Fume emission when welding stainless steel

Health aspects of chromium compounds in welding fume are a subject of much current concern, and hence there is particular interest in measurements of fume emission in stainless steel welding. J Moreton, E A Smårs and K R Spiller measured fume emission rates from a variety of stainless consumables, and demonstrated effects of changing welding process and conditions.

A previous article described measurement of fume emission rates using a fume box technique, and subsequent chemical analysis of fumes from a range of open arc welding processes.[1] The feasibility of testing consumables from different processes by the fume box method allows between-process comparisons to be made for fume emission potential, especially in cases where the quantity and/or toxicity of the fume may be critical. With the current worldwide concern regarding health aspects of chromium compounds in welding fume,[2] measurements of fume emission during welding of stainless steel are of special interest.

In the study reported here, fume emission rate measurements were made by the fume box technique[3] on typical 18:10:3 Cr:Ni:Mo stainless consumables, as follows:

A—manual metal arc (MMA) electrode;

B—metal active gas (MAG) consumable with Ar-2%O_2 shielding gas;

C—flux cored wire (FCW) self-shielded consumable;

D—metal cored wire (MCW) gas shielded consumable.

Specifications are given in Table 1. All these consumables can be used for the same welding application. The MAG consumable B was also tested (B1-B5) under five different welding conditions, to provide an indication of the possible range of fume emission rates for a single consumable within a process. Because of the possibilities of using dip, globular, spray and pulse modes of metal transfer, the range of corresponding fume emission rates with a given MAG consumable is probably greater than with those consumables used for the other processes.

Although there is a considerable practical demand for a fume emission rate test method, no standard for such a method currently exists in the UK. The method used is derived from the Swedish Standard[4] for measurement of fume emission rates and related parameters for MMA consumables only. Therefore, the work described employs what are currently Welding Institute in-house test methods. The results, however, have a general comparative significance.

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EMISSION RATE MEASUREMENTS

Welding fume emission rate (FER) measurements were made on consumables A, B, C and D using the fume box described in ref. 1. Horizontal-vertical fillet welds were made on 250×50×10mm, 316 stainless steel testpieces in the fume box, and the particulate fume emitted was extracted on to a 240mm diameter preweighed filter. The weight of fume collected per unit arcing time (or per unit weight of deposited metal) gives the FER of the consumable.

Welding details are given in Table 1. Results of the fume analyses are given in Table 2. The analysis of the stainless steel base plate materials used in the test, and of the consumables (coatings, cores, sheaths and wires) was made by Xray fluorescence spectroscopy, and is reported in Table 3. Because of the diversity of welding conditions required by the different consumables, it was not possible to use the same welding equipment for all tests. The fume emission rate of the MAG wire, B, was investigated under a range of parameters, with Ar-2%O_2 gas shield: dip transfer, B1a and B1b, globular, B and B2, spray, B3 and B4, and pulse, B5.

For the MAG welding tests (B1-B5 inclusive), it was considered important to define closely the mode of transfer of each test, not only in terms of monitored welding parameters (Table 1), but also to ensure that the welds produced in the fume box were of a comparable standard to those common in industry. Prior to welding, the required parameters for the various modes of metal transfer were established. The fillet weld specimens were then completed by a welder of average ability who had experience in using the gas shielded arc welding process. Tests B1a and B1b, using a dip transfer condition are replicate sets using two different welding power sources and illustrate that possible varying inductances and widely differing open circuit voltages at constant arc voltage appear not to influence the FER results. It was not practicable in either power source to adjust the inductance, this being a preset factor within the power units for a given wire diameter. In all MAG tests, each fillet weld was made using the conventional leftward technique, *i.e.* traversing the welding gun from right to left, the gun preceding the deposited weld bead. Throughout the trials the nozzle of the welding gun to work distance was maintained to within 10-15mm. Observations of the welding operation and of the fillet welds produced using each of the selected modes of metal transfer and associated welding parameters clearly indicated that acceptable welds were being produced. On completion of the welding programme, the fillet welded specimens were seeded into their representative groups and visually examined, with measurements being taken to determine the leg lengths of each weld. The results of this examination, albeit a subjective one, are summarised in Table 4.

For each set of experiments, A-D, B1-B5, gravimetric tests were made with humidity-stable glass fibre filters. The filters were weighed before and after welding, as were the corresponding test plates. These weights, and the relevant arcing times were used to calculate the fume emission rates illustrated in Fig. 1 in terms of mg/g of deposited metal and mg/sec of arcing time.

For the MMA consumable (A), nominal arcing time was 60sec, for the MAG wire (B) it was usually 30sec, and for the FCW and MCW consumables, C and D respectively, it was reduced to 20sec.

During sampling, for each experiment, a bulk sample of at least 1g fume was collected where possible, on a 240mm diameter filter paper. This fume was removed by careful brushing with a camel hair brush, and stored in a dry box for analysis, by the following techniques:

a Fluorine (samples A and B only) by pyrohydrolysis, using a volumetric finish with thorium nitrate;

Table 1 Consumables and welding parameters

Code	Process	Standard grade	Dia, mm	Welding parameters: Current, A	Voltage, V	O/C, V	WFS, m/min	Stickout, mm	Gas shield	Gas flow, l/min
A	Manual metal arc (MMA)	BS 2926 (1970) 19 12 3LR AWS A5. 4 81 E316L-16	4.0	145±10	28-29	70DC+				
B	Gas shielded solid wire (MAG)	BS 2901 Pt 2, 316S 93 AWS A5. 9 77 ER316L Si	1.2	190±10	19-20	35DC+	6.0	15	Ar/2%O_2	16
C	Flux cored wire (FCW) self-shielded	AWS A5. 22 80 E316LT-3	2.0	250±10	24	37DC+	5.5	20-25		
D	Metal cored wire (MCW) gas shielded	AWS A5. 22 80 E316LT, 1, 2, 3	1.6	290±10	24-25	32DC+	7.2	15-20	Ar/2%O_2	16
B1a	MAG dip transfer	As B	1.2	150-160	17.9 (mean)	68DC+	4.2	10	Ar/2%O_2	16
B1b	MAG dip transfer	As B	1.2	150-160	17.0 (mean)	26DC+	4.8	10	Ar/2%O_2	16
B2	MAG globular transfer	As B	1.2	210-220	21.6 (mean)	70DC+	6.7	15	Ar/2%O_2	16
B3	MAG spray transfer	As B	1.2	275-280	25.2 (mean)	36DC+	11.6	15	Ar/2%O_2	16
B4	MAG spray transfer	As B	1.2	280-290	27.6 (mean)	41DC+	9.3	15	Ar/2%O_2	16
B5	MAG pulse transfer	As B	1.2	165-170 (mean)	22.0 (mean)	74DC+	4.6	10	Ar/2%O_2	16

Table 2 Chemical analyses of fumes, wt %

Code	Si	Ti	Zr	Al	Fe	Mn	Ca	Mg	Na	K	Li	F	Ba	Ni	Mo	Nb	V	Cu	Cr	Total CrVI
A	10.0	2.1	<0.2	1.4	5.1	5.0	0.4	<0.2	7.3	19.9	<0.2	14.9	<0.1	0.4	<0.2	<0.1	<0.1	<0.1	5.0	4.1
B	1.7	0.1	<0.2	0.2	33.3	12.6	<0.2	<0.2	0.2	<0.1	<0.2	–	<0.1	4.9	0.6	<0.1	<0.1	0.6	13.4	0.2
C	4.0	2.7	<0.2	2.4	13.4	4.8	1.9	0.9	17.0	3.0	<0.2	15.5	<0.1	1.3	0.4	<0.1	<0.1	<0.1	5.1	2.7
D	3.6	0.2	<0.2	0.8	31.9	9.3	<0.2	<0.2	0.4	<0.1	<0.2	–	<0.1	4.7	0.8	<0.1	<0.1	<0.1	11.7	0.2
B1a					27.6	11.0	<0.1	<0.1		<0.1			<0.1	3.8	0.8	<0.1	<0.1	0.2	9.5	0.3
B2					29.9	9.9	<0.1	<0.1		<0.1			<0.1	4.5	0.8	<0.1	<0.1	0.2	10.0	0.3
B3					34.5	7.5	<0.1	<0.1		<0.1			<0.1	5.7	1.1	<0.1	<0.1	0.2	8.9	0.4
B4*					36.0	14.7	<0.1	<0.1		<0.1			<0.1	4.4	<0.1	<0.1	<0.1	0.5	11.6	0.2
B5*					22.4	17.6	<0.1	<0.1		<0.1			<0.1	2.6	<0.1	<0.1	<0.1	0.4	8.2	0.2

* *Reduced analytical accuracy since only 0.3g fume available.*

Table 3 Consumables analysis, wt %

a) **Plates**

Plate	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Co
23587	0.046	0.014	0.047	0.70	2.01	10.5	17.0	2.38	0.06	0.38	<0.01	<0.1	0.25
23776	0.043	0.020	0.036	0.70	1.57	9.6	17.7	0.31	0.03	0.28	<0.01	0.30	0.16

b) **MMA coating**

Consumable coating	Si	Ti	Zr	Al	Fe	Mn	Ca	Mg	Na	K	Li	F	CO_2	Ba	Ni	Cr	Mo	Nb	V	Cu
A	9.1	17.9	0.2	2.0	9.8	4.8	4.3	0.4	1.4	2.3	<0.2	2.3	2.8	0.1	1.0	11.1	0.3	0.1	0.2	<0.1

c) **Consumables**

	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Co
MMA core, A	0.014	0.005	0.013	0.06	1.32	12.8	18.5	2.68	0.04	0.10	<0.01	0.01	0.05
MAG wire, B	0.027	0.005	0.024	0.71	1.89	12.1	18.4	2.53	0.06	0.22	<0.01	0.02	0.05
MCW wire, D	0.015	0.016	0.011	0.78	1.43	11.5	18.5	2.23	0.01	0.03	<0.01	0.01	0.01
MAG wire, B1-5	0.029	0.010	0.026	0.82	1.59	12.7	18.9	2.52	0.05	0.14	<0.01	0.02	0.09

Note: Consumable C has not been included, since it was impossible to separate core and sheath of a 2.0mm diameter FCW in a satisfactory manner for analysis.

b Total hexavalent chromium, by alkaline extraction and s-diphenyl carbazide colorimetric finish, based on the method described by Moreton *et al.*[5] Total chromium figures were obtained by a fusion technique described in the same

·r;

c Sodium and lithium (samples A, B, C and D only) by fume emission spectrophotometry;

d Xray fluorescence analysis was performed for the remaining elements, on a bead fused from a mixture of fume, lanthanum oxide and lithium tetraborate.[6]

RESULTS AND DISCUSSION

Application of the fume box

This study confirms previous findings that the fume box is an appropriate tool for fume sampling, and measurement of fume emission rates of MMA, MAG, and flux and metal cored wire welding. Compared with the Swedish Fume Box,[7] designed solely for MMA tests, the revised box allows improved access of the MAG gun in gas shielded arc welding and a more conventional gun angle, while the larger chamber volume means that there is less disturbance of the gas shield. The only difficulties were encountered with the pulse arc condition, MAG wire, test B5, when the fume emission rate was so low that there were problems in collecting sufficient fume sample for analysis.

me emission rates

..producibility of fume emission rate results, as illustrated in Fig. 1, has been shown[6, 8] to depend critically on variations in current, and particularly voltage during tests, and is similar for all four processes tested. No values for standard deviations (sd) were calculated, since only three or four replicate tests were made for each consumable, but previous work suggests a value for 2sd of about ±10%. Figure 1 shows, for each set of tests, the *range*, which in all cases is about 10% of the value of the *average* for a set of observations.

FER results for MMA, MAG and MCW consumables lie within the respective ranges predicted by previous results held on the Fume Emission Database (FED),[1, 9] although the number of results held on the database is still small, and does not allow a balanced statistical assessment. Similarly, results for the MAG tests B, B1a or B1b, B2 and B4 lie within the range expected from the corresponding results on the Database. The low arc voltage spray condition, B3, produces an FER greater than average, whereas the pulse condition, B5 gives an FER considerably less than the expected range for MAG. However, no tests had been performed previously on the pulse arc MAG condition.

Chemical analysis

The results of chemical analysis of the fume (Table 2) are in line with previous analogous results.[5] Of particular occupational hygiene interest are the chromium contents of the fumes. Since the Occupational Exposure Limit (OEL)[10] for the trivalent form, CrIII is 0.5 mg/m^3, whilst the OEL for the hexavalent species, CrVI, is 0.05 mg/m^3, there is clearly a strong incentive to reduce amounts of chromium in fume in general, and proportions of CrVI in fume in particular.

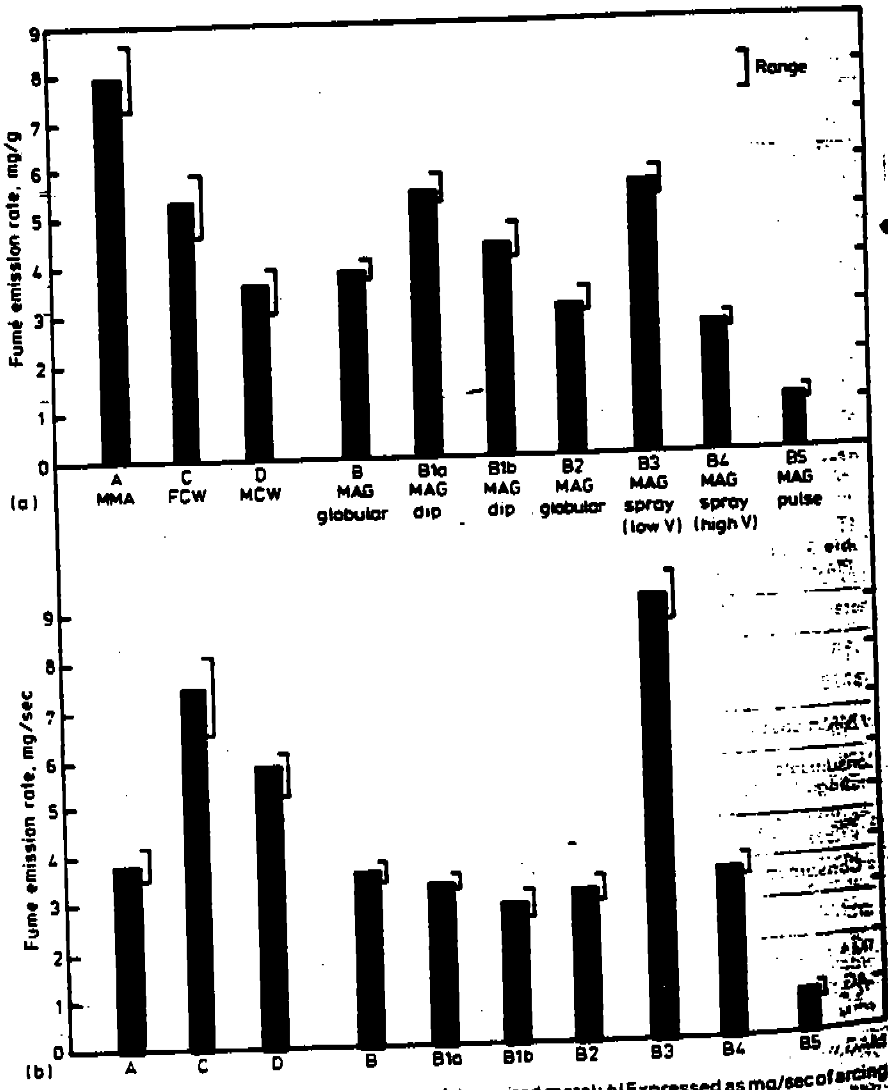
Fumes A and C give 5% total chromium, for the MMA and FCW tests respectively. The CrVI contents for A and C of 4.1 and 2.7% respectively, represent a large proportion (*i.e.* 80 and 60%) of the total Cr. Such proportions of CrIII/CrVI in the fume have been noted previously with MMA and FCW consumables.[1, 5, 11]

Wire B is a solid MAG wire, and wire D an MCW type described by the manufacturer as containing no flux. It is in accord with previous experience that the total chromium in fume from MAG wire is about 12% and that very little of this chromium is in the hexavalent state (Table 2).[5, 12] For the tests B and B1-B5, MAG wire, the CrVI amounts in the fume obtained by alkaline leach and the s-diphenyl carbazide method were low for all samples, and only just above the limit of detection (0.1-0.2%). Total Cr was obtained on small weight fume samples B1-B5 by a fuming technique, and there was no marked compositional variation through the set.

Previous fume analyses from the same wire were 9-13% by six co-operating analysts.[5]

Nickel contents of the fumes are as expected from previous experience.[5] It is known that Ni is present in an insoluble form as the oxide in welding fumes and therefore the OEL[10] of 1 mg/m^3 is relevant. One anomaly in the results (Table 2) is the small amount of sodium, at the detection limit, in fume B, from the MAG process. This is thought to be caused by airborne contamination, but is not important from an occupational hygiene viewpoint. Also, in fume B, the copper amount of 0.6% is higher than normal, but similar levels have been found previously in fume from this consumable.[5]

The reduced analytical accuracy resulting from small fume sample weights



1 Fume emission rates: *a)* Expressed in mg/g of deposited metal; *b)* Expressed as mg/sec of arcing time.

Table 4 Summary of results following visual assessment of welded specimens

Test specimen numbers	Mode of metal transfer	General comments
B1a (3 specimens)	Dip	Bead profile convex with a slightly pronounced rippied surface. The weld toes fusing into each plate with a 5mm leg length fillet weld present. Fine spatter achering to the plates.
B1b (3 specimens)	Dip	Bead profile convex, the convexity being more pronounced than those produced in group B1a. The bead was however of a smoother rippled surface. The weld toes, although fused into each plate, were distinctly rolled along the base plate with a 5mm leg length. There was also marked reduction in the fine spatter formation.
		Welds B1a and B1b may be considered as typical of industrial practice for this joint type and plate thickness.
B2 (3 specimens)	Globular	Bead profile only slightly convex with a herringbone rippled surface. The weld toes fusing smoothly into the parent plates but assuming a 'scalloped' effect with a 6mm leg length. Some fine spatter.
B3 (3 specimens)	Spray (low volts)	Bead profile slightly convex with a smooth fine herringbone rippled surface. The weld toes fusing into the parent plates with a slight 'scalloping' along the base plate toe, with a 7mm leg length. No spatter.
B4 (3 specimens)	Spray (high volts)	Bead profile flat to slightly concave with a smooth very fine herringbone rippled surface. The weld toes fusing smoothly into the parent plates with a 6mm leg length. No spatter.
B5 (3 specimens)	Pulse	Bead profile flat to slightly convex with a semi herringbone rippled surface. The weld toes, although fused into the parent plates were slightly irregular along the length of the specimen with a 7mm leg length. No spatter.

available in tests B4 and B5 means that no firm conclusions should be based on the compositional variations of Fe, Ni, Mn, *etc*, of tests B1-B5. However, fume analyses for test B, with the same wire, were in good agreement with fume analyses carried out in 1983,[5] where 31-33%Fe, 12-15%Mn and 3-5%Ni were found by six analysts. These results are thus in general agreement with the series B1-B5.

Table 3 provides data on consumable analyses. Two separate reels of wire B were used for the tests, and had marginally different composition. Such differences were not thought to be significant. Results are not given for wire C, as it was not found possible to separate the core and sheath of this flux cored consumable for analysis.

IMPLICATIONS FOR STAINLESS STEEL WELDING

This work with MMA, FCW, MCW and MAG processes (all of which are applicable to routine stainless steel fabrication) illustrates the range of fume emissions which can be obtained, and suggests that use of the MAG process is feasible to reduce the CrVI/CrIII ratio to one which is preferable from an occupational hygiene viewpoint. This is the case providing that total fume amounts are also adequately controlled by local extraction. It should be borne in mind that whilst it is fairly well documented that MAG welding invariably produces only low amounts of hexavalent chromium in the fume,[5, 11, 12] there are differences in FERs and fume composition with different MAG consumables. Shielding gas mixtures may also have an effect. However, equally notable are the variations in FER which can be obtained by use of different welding conditions applied to the same consumable, within a band of commercially acceptable resultant weld qualities. Thus, it has been shown possible when employing a low voltage spray arc mode of transfer in test B3 to obtain a very high fume emission rate. This result points to the importance of considering fume formation during preliminary trials to establish welding procedures for fabrication purposes.

Far more important is the discovery that conventional pulse arc welding is capable of producing very low fume amounts indeed (commensurate with conventional TIG and the hot wire TIG process[1]) at the same time as having a deposition rate of the order of the dip mode. Although it is known that the pulse arc condition is guilty of producing enhanced amounts of ozone (not readily measurable in the fume box), this test points the way to a possible considerable overall reduction in pollutant levels, particularly in situations where the reduction of particulate fume is critical (*e.g.* welding in a hyperbaric environment).[13] Figure 2 shows the results in terms of a measure of the toxicity of fume from different processes. The value of the FER has been divided by an additive threshold limit value[14] for fume given by:

$$TLV_{fume} = \frac{1}{\frac{A}{a}+\frac{B}{b}+\frac{C}{c} \ldots} \text{ mg/m}^3$$

where A, B, C are the % weights of elements of hygienic significance in the fume, and a, b and c are the corresponding occupational exposure limits.

This calculation is one step in the classification of fumes into classes, which forms part of the Swedish Standard.[4] This standard, and in particular, its adoption of fume classes is not accepted in the UK, nor is the method of adding together components of a mixture of pollutants presently accepted by the Health and Safety Executive, although the additive formula above is used by the American Conference of Governmental Industrial Hygienists (ACGIH)[14] for airborne pollutant mixtures in general.

Nevertheless, as an aid to considering the relative hazards of fumes from different processes and consumables used for welding stainless (and high alloy) steels, the diagram can be thought provoking. Using UK OEL values[10] in the calculation, the combination of low FER, and the absence of significant amounts of CrVI in the fume potentially makes the fume from pulse arc welding (test B5) an order of magnitude less hazardous than the equivalent MMA conditions during the deposition of equal amounts of weld metal. For conventional dip and spray MAG conditions, the three factors of: *a)* very low CrVI; *b)* average FER; and *c)* high total Cr (12-15% compared with 4-8% for MMA), have to be borne in mind when considering control of fume emission at source.

These considerations thus suggest that it is perhaps unacceptable to adopt the same value of OEL for particulate welding fume[10] from two different processes, although nominally these processes may deposit weld metal of similar composition. The authors suggest that considerably more research is required into fume emission rates of competing open arc processes (*e.g.* different shielding gas mixtures, and a range of stainless and highly alloyed MAG wires) before any firm conclusions can be drawn.

CONCLUSIONS

1 The fume box has proved a useful tool for measurement of fume emission rates of consumables from the MMA, MAG, FCW and MCW processes.

2 Fume emission rates found in this investigation lie within the ranges, process by process, expected from previous experience.

3 The MAG process, with a single stainless steel wire, type 316S93, and Ar-2%O_2 shielding gas, used under a wide range of welding conditions, has shown itself capable of lower fume emission rates than the self-shielded (MMA and FCW) processes.

4 For the MAG process, small alterations in arc voltage within the spray range can have marked (factor of three) effects on total fume emission. The higher fume

emission rates were obtained with the low arc voltage.

5 The pulse arc transfer mode during MAG welding has extremely low fume emission rates.

6 Of particular interest is the presence of hexavalent chromium, CrVI in fume, because of the recent debate concerning possible carcinogenic hazards relating to CrVI. These investigations indicate that gas shielded welding gives emission rates of CrVI that are lower than those given by self-shielded methods by a factor of 1/15 to 1/25. For pulse transfer MAG welding, the same factor is of the order of 1/100. If a 'low' voltage spray transfer mode is used, the factor reverts to 1/4 to 1/5.

7 No measurements of ozone formation were made. In considering the potential air pollution problems when welding stainless steels, attention should also be paid to the ozone, particularly when using the pulse arc MAG process.

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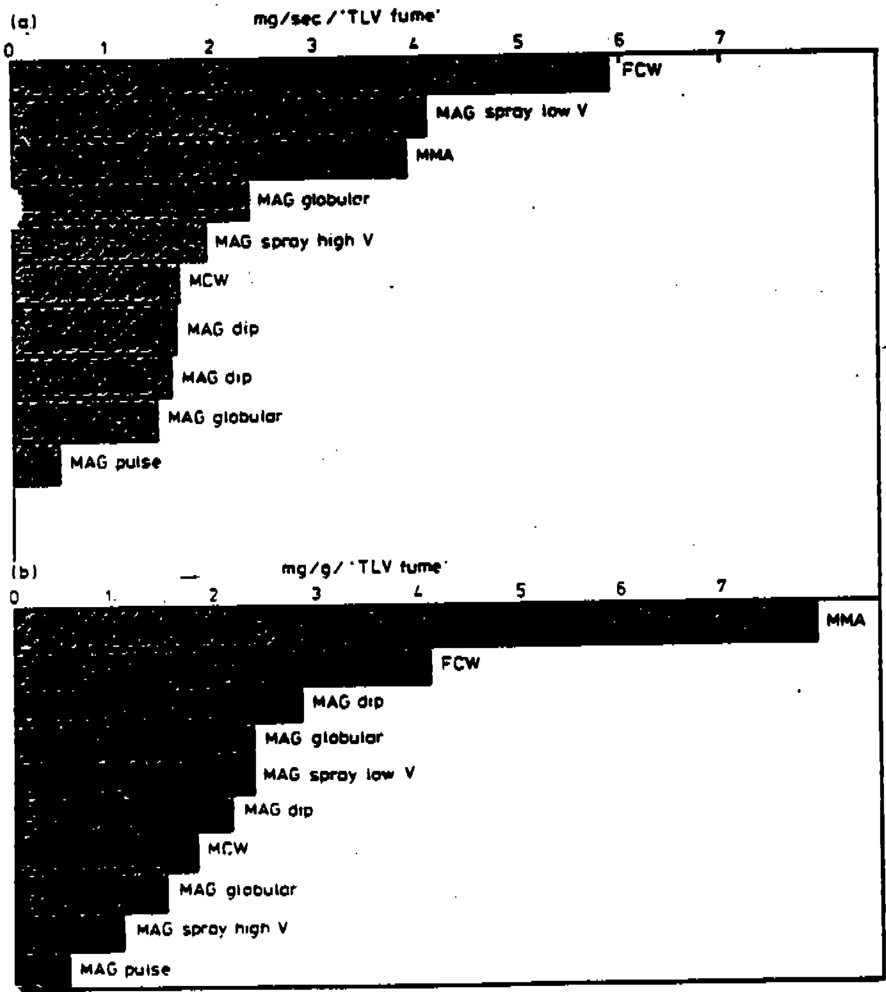

2 Relative toxicity of fume from different welding processes: *a)* Expressed as mg/sec/'TLV fume'; *b)* Expressed as mg/g/'TLV fume'.

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Fume emission rates were determined for MMA (AWS A5.4 81, E316L-16), MAG ($Ar+2\%O_2$, metal cored wire AWS A5.22 80, E316 LT. 1, 2, 3 or solid wire AWS A5.9 77, ER316L Si, dip, spray (various voltage levels), globular or pulsed metal transfer), or self-shielded flux cored wire welding (AWS A5.22 80, E316LT-3). Horizontal-vertical fillet welds were made in a fume box on Type 316 stainless steel (17%Cr, 10%Ni, 2.38 or 0.31%Mo) and particulate fume was collected for weighing and chemical analysis (especially for total chromium and hexavalent chromium). Pulsed MAG welding gave very low levels of fume.