying the laser beam welding process was investigated using an experimental testing station composed of the four primary elements (Fig. 3) [7, 10]:

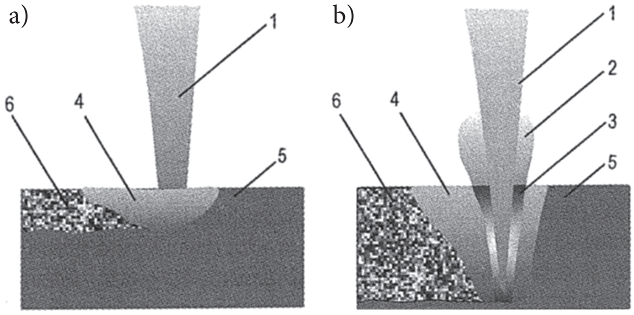

Fig. 2. Laser beam welding process: a) melt-in technique and b) key-hole technique: 1 – laser beam, 2 – plasma cloud, 3 – capillary (key-hole), 4 – molten metal pool, 5 – base material and 6 – molten material [9]

- *fume chamber* – chamber, where the welding process was performed. The design of the chamber prevented the release of contaminants outside. The side part of the chamber was provided with an exhaust nozzle containing a dust filter. The chamber was fixed; the element subjected to welding rotated being placed on a welding turntable,
- *robotic laser beam welding station* – station, which consisted of a TruDisk 12002 industrial solid-state laser having a maximum laser beam power of 12 kW and a KR30HA industrial robot (KUKA),
- *exhaust system* – system composed of a fan and a flexible suction hose. The air flow rate enabled the complete capture of pollutants, prevented the

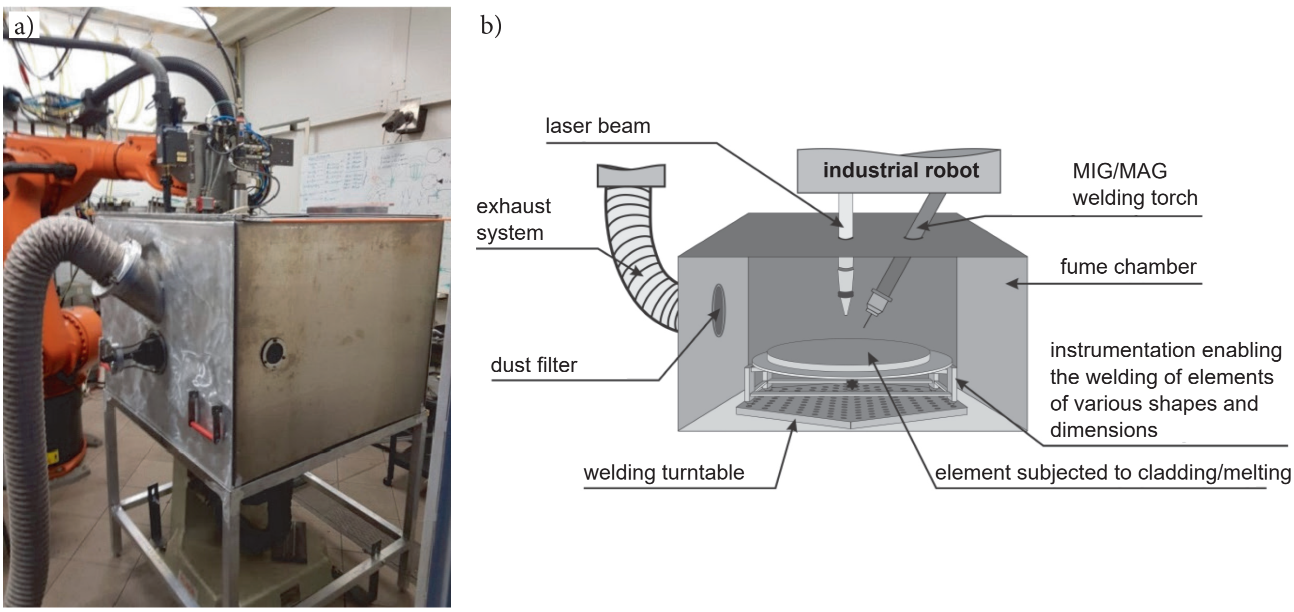

Fig. 3. Experimental station for testing the emission of pollutants during laser beam welding: a) main view and b) schematic diagram [7, 10]

deposition of dust on the chamber walls and did not affect the welding process,
- *turntable* (*DKP-400*) – table (additionally) equipped with instrumentation enabling the welding of elements of various dimensions.

The methodology applied to assess the emission of pollutants formed during arc welding was developed in accordance with the requirements specified in the PN-EN ISO 15011 standard. The above-named methodology was used to develop another methodology, enabling the identification of welding fume emission during laser and hybrid welding and involving the use of a fume chamber (Fig. 3b). Fume specimens used in the determination of emission were sampled using the gravimetric method. The emission of fume was calculated as the difference between the weight of filters before and after the welding process (within a previously assumed time).

Effect of the laser beam welding technique and technological process parameters on total dust emission

The analysis of test results concerning the emission of total dust generated during laser welding aimed to determine the effect of the (melt-in/key-hole) welding technique and technological process parameters on the emission of dust pollutants. The welding rate was restricted within the range of 0.5 m/min to 1.5 m/min, whereas laser beam power was restricted within the range of 2500 W to 4500 W.

Effect of the laser beam welding technique

Figure 4 presents the effect of the technique of the laser beam welding of steel grade 1.4301 on the emission of total dust.

During the welding of steel 1.4301, higher total dust emission was detected in relation to the key-hole technique. As regards the sets of technological parameters, differences between both welding techniques amounted to between 4% and nearly 30%. For instance, during the melt-in welding process performed using a laser beam power of 2500 W and a welding rate of 0.5 m/min the emission amounted to 0.45 mg/s, whereas the key-hole welding process resulted in emission increased by nearly 30% (0.58 mg/s).

The analysis of test results concerning the effect of the welding technique on the emission of pollutants revealed that the melt-in process was more favourable with respect to the reduction of total dust emission.

Effect of laser beam power

Figure 5 presents the emission of welding fume during the laser welding of steel 1.4301 in relation to three values of laser beam power (2500 W, 4500 W and 6500 W) and the key-hole technique as well as in relation to two values of laser beam power (2500 W and 4500 W) and the melt-in technique.

An increase in laser beam power translated into an increase in total dust emission both during the key-hole and the melt-in laser beam welding processes. The emission of total dust during the melt-in welding of steel 1.4301 performed using a welding rate of 0.5 m/min and a laser beam power

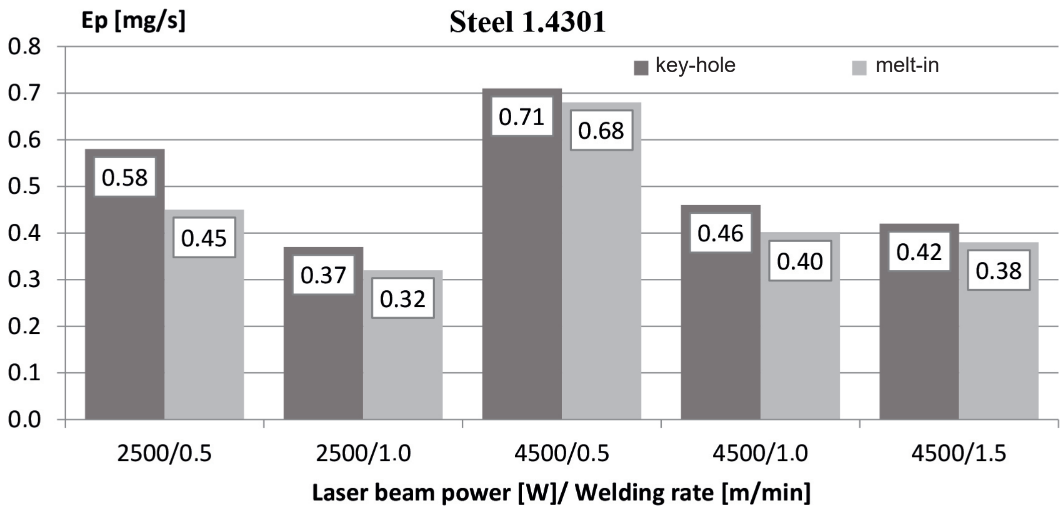

Fig. 4. Effect of a welding technique on the emission of welding fume in time during the laser beam welding of steel 1.4301 [7]

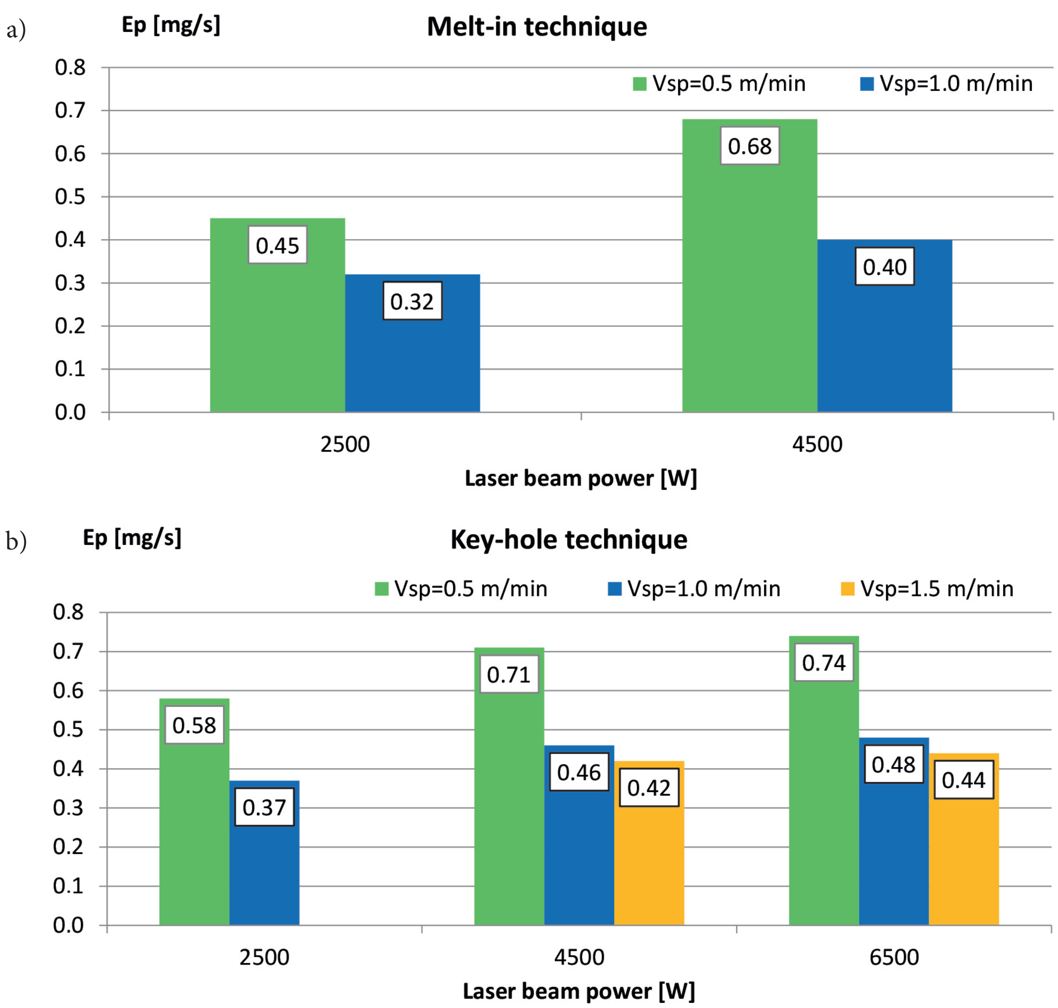

Fig. 5. Effect of laser beam power on the emission of total dust in time during the laser beam welding of steel 1.4301: a) melt-in technique and b) key-hole technique [7]

of 2500 W amounted to 0.45 mg/s. Increasing the laser beam power to 4500 W led to an increase in the emission of dust by more than 50% (0.68 mg/s).

The emission of total dust during the key-hole welding of steel 1.4301 performed using a welding rate of 0.5 m/min and a laser beam power of 2500 W amounted to 0.58 mg/s. Increasing the laser beam power to 4500 W lead to an increase in the emission of dust by more than 22% (0.71 mg/s). In relation to a laser beam power of 6500 W the emission of total dust amounted to 0.74 mg/s, i.e. which was nearly 28% higher than that observed in the process performed using a laser beam power of 2500 W and 4% higher in comparison with the process performed using a laser beam power of 4500 W.

Effect of the welding rate

Figure 6 presents the effect of the welding rate of the laser beam welding of steel grade 1.4301 on the emission of total dust

The diagrams present data concerning the emission of pollutants in relation to three welding rates (0.5 m/min, 1.0 m/min and 1.5 m/min). The tests were performed using three values of laser beam power (2500 W, 4500 W and 6500 W) during the key-hole welding process and two values of laser beam power (2500 W and 4500 W) during the melt-in welding process.

An increase in the welding rate triggered a decrease in the emission of total dust during the laser beam welding process both in terms of the key-hole and the melt-in technique.

The melt-in laser beam welding of steel 1.4301 performed using a welding rate of 0.5 m/min and a laser beam power of 2500 W triggered a total dust emission of 0.45 mg/s. An increase in the welding rate to 1.0 m/min resulted in the reduction of emission by nearly 30% (0.32 mg/s).

The emission of total dust during the key-hole laser beam welding of steel 1.4301 performed using a welding rate of 1.0 m/min and a laser beam power of 2500 W amounted to 0.37 mg/s and was by more than 35% lower than that recorded during the welding process performed using a welding rate of 0.5 m/min (0.58 mg/s).

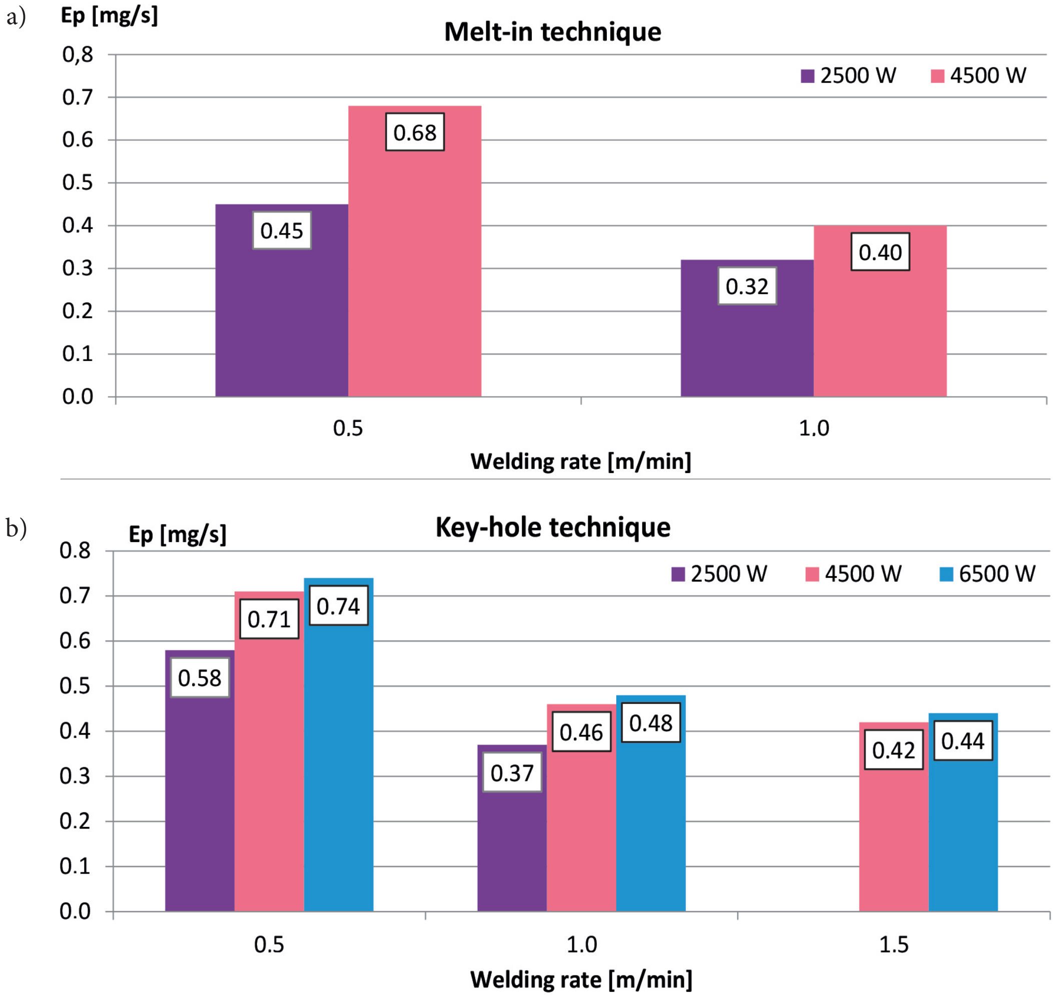

Fig. 6. Effect of the welding rate on the emission of total dust in time during the laser beam welding of steel 1.4301: a) melt-in technique and b) key-hole technique [7]

Effect of HLAW technological parameters on the emission of total dust

The analysis discussed below aimed to assess the effect of technological parameters used in the HLAW process on the emission of dust pollutants. The parameters subjected to analysis included laser beam power, welding rate and the amount of molten filler metal (characterised by the filler metal wire feed rate). The power of laser beam was restricted within the range of 2500 W to 6500 W, the welding rate was restricted within the range of 0.8 m/min to 1.5 m/min, whereas the filler metal wire feed rate was restricted within the range of 6.5 m/min to 10.5 m/min.

Effect of laser beam power

Figure 7 presents the results of assessment concerning the effect of laser beam power on the emission of total dust during the Ar-shielded hybrid welding of corrosion-resistant steel 1.4301 performed using solid wire 308 L Si having a diameter of 1.2 mm. The tests were conducted in relation to the above-presented ranges of parameters; the filler metal wire feed rate was constant and amounted to 8.5 m/min.

Similar to laser beam welding, the tests revealed that an increase in laser beam power (combined with the constant welding rate) led to an increase in the emission of total dust.

The emission of total dust during the laser beam welding of steel 1.4301 performed using a laser beam power of 2500 W and a welding rate of 0.8 m/min amounted to 1.34 mg/s. An increase in laser beam power to 4500 W translated into an increase in the emission of total dust by 9% (1.46 mg/s). In relation to a beam power of 6500 W the emission of total dust amounted to 1.51 mg/s and was 13% higher if compared with the emission accompanying the process performed using a laser beam power of 2500 W and only slightly higher (i.e. 3.5%) in comparison with the emission of total dust observed during the process where the laser beam power amounted to 4500 W.

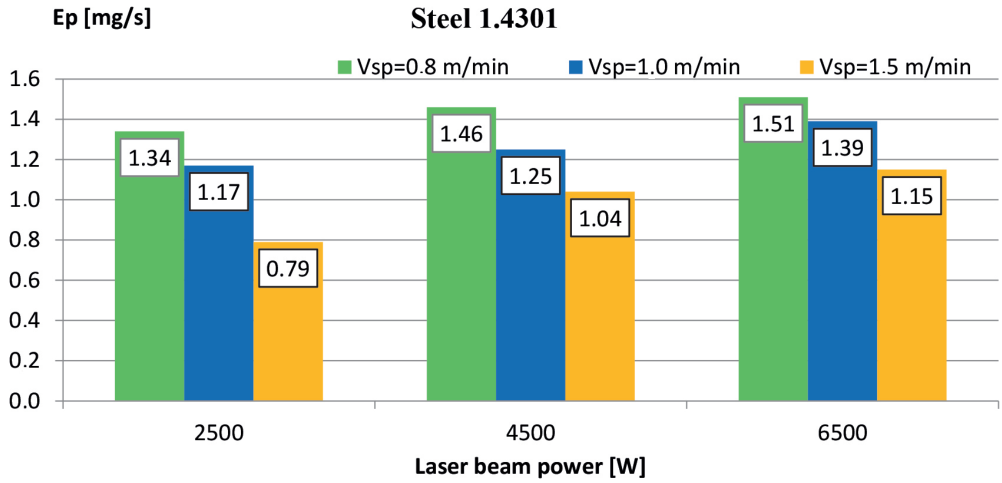

Fig. 7. Effect of laser beam power on the emission of total dust in time during the hybrid welding (HLAW) of steel 1.4301 [7]

Effect of the filler metal wire feed rate

Figure 8 presents data concerning the emission of pollutants in relation to three filler metal wire feed rates (6.5 m/min, 8.5 m/min and 10.5 m/min), corresponding to the amount of the molten filler metal. The remaining technological parameters, i.e. a laser beam power of 4500 W and a welding rate of 1.0 m/min, were constant.

An increase in the filler metal wire feed rate (i.e. the amount of molten filler metal) led to an increase in the emission of total dust.

In relation to a filler metal wire feed rate of 6.5 m/min the emission of dust amounted to 1.01 mg/s. An increase in the filler metal wire feed rate to 8.5 m/min translated into an increase in emission by nearly 25% (1.25 mg/s). An increase in the filler metal wire feed rate to 10.5 m/min led to a total dust emission of 1.41 mg/s, i.e. nearly 40% higher than emission accompanying the process performed using a filler metal wire feed rate of 6.5 m/min and nearly 13% higher than emission generated during the process where the filler metal wire feed rate amounted to 8.5 m/min.

Effect of the welding rate

The effect of the welding rate of the hybrid welding of steel 1.4301 on the emission of total dust is presented in Figure 9. The tests were performed in relation to three values of laser beam power and various welding rates; the filler metal wire feed rate was constant and amounted to 8.5 m/min.

The analysis of the test results revealed that in all of the tests an increase in the welding rate used in the hybrid process led to a decrease in the emission of dust. The same correlation was observed in terms of the laser beam welding process.

The emission of total dust during the welding of steel 1.4301 performed using a welding rate of 0.8 m/min and a laser beam power of 2500 W amounted to 1.34 mg/s. An increase in the welding rate up to 1.0 m/min decreased the emission

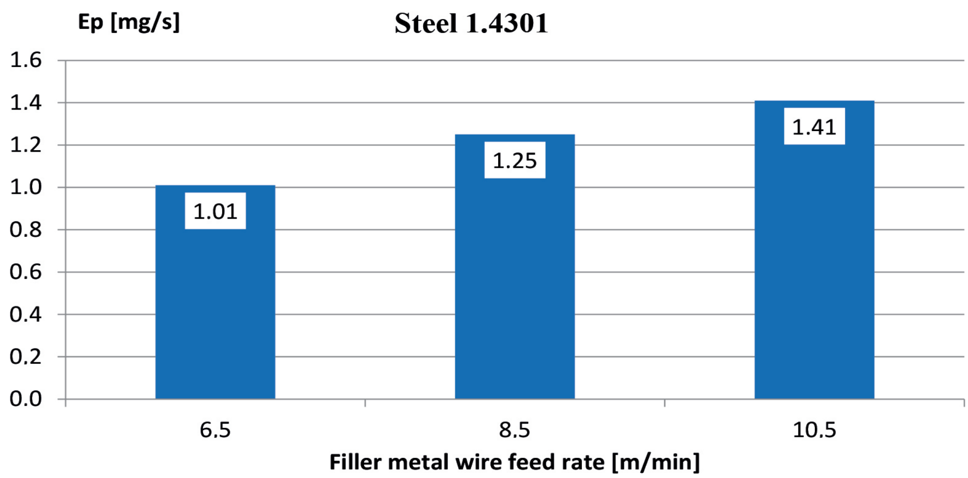

Fig. 8. Effect of the filler metal wire feed rate on the emission of total dust in time during the hybrid welding (HLAW) of steel 1.4301 [7]

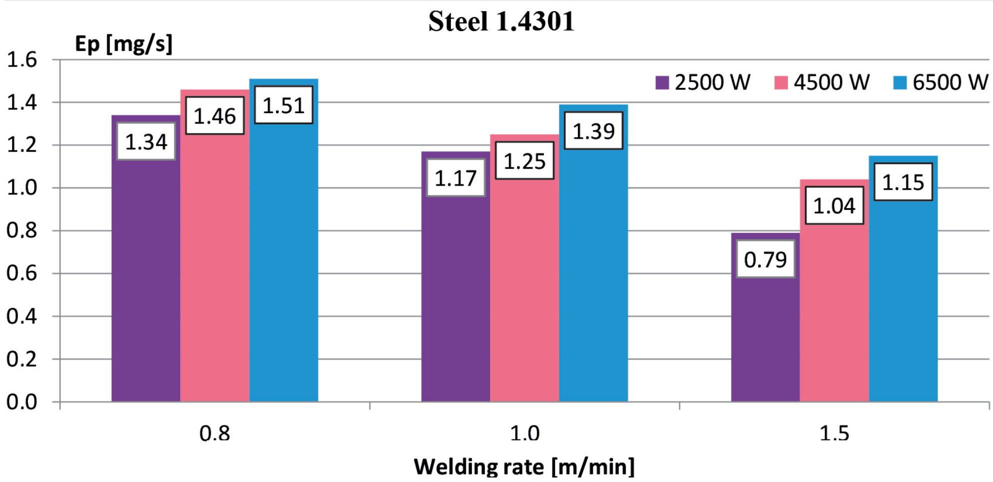

Fig. 9. Effect of the welding rate on the emission of total dust in time during the hybrid welding (HLAW) of steel 1.4301 [7]

of dust by nearly 13% (1.17 mg/s). In relation to a welding rate of 1.5 m/min the emission of total dust amounted to 0.79 mg/s and was by 41% lower than emission accompanying the process performed using a welding rate of 0.8 m/min and by more than 30% lower than emission generated during the process performed using a welding rate of 1.0 m/min.

Comparative analysis of the laser beam welding and HLAW processes

The comparison concerning the emission of total dust during the Ar-shielded laser beam welding and the hybrid welding of stainless steel X5CrNi18-10 is presented in Figure 10. The hybrid welding process involved the use of solid wire 308 L Si having a diameter of 1.2 mm.

The diagrams below contain data concerning the emission of dust pollutants in relation to two (i.e. melt-in and key-hole) laser beam welding techniques and the hybrid welding process as well as the following technological process parameters:

- laser beam power restricted within the range of 2500 W to 6500 W,
- welding rate: 1.0 m/min,
- filler metal wire feed rate V_{dr} = 8.5 m/min (in hybrid welding).

The analysis of test results revealed the effect of the method used in the laser beam welding of steel 1.4301 on the emission of total dust in time. The hybrid welding processes (HLAW) were characterised by the highest emission of total dust in comparison with the two remaining processes. The laser beam welding process was characterised by

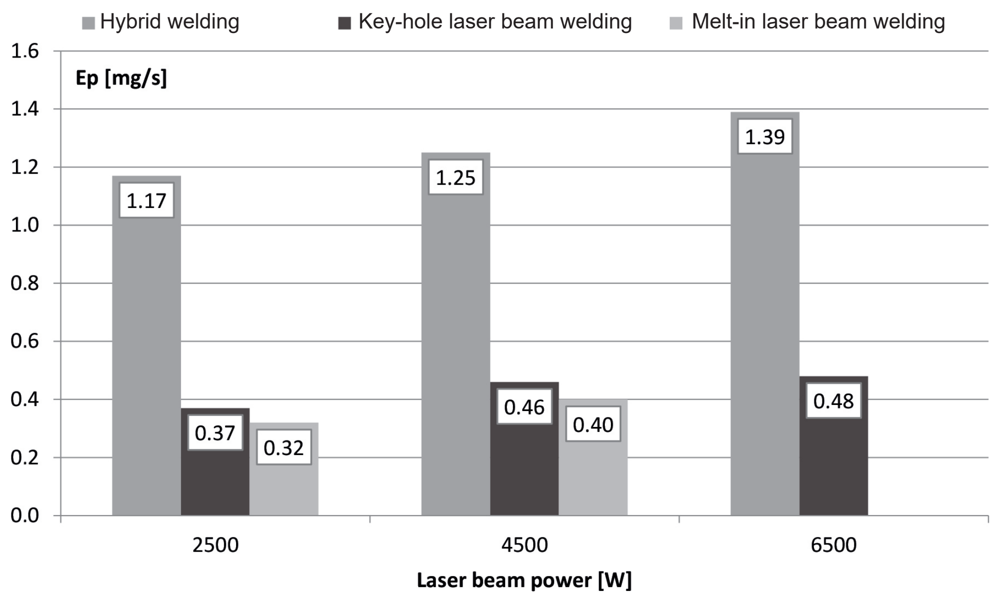

Fig. 10. Comparison of indicators concerning the emission of total dust in time in relation to the laser beam welding and hybrid welding of steel 1.4301 [7]

significantly lower total dust emission, where (as was demonstrated in previous analyses) the indicators obtained in relation to the key-hole technique were higher than those obtained for the melt-in technique. The comparison of the results concerning the emission of total dust in relation to all laser beam power values revealed that the emission accompanying the hybrid welding process was approximately threefold higher than that observed during the key-hole laser beam welding process.

The above-presented significant difference in relation to total dust emission was connected with the technological characteristics of the laser beam and the hybrid (laser + MIG) welding processes. During the hybrid welding process, the formation of dust (i.e. welding fume) resulted from the welding arc effect on the filler metal wire and the laser beam effect on the liquid weld pool. In turn, during the laser beam welding process, the only source of dust emission was the laser beam affecting the base material.

Summary

The analysis of the test results revealed the effect of the technological parameters used during the laser beam welding (i.e. laser beam power and the welding rate) and the hybrid welding (i.e. laser beam power, filler metal wire feed rate and the welding rate) of steel 1.4301 on the emission of dust pollutants (Table 2). The tests also revealed the effect of the laser beam welding technique on the emission of dust pollutants, where the melt-in method proved more favourable in terms of emission reduction.

During hybrid welding, an increase in the filler metal wire feed rate led to the increased emission of total dust. The increased emission (triggered by an increase in the filler metal wire feed rate) resulted from supplying a greater amount of the filler metal, whose evaporation in the liquid metal pool translated into the higher emission of dust pollutants.

An increase in laser beam power triggered an increase in total dust emission. An increase in laser beam power led to the greater depth of penetration, which, in turn, translated into the extension of the liquid metal evaporation area and resulted in the higher emission of total dust. The above-named dependence was observed both during the laser beam and the hybrid welding processes.

In turn, an increase in the welding rate led to a decrease in the emission of total dust. The reduction of welding fume emission resulted from providing a smaller amount of the filler metal per the area unit, which, in turn, translated into the shallower depth of penetration. The smaller area of evaporation resulted in the lower emission of pollutants (in both welding methods subjected to analysis).

Table 2. Effect of technological parameters of the laser beam welding and hybrid welding processes on the emission of total dust

	Increase	Welding fume emission
Key-hole laser beam welding	P	↗
	V_{sp}	↘
Melt-in laser beam welding	P	↗
	V_{sp}	↘
Hybrid welding (HLAW)	P	↗
	V_{dr}	↗
	V_{sp}	↘

↗ – increase; ↘ – decrease, – – no correlation
V_{dr} – filler metal wire feed rate [m/min], V_{sp} – welding rate [m/min] and P – laser beam power [W]

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