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RESEARCH PAPER

New weldable 316L stainless flux-cored wires with reduced Cr(VI) fume emissions: part 2—round robin creating fume emission data sheets

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Abstract

Welding fumes have been found to be carcinogenic and stainless steel welders may be at higher risk due to increased formation of hexavalent chromium (Cr(VI)). The slag-shielded methods, identified to generate most airborne particles and Cr(VI), would potentially be most harmful. With ever-stricter limits set to protect workers, measures to minimize human exposure become crucial. Austenitic stainless steel flux-cored wires of 316L type have been developed with the aim to reduce the toxicity of the welding fume without compromised usability. Collected particles were compared with fumes formed using solid, metal-cored, and standard flux-cored wires. In part 1, the new wires were concluded to have improved weldability, to generate even less Cr(VI) in wt.-% than with solid wire and to be less acute toxic in cultured human bronchial epithelial cells as compared to standard flux-cored wires. In part 2, two additional institutes created fume emission datasheets for the same wires for correlation with the fume data obtained in part 1. The reported values showed large variations between the three laboratories, having a significant effect on the standard deviation. This is suggested to be the result of different welding parameters and various ways to collect and analyze the fume. More stringent specifications on parameter settings and fume collection would be required to increase the accuracy. This means that at present, it may not be possible to compare fume data on datasheets from two different wire producers and care should be taken in interpretation of values given in the available literature. Nevertheless, the laboratories confirmed the same trends for Cr(VI) as presented in part 1.

Keywords Welding fumes · Fume emission rate · Flux-cored wire · Metal-cored wire · Solid wire · Austenitic stainless steel · Hexavalent chromium · Cr(VI) · Manganese

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1 Introduction

Strong evidence suggests that all welding fumes can be carcinogenic and can induce chronic inflammation in the respiratory tract [1–6]. Stainless steel welders are additionally subject to inhalable hexavalent chromium, Cr(VI), reported to increase the risk of health-related issues, such as lung cancer, asthma, and bronchitis [7–13]. Since the base material only contributes 5–10% to the total fume particle mass, the welding consumable composition becomes most important [14, 15]. Fillers containing more Cr typically result in aerosols with higher amounts of Cr(VI) [9, 16–19]. Other elements of concern are nickel (Ni), iron (Fe), and manganese (Mn) [20–23].

The highest emission rate and content of Cr(VI) have been confirmed for shielded metal arc welding (SMAW), but also flux-cored arc welding (FCAW) and gas metal arc welding (GMAW) generate substantial amounts [24, 25]. The general solubility of the fume is significantly higher for the SMAW and FCAW processes than with GMAW [15]. This is of importance as pulmonary toxicity can be associated with soluble forms of transition metals and their doses [27, 28].

The concentration of elements in the welding fume can be significantly higher than what is expected from the electrode composition [16, 28]. Evaporation follows at the high temperatures reached at the electrode tip, causing vapor emission followed by condensation and oxidation [29, 30]. The temperature increases with the welding current, which results in additional fume emissions and Cr(VI) formation [18, 31]. The process parameters thus have a large effect on the formation of aerosols. Each wire manufacturer offers unique formulations using different philosophies. Since various strips, raw materials, and coatings are applied to optimize welding conditions and feedability, also emission rates and Cr(VI) composition vary considerably [17, 18, 32].

Spray arc welding with solid, flux-cored, and metal-cored wires can after parameter adjustments be performed using the same power source, but different shielding gases. The choice of gas is important for the arc transfer, arc stability, spatter formation, material transfer, oxide formation, and loss of alloying elements, but has also been reported to affect the fume formation rate and Cr(VI) content [18, 31, 33, 34]. To improve the arc stability and retain the corrosion resistance and mechanical properties of the stainless weld metal, the GMAW process is preferably welded with Ar + 2–3% CO_2 or multicomponent shielding gases containing helium. Higher amounts of CO_2 have been reported increase the fume generation by impeding the arc transfer [35]. For flux-cored wires, the slag cover protects the melt and individual droplets from oxidation and the shielding gas selected for enhanced arc stability and mechanical properties is usually Ar + 18% CO_2.

Various recommendations and binding occupational exposure limits (OEL) of especially Cr(VI) and Mn exist in most industrial countries to protect workers, and are becoming increasingly stricter as more research is made available [14, 36–39]. To avoid exceeding the OEL given by the local authorities, many welding companies try to theoretically estimate the fume generation for a certain process, to predict the total exposure and determine the maximum allowed welding hours in the workshop. When fume emission datasheets are available for the stainless filler metal, information about the fume emission rate (FER) and the principal components of the welding fume Fe, Cr, Ni, Mn, and Cr(VI) are known. When more filler metal suppliers offer the same product, the emission data offered may become a part of the selection process. Fume can be collected and analyzed as described in, for instance, ISO 15011–1 [40], ISO 10882–1 [41], and AWS F1.2 [32]. ISO 15011–4 [42] gives more details on how to establish fume emission datasheets.

The possibility to reach the highest productivity in all positions with the FCAW process serves as a driving force to decrease the emission rate and the amount of Cr(VI) in the welding fume. Experimental 316L flux-cored wires for reduced Cr(VI) in the fume emissions were investigated in an earlier work [43]. The results demonstrated that fumes containing lower amounts of Cr(VI) were less acute toxic regarding both cytotoxicity and DNA damage compared to the standard wires. However, inflammatory effects were observed in response to the Cr(VI) reduced fumes, likely due to the presence of other toxic components. The weldability of the wires studied was not completely satisfactory and especially the arc stability could be improved. Therefore, the wires have undergone further development to become more user-friendly. The goal was to reduce the fume generation rate, Cr(VI) formation, and toxicity of the respirable particles as compared to the standard flux-cored wire, while maintaining the welding performance. Divided in two papers, the focus in part 1 [44] was on the health aspects of welding fume generated with the newly developed consumables as compared to solid, flux-cored, and metal-cored wires. The particle morphology, composition, and release of metals were determined and correlated to the cytotoxicity in a simulated lung environment. The development was concluded to have been successful with improved weldability, largely reduced Cr(VI) in the welding fume, lower fume emission rate, and substantially reduced cytotoxicity than with standard flux-cored wires. In part 2, three different institutes received solid, flux-cored, and metal-cored wires from the same batches to establish fume datasheets in accordance with ISO 15011–4 [42]. The objective in the round robin was to generate average emission rates and chemical compositions for the collected aerosols and to evaluate the accuracy of analyses performed by various laboratories. The aim was to use the information to investigate if it is possible to compare fume data given on product datasheets from different filler metal producers.

2 Experimental

The investigated Ø 1.2 mm wires included one E316LSi solid wire (SW), one standard E316LT1 flux-cored wire (FW), three new-developed E316LT1 flux-cored wires for fume reduction (FR), and one standard metal-cored wire (MC). The chemical composition of the wires can be found in Table 1.

Wires from the same batch were divided by three institutes to provide fume emission datasheets as given in ISO 15011–4 [42]. Denoted Lab A, B, and C, Lab A was the identical group behind the work in part 1 [44]. Labs B and C are highly experienced in providing fume information to the industry and represent potential sources of the information given on datasheets.

To simulate typical working conditions, the current was set to 200 A for the cored wires. No further instructions were given as all parties already have established procedures for this type of measurement. Lab B and C also determined the FER and chemical composition at 270 A, which represents 90% of the maximum recommended current for the standard flux-cored wire. The parent material plates had a dimension of 50 × 10 × 250 mm. Lab A chose the matching AISI 316L (EN 1.4404/UNS S31600), Lab B the non-alloyed structural steel S235JR (1.0028/ASTM A 283C), and Lab C an austenitic stainless steel of AISI 304 (1.4301/UNS S30400) type. Detailed information about the chemical composition was not provided.

All welding was carried out bead-on-plate with DC + polarity and in spray arc mode. The shielding gas was Ar + 2.5% CO_2 for the solid and metal-cored wires and Ar + 18% CO_2 for the flux-cored wires. All reported welding parameters from the three laboratories are presented in Table 2. Three different welding machines were used: an EWM alpha Q 552 PULS MM RC (lab A), an EWM Titan XQ 400 puls (lab B), and a Fronius VR7000 CMT (lab C).

Fume particles were collected on filters as described in ISO 15011–1 [40]. Lab A selected glass fiber filters without binders (Macherey–Nagel MN 85/90 BF) for determination of the fume emission rate (FER) and cellulose filters of Macherey–Nagel MN 640 w for chemical composition (Ø 240 mm). The latter had an ash content < 0.01 wt.-% and was chosen after confirming low background contamination. Similarly, lab B applied a glass fiber filter and a Macherey–Nagel MN 640 w cellulose filter (Ø 150 mm). The motivation for selecting different filters was that cellulose filters may be hygroscopic and thereby prevent consistent gravimetric measurements, while chemical analysis after dissolution is not feasible with glass fiber filters due to chemical reactions. Lab C collected all fumes using a MG 227 glass fiber filter with binders from Sartorius. Welding was carried out until a sufficient mass of particles was collected on each filter. The FER expressed as in mg/s was calculated as the filter weight difference before and after fume collection, divided by the welding duration.

The key components of the welding fume Fe, Cr, Ni, and Mn were analyzed after extraction in aqua regia. Lab A used inductively coupled plasma mass spectroscopy (ICP-MS) (Agilent 7700x, Agilent Technology, Santa Clara, CA) to measure the fume composition of the wires FR1, FR2, FR3, and MC and flame atomic absorption spectroscopy (AAS) (AAnalyst 800, Perkin Elmer, Waltham, MA) for the wires SW and FW. Lab B performed the chemical analysis using flame AAS (novaAA® 300, Analytik Jena GmbH, Jena, Germany) and Lab C inductively coupled plasma optical emission spectroscopy (ICP-OES) (Agilent ICP-OES-715-ES, Agilent Technology, Santa Clara, CA). To dissolve Cr(VI) for analysis, lab A immersed filter cutouts of 2 × 2 cm size in phosphate buffered saline (PBS) and quantified Cr(VI) through a pink complex with 1.5-diphenylcarbazide (DPC). Cr(VI) concentrations were determined by UV–Vis spectroscopy using an Cary 8454 UV–vis (Agilent Technology, Santa Clara, CA) instrument for wires FR1, FR2, FR3, and MC, and a Jenway 6300 (Staffordshire, UK) for wires SW and FW. More detailed information regarding the procedures used by lab A can be found in part 1 [44]. Lab B followed NIOSH NMAM 7605 [45] and measured the Cr(VI) content

Table 1 Chemical composition of filler wires, wt.-%

	Designation*	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
SW	ER316LSi	0.008	0.83	1.67	0.017	0.011	18.37	12.12	2.64	0.08
FW	E316LT1	0.022	0.72	1.53	0.024	0.008	18.68	11.86	2.72	0.12
FR1	E316LT1	0.024	0.83	1.35	0.024	0.009	18.25	11.82	2.87	0.12
FR2	E316LT1	0.023	0.79	1.31	0.023	0.009	18.20	11.60	2.55	0.12
FR3	E316LT1	0.029	0.84	1.36	0.024	0.009	18.25	11.73	2.86	0.12
MC	EC316L	0.025	0.44	1.22	0.021	0.011	18.67	12.17	2.59	0.03

*Classification in accordance with the American Welding Society standards AWS 5.9 for solid wires and AWS 5.22 for cored wires

Table 2 Welding parameters used for collecting fume (*N/A* no information provided)

Wire	Shielding gas	Wire feed rate, m/min	Welding speed, m/min	Arc length, mm	Stick-out, mm	I, A	U, V	Gas flow, l/min	Lab
SW	Ar+2.5% CO_2	N/A	0.80	3–4	18	265	28.0	18	C
SW	Ar+2.5% CO_2	10.0	0.40	~3*	20	265	28.2	16	A
SW	Ar+2.5% CO_2	N/A	0.55	N/A	20	290	28.3	18	B
SW	Ar+2.5% CO_2	N/A	0.55	N/A	20	339	28.4	18	B
FW	Ar+18% CO_2	11.7	0.80	3–4	20	207	29.5	18	C
FW	Ar+18% CO_2	10.0	0.40	~3*	20	190	29.1	16	A
FW	Ar+18% CO_2	18.5	0.80	3–4	20	267	35.2	18	C
FR1	Ar+18% CO_2	12.3	0.80	3–4	20	200	28.5	18	C
FR1	Ar+18% CO_2	10.0	0.40	~3*	20	191	30.3	16	A
FR1	Ar+18% CO_2	11.0	0.55	3.8*	18	201	29.5	18	B
FR1	Ar+18% CO_2	11.8	0.55	2.6*	18	212	26.5	18	B
FR1	Ar+18% CO_2	18.6	0.80	3–4	20	263	32.6	18	C
FR1	Ar+18% CO_2	16.0	0.55	N/A	15	267	29.3	18	B
FR2	Ar+18% CO_2	12.3	0.80	3–4	20	205	28.6	18	C
FR2	Ar+18% CO_2	10.0	0.40	~3*	20	190	29.3	16	A
FR2	Ar+18% CO_2	11.0	0.55	3.9	18	205	30.4	18	B
FR2	Ar+18% CO_2	11.8	0.55	2.6	18	204	26.7	18	B
FR2	Ar+18% CO_2	18.6	0.80	3–4	20	272	32.8	18	C
FR2	Ar+18% CO_2	16.0	0.55	N/A	15	264	29.4	18	B
FR3	Ar+18% CO_2	12.0	0.80	3–4	20	209	28.2	18	C
FR3	Ar+18% CO_2	10.0	0.40	~3*	20	190	29.0	16	A
FR3	Ar+18% CO_2	11.0	0.55	3.8	18	204	29.5	18	B
FR3	Ar+18% CO_2	11.8	0.55	2.6	18	203	26.7	18	B
FR3	Ar+18% CO_2	18.3	0.80	3–4	20	273	31.9	18	C
FR3	Ar+18% CO_2	16.0	0.55	N/A	15	267	29.4	18	B
MC	Ar+2.5% CO_2	8.5	0.80	3–4	20	200	23.8	18	C
MC	Ar+2.5% CO_2	10.0	0.40	~3*	20	220	28.2	16	A
MC	Ar+2.5% CO_2	8.0	0.55	3.7*	18	203	26.1	18	B
MC	Ar+2.5% CO_2	13.5	0.80	3–4	20	267	26.1	18	C
MC	Ar+2.5% CO_2	11.7	0.55	4.7*	18	263	28.8	18	B

*Controlled with high-speed imaging

by means of flame AAS (novaAA® 300, Analytik Jena GmbH, Jena, Germany). Lab C applied ISO 16740 [46, 47] in combination with ICP-OES (Agilent ICP-OES-715-ES, Agilent Technology, Santa Clara, CA). For the chemical compositions, labs A and B repeated the procedure for three filters for mean values and standard deviation, while lab C analyzed the values for one filter only.

3 Results and discussion

3.1 Welding parameters

When comparing the welding parameters in the round robin test, it is clear that the internal settings may not be the same for all laboratories. For the flux-cored wires, the wire feeding rates selected to reach 200 and 270 A were 10.0–12.3 and 16.0–18.6 m/min, respectively. The stick-out for each wire ranged from 15 to 20 mm and the welding speed was 0.40–0.80 m/min. Slower welding would mean deeper penetration and possibly more influence of the parent material. Höfer et al. [48] reported lower FER from stainless cored wires when increasing the welding speed. ISO 15011–1 [40] suggests that the welding speed should be set by an experienced welder to provide a visually satisfactory weld deposit and gives a typical range of 0.25–0.30 m/min. ISO 15011–4 [42] mentions that the welding speed has little effect on the results and that it is appropriate to carry out tests using an optimum welding speed, as established by an experienced welder. For 1.2 mm diameter wires, ISO 15011–4 [42] states that the distance between the contact tip and the workpiece should be 18 mm and 20 mm for solid and cored wires, respectively. This was supported for flux-cored wires in the work of Höfer et al. [49], but for metal-cored wires, lower FER were measured at both 18 and 22 mm.

While the pre-defined current was rather constant, the voltage range deviated up to 5 V for the same wire tested. The combination of many variables and limited data makes the interpretation challenging. As for example, 26.1 V was used for welding the MC wire both at 200 A by lab B and at 270 A by lab C. The largest effect was observed when the arc length had not been optimized to the preferred 3–4 mm. It suggests that the individual operator can largely affect the outcome. Use of high-speed imaging was efficient to confirm that the process was stable and to minimize the FER [50]. The fume formation is related to the arc stability found at an optimal arc length and can increase at both too low and too high voltage [31, 34, 51]. There is a correlation between arc stability, fume, and spatter formation, where both the spatter and fume generation increase with arc instability [52, 53]. In GMAW, the voltage has also been reported to influence the amount of ultra-fine-sized particles and the concentration of Mn [54].

The shielding gas flow of 16–18 L/min was within the recommendation of the filler metal supplier and is not expected to have a noticeable effect on the FER and chemical composition [42].

3.2 Fume emission data from three different laboratories

Table 3 shows the emission rate and chemical composition for the fume collected and analyzed. The voltage increased and the FER decreased with longer arc length

Table 3 Fume emission rates (FER) and measured chemical compositions of fume particles collected on filters

Wire	Arc length mm	I, A	U, V	FER, mg/s	Fe, %	Mn, %	Ni, %	Cr, %	Cr(VI), %	Cr(VI) mg/s	Mn mg/s	Lab
SW	3–4	265	28.0	2.0	34	14	4.4	11	0.7	0.014	0.28	C
SW	~3*	265	28.2	N/A*	11 ± 5.1	3.4 ± 0.534	1.6 ± 0.184	1.9 ± 0.80	0.33 ± 0.11	N/A	N/A	A
SW	N/A	290	28.3	1.5	19	4.6	8.1	11	0.8	0.012	0.069	B
SW	N/A	339	28.4	1.8	19	4.5	7.6	10	0.8	0.014	0.081	B
FW	3–4	207	29.5	5.5 ± 0.34	14	8.1	1.4	5.7	1.3	0.072	0.44	C
FW	~3*	190	29.1	N/A*	4.9 ± 0.11	8.7 ± 0.18	0.50 ± 0.027	1.1 ± 0.020	1.4 ± 0.025	N/A	N/A	A
FW	3–4	267	35.2	7.5 ± 0.4	17	6.6	1.5	7.5	2.5	0.19	0.49	C
FR1	3–4	200	28.5	3.7 ± 0.18	17	9.2	2.5	5.1	0.046	0.0017	0.34	C
FR1	~3*	191	30.3	3.3 ± 0.06	7.0 ± 1.3	8.4 ± 1.07	0.40 ± 0.015	1.1 ± 0.099	0.11 ± 0.013	0.0038	0.28	A
FR1	3.8*	201	29.5	3.2 ± 0.08	11 ± 0.1	9.0 ± 0.23	1.5 ± 0.03	9.0 ± 0.09	0.14 ± 0.2	0.0045	0.29	B
FR1	2.6*	212	26.5	5.4 ± 0.4	21 ± 0.3	9.0 ± 0.10	2.9 ± 0.03	9.0 ± 0.10	0.15 ± 0.002	0.0081	0.49	B
FR1	3–4	263	32.6	4.4 ± 0.21	17	8.3	1.6	6.0	0.18	0.0079	0.36	C
FR1	N/A	267	29.3	3.8 ± 0.3	18 ± 0.3	7.3 ± 0.11	1.9 ± 0.03	9.2 ± 0.1	0.11 ± 0.02	0.0042	0.28	B
FR2	3–4	205	28.6	3.5 ± 0.15	15	9.8	1.5	4.4	0.027	0.00090	0.34	C
FR2	~3*	190	29.3	2.9 ± 0.08	7.8 ± 0.93	8.4 ± 1.1	0.53 ± 0.081	1.1 ± 0.17	0.15 ± 0.015	0.0043	0.25	A
FR2	3.9	205	30.1	3.1 ± 0.09	11 ± 0.10	9.6 ± 0.06	1.3 ± 0.03	8.5 ± 0.2	0.18 ± 0.002	0.0056	0.30	B
FR2	2.6	204	26.7	5.4 ± 0.1	21 ± 0.2	7.7 ± 0.10	3.0 ± 0.04	9.0 ± 0.19	0.23 ± 0.001	0.012	0.42	B
FR2	3–4	272	32.8	4.7 ± 0.23	18	7.5	1.5	6.4	0.24	0.011	0.35	C
FR2	N/A	264	29.4	4.2 ± 0.1	16 ± 0.3	7.5 ± 0.10	1.9 ± 0.03	8.7 ± 0.19	0.14 ± 0.002	0.0059	0.32	B
FR3	3–4	209	28.2	3.1 ± 0.17	15	9.8	0.17	6.3	0.058	0.0018	0.30	C
FR3	~3*	190	29.0	3.0 ± 0.1	6.9 ± 0.67	8.9 ± 0.93	0.49 ± 0.034	1.1 ± 0.084	0.084 ± 0.022	0.0025	0.26	A
FR3	3.8	204	29.5	3.0 ± 0.02	11 ± 0.23	9.6 ± 0.09	1.4 ± 0.02	8.6 ± 0.18	0.10 ± 0.002	0.0030	0.29	B
FR3	2.6	203	26.7	5.2 ± 0.3	22 ± 0.1	6.7 ± 0.10	2.9 ± 0.02	9.7 ± 0.11	0.26 ± 0.003	0.014	0.35	B
FR3	3–4	273	31.9	4.0 ± 0.22	18	9.1	1.4	6.7	0.32	0.013	0.36	C
FR3	N/A	267	29.4	4.2 ± 0.1	20 ± 0.3	7.8 ± 0.09	1.9 ± 0.03	9.1 ± 0.2	0.20 ± 0.001	0.0084	0.33	B
MC	3–4	200	23.8	1.6 ± 0.07	21	11	3.2	6.7	0.65	0.010	0.17	C
MC	~3*	220	28.2	1.5 ± 0.06	16 ± 1.5	13 ± 1.2	1.8 ± 0.20	3.8 ± 0.41	0.11 ± 0.015	0.0016	0.20	A
MC	3.7*	203	26.1	1.3 ± 0.1	28 ± 0.3	10 ± 0.2	5.1 ± 0.1	12 ± 0.4	0.23 ± 0.001	0.0030	0.13	B
MC	3–4	267	26.1	1.5 ± 0.15	33	12	5.5	6.9	0.56	0.0084	0.17	C
MC	4.7*	263	28.8	1.7 ± 0.1	30 ± 0.4	8.9 ± 0.1	4.8 ± 0.1	10 ± 0.4	0.36 ± 0.004	0.0061	0.15	B

*Values were obtained, but the institute reported problems with low retention capacity until an optimum of 3–4 mm was reached through the arc length correction function. When the arc length was shorter than 3 mm, the contents of Mn decreased and Cr increased slightly for wires FR1, FR2, and FR3. The highest amounts of welding aerosols were collected for FW and the lowest for the wires SW and MC. The FER increased when applying higher currents. For the flux-cored wires, for which the arc length was within the recommended 3–4 mm, the fume contents of Cr(VI) increased and Mn decreased with the current. The opposite results were obtained for the MC wire, where the Mn increased and Cr(VI) decreased. The SW and MC wires generally generated higher Fe and Ni contents, while most Cr(VI) was observed for FW. At 270 A, all cored wires showed more Cr(VI) when 304 was used as base metal as compared to S235JR.

The values in Table 3 were combined after removing the data generated with an insufficient arc length (2.6 mm), and are shown in Fig. 1. The standard deviation was fairly large, but some tendencies could be discerned. The highest FER and Cr(VI) were measured for the standard flux-cored wire FW. Wires SW and MC showed the highest amount of Fe, Ni, and Cr, but the lowest Mn content per time unit. The three fume-reduced wires FR1, FR2, and FR3 contained the least amount of Cr(VI) in wt.-%, but the same amount as MC when expressed as amount per second. More Mn was produced in mg/s compared with the SW and MC wires, but less than with FW.

The measurements of fume generation rate and resulting chemical composition showed noteworthy deviations. Apart from the various power sources, welding parameters, and parent metals used by the three laboratories, the process conditions for fume collection and methods for chemical analysis may contribute.

As described in ISO 15011–1 [40], different designs of test chambers and extraction units exist. It is not known which exact type was utilized by the different institutes or which capacity the equipment had. The laboratories may also have had different set ups where either the torch or the workpiece can be moving.

A critical parameter is the choice of filter for the measurements, as the ability to retain particles will affect the fume rates [31]. ISO 15011–1 [40] recommends glass and quartz filters for fume emission rate testing as these provide good mass stability with respect to humidity, but for chemical analysis, cellulose filters are preferred. Höfer et al. [48] noted large differences in estimated FER between various glass fiber filters. In the present work, lab A confirmed that the choice of filter could be critical to determining the fume

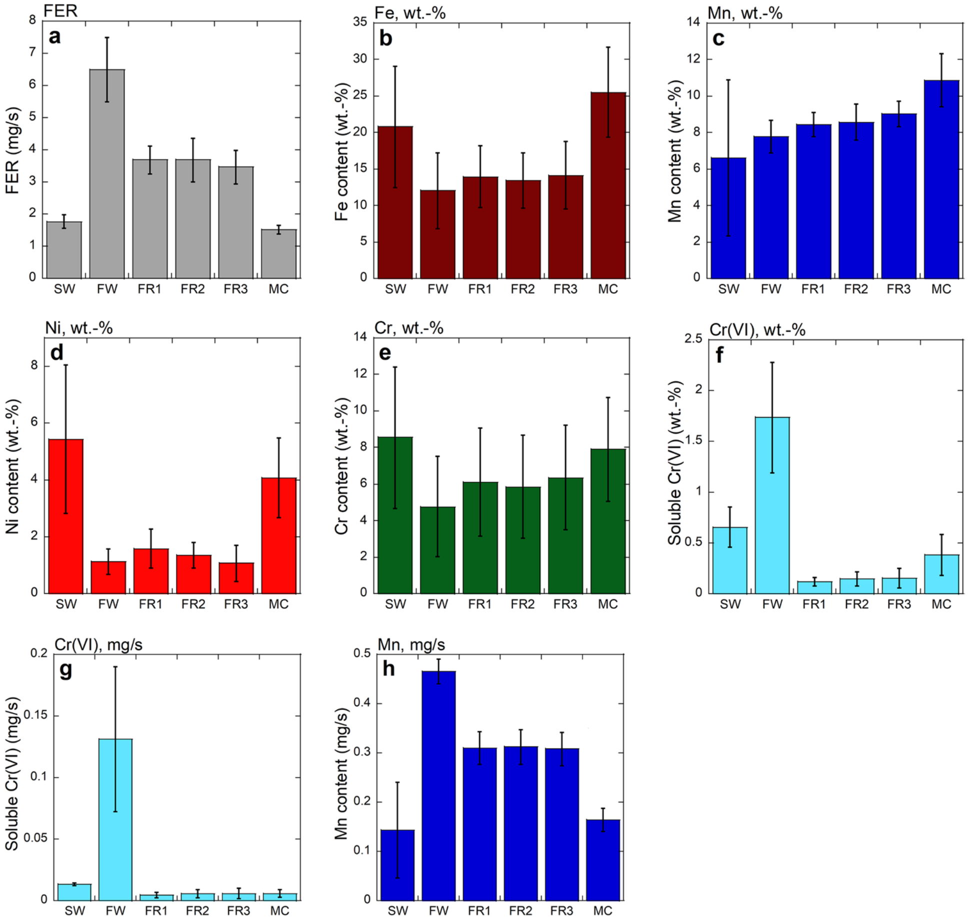

Fig. 1 Combined FER and relative chemical composition of Fe, Mn, Ni, Cr, and Cr(VI) (wt.-%) and amounts of Cr(VI) and Mn per second (mg/s) in the different fumes

composition. When different cellulose and glass fiber filters were tested on their background contamination in PBS, there was some release of both Fe and Ni from fresh filters. The chosen cellulose filter type, a Macherey Nagel MN 640 w, showed very low levels of contamination. AWS F1.2 [32] suggests using pre-dried glass fiber filters to determine the FER and cellulose filters for sample collection for analysis. The document states later that the paper filters are not acceptable for measuring Cr(VI), but gives no recommendation on suitable alternative filters. The suggested revision of ISO 15011–1 that was withdrawn in 2015 mentions that the cellulose filters may react with hexavalent chromium compounds and cause hexavalent chromium to be reduced to trivalent chromium during the process. Instead, filters made of PVC, PVF, or PTFE were mentioned as suitable replacements. As this standard revision was never implemented, this information may not have been available to the institutes in this round-robin work.

The different extraction and digestion methods may affect the measured chemical composition. In a previous work by Hedberg et al. [19], the PBS procedure applied by lab A was compared to ISO 16740 [47] used by lab C. The ranking trend was equal for both methodologies, but consistently less Cr(VI) was released during the ISO 16740 procedure and this could partly be explained by shorter extraction time. The analysis of the key components in the welding fume was performed with ICP-MS, flame AAS, ICP-OES, and UV–Vis spectroscopy. As not only the methods varied, but also the models, proper calibration of the instruments is required for high precision, and there might have been differences in sensitivity and detection limits. Another important aspect is the time between the collection of the fume and the actual analysis, where the concentration of Cr(VI) may be altered, most likely by reduction to Cr(III) in the presence of water or humid air [55, 56]. Antonini et al. [26] pointed out that freshly generated stainless steel welding fume more readily induces lung inflammation in rats as compared to aged fume. The duration was not reported by the institutes in this work, but as none of the labs carried out the analysis in-house, it can be assumed that the fume samples were not analyzed immediately. This may have affected the quantitative results somewhat, though the ranking is still assumed to be accurate. Lab A used air-sealed packaging for the filters directly after fume collection and stored the filters in a desiccator (lower relative humidity than 10%) prior to and between analyses. Using this procedure, the Cr(VI) release was not altered for filters tested directly and after one year of storage [19, 43].

For the measurement of the chemical composition of the fume and FER, ISO 15011–4 [42] states that a test piece of unalloyed steel should be used to generate fumes also for high-alloyed materials. In reality, some flux-cored wires are used for overlay welding of mild steel, but the majority is applied for joining of stainless plates. As the dilution from the parent material may contribute to evaporation [57] and fume composition [51], it would be more relevant to test the actual base material intended for the specific application. This is reflected in the majority of the fume emission studies, where the parent material chosen to evaluate stainless fillers normally also is the matching high-alloyed grade [58]. Most fillers can be used for a wide range of alloys. To simplify comparison of different welding methods and filler metals, the austenitic stainless steel 304 is frequently chosen to have a base material plate containing Cr and Ni. In ISO 15011–1 [40], the base metal is not specified and leaves room for interpretation. The different qualified laboratories in this work have different philosophies—lab B follows the ISO 15011–4 standard and uses an unalloyed steel, while labs A and C adapt their procedure to increase the relevance of the test with a stainless base metal.

3.3 Other variables affecting values given on fume datasheets

If a stainless steel flux-cored wire of 1.2 mm diameter is made with a somewhat thinner strip, a higher amount of slag formers will be present than in a wire of thicker sheath. With increased filling ratio, the amount of fume increases, especially at lower amps [59]. This typically means that the former generates more welding fume for a given current, while the latter can be loaded with more amps and then generate additional fumes. It is clear that the FER increases with the current. ISO 15011–4 [42] states that the measurements should be carried out at 90% of the maximum of the current range given by the manufacturer. It does not necessarily help if these values are intentionally lowered as operators often apply currents and voltages, which exceed the suggested values, to enhance the productivity [17]. A wire allowing higher wire feeding rate may save the welder a few beads when multipass welding thicker materials. The deposition rate and hence the productivity increase with wire feed speed and welding current, but at the same time higher feeding rate and current cause a higher fume formation [59]. Similarly, the use of larger wire diameters may also increase the FER [42, 60]. Also, the stick-out and contact tip-to-work piece distance may have minor effects.

The choice of shielding gas affects the generation of welding fume. While the majority of the flux-cored wires have dual classifications and can be run on both mixed gas and on straight CO_2, Ar + 18–25% CO_2 typically results in the most attractive surface appearance, highest toughness, and lowest FER [18, 32, 49, 61, 62]. For fume emission measurements, ISO 15011–4 [42] suggests to use the gas type recommended by the manufacturer or, if more than one shielding gas is recommended, the most oxidizing mixture. As most gas-shielded flux-cored wires can be used with both mixed gas and straight CO_2, this means that the fume emission datasheet should always be created using 100% CO_2. This information would, however, not be relevant for the companies welding with Ar + 18–25% CO_2, so the datasheets should clearly indicate which shielding gas has been used, and preferably present FER data for all recommended gases.

The direction of welding is rarely mentioned in the literature, but can be most critical for the final result [61]. The GMAW process is normally welded pushing (forehand) to avoid cold laps in the flat and horizontal positions. FCAW is instead welded with the backhand (trailing) technique for good weld pool control and defect-free side-wall fusion. Dragging the torch improves slag detachability, minimizes spatter formation, and gives a deeper penetration. When flux-cored wires are pushed, the risk increases to form large slag inclusions, slag pockets, and lack of fusion. In the standards for measuring fume, there is no information given about the recommended welding direction. ISO 15011–4 [42] does not bring up the welding direction at all. In ISO 15011–1 [40], it is stated that welding with GMAW, FCAW, and metal-cored arc welding (MCAW) can be carried out using either a pushing or pulling technique, and in AWS F1.2 [32], there is an example of a solid wire that should be dragged. In reality, welders may use both leading and dragging techniques, but the effect on fume formation has not been quantified.

It appears that the industry would benefit from a more specific, unified, and stricter standard for fume emission rate measurements and determination of the chemical composition. More research on the effect of the different parameters on the fume generation and resulting content would be advantageous for further suggestions.

3.4 Validation of fume emission datasheets

The round robin results in this work and room for interpretation in the standards indicate that two different fume emission datasheets may not be directly compared. The results may vary considerably depending on where, how, and by whom the measurements are made. It may be possible to rank wires by having the same laboratory to test them after specifying the parameters and especially the arc length. Generated values may, however, not be completely representative of the actual process in the workshop as already small changes in welding parameters can have a large influence on the emissions [25]. Manual welding inheritably means variations in arc length and there may be as many variations in the settings as there are welders. Robotic or automated welding would therefore be preferred to minimize both deviations and exposure [63].

Part 1 of this paper series presented new 316L flux-cored wires with good weldability, lower fume emission rate, largely reduced Cr(VI) in the welding fume, and substantially reduced cytotoxicity, when compared with standard flux-cored wires. Despite the variations induced by different welding parameters and laboratory settings in the round robin test presented here in part 2, these conclusions were confirmed by all three laboratories.

4 Conclusions

Austenitic flux-cored wires of E316LT1 type have been developed to reduce the amount of Cr(VI) in the fume emissions. Three experienced laboratories received the new wires together with 316L standard flux-cored, solid, and metal-cored wires to produce fume emission datasheets.

The values obtained from the different institutes showed substantial differences and the standard deviation became significant. Nevertheless, some trends could be seen. The standard flux-cored wire clearly generated the highest FER and Cr(VI). With the new formulation, the fume formation could on average be reduced by 45% and the Cr(VI) content by more than 90%. The results for the three optimized wires were very similar and the weldability was satisfactory with stable arc transfer. The solid and metal-cored wires showed the lowest fume generation rate and highest Fe and Ni contents.

Large inter-laboratory deviations in determined emission rates and chemical compositions are explained by differences in actual welding parameters, filters, and base materials, but also extraction and digestion methods. A more unified specification would be required to ensure that suitable settings are used. Apart from the classic parameters current, wire feeding rate, and travel speed, the arc length and welding direction control the arc stability, being decisive for the final result. In practice, this means that it may not be possible to compare fume data from two different wire manufacturers and care should be taken in interpretation of values given in the available literature.

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