UNDERSTANDING FUME FORMATION BY GMAW

Deam R.[1], Bosworth M.[1], McAllister T.[1], Norrish J.[2], Brooks G.[2], Zhou S.[2], Haidar J.[3], Lowke J.[3], Farmer A.[3], Simpson S.[4]

Abstract

The control of exposure to welding fume is necessary to meet health and safety obligations. The work reported here is a continuation of a successful Cooperative Research Centre project, that has revealed how two different mechanisms are responsible for generation of fume in Gas Metal Arc Welding (GMAW). Models of fume formation have now been developed and compared with experimental measurements of total fume formation rate, fume composition and the fraction of Chrome VI in the fume from stainless steel GMAW. These models give an insight into how process modification might be used to control fume at source. Control at source is believed to be the most cost effective and energy efficient technique for dealing with welding fume. It is anticipated that the understanding, gained from this project, will be applied to determine the practical limits for the control of welding fume at its source.

Keywords

Welding, Bulk Fume, GMAW, Experiments, Arc Modelling, Thermodynamic and Chemical Kinetic Modelling.

Author Details

1. CSIRO, Manufacturing Science and Technology, - A Core Partner of the CRC-WS
2. University of Wollongong, - A Core Partner of the CRC-WS
3. CSIRO, Division of Telecommunications and Industrial Physics
4. University of Sydney, - A Core Partner of the CRC-WS

All the authors are members of the CRC Welded Structures project group: Understanding welding fume.

1. INTRODUCTION

Gas Metal Arc Welding (GMAW) is a very convenient, flexible, and high productivity means of joining metals. Under most circumstances, where the proper care is taken, GMAW is also a safe process. However, one inherent drawback is the higher levels of fume produced when compared with other welding processes such as Gas Tungsten Arc Welding (GTAW) or Submerged Arc Welding (SAW). This means that extra care has to be taken to ensure that GMAW welders' exposure to welding fume is minimised. Many studies have been carried out on the health effects of welding fume. Hewitt [1] provides an excellent review of these studies. Also, WTIA Technical Panel 9 has recently held colloquia covering all aspects of occupation health and safety in welding [2], including welding fume.

The CRC for Materials Welding & Joining set up the project group in June 1997, specifically to gain an understanding of the processes that control the level and composition of welding fume in GMAW. The emphasis of the work is to understand the fume formation process, the reasoning is that once the understanding has been gained, a strategy to control and minimise fume formation at source could be developed. It is also hoped that the practical limits of control at source can be identified. The Group has carried out a concentrated experimental programme of work, which has stimulated the development of mathematical models of fume formation. It is from these models that the understanding is growing. The modelling activity is not meant to be used to predict precisely the level and composition of GMAW fume (which could be done given time and resources), rather to enable the controlling features of the welding process and procedures to be understood well enough to enable the confident development of equipment, consumables and procedures that will minimise fume generation and its toxicity.

2. PROCESS DESCRIPTION

Welding fume has been the subject of numerous studies. Levchenko [3] provides a recent review, and Quimby & Ulrich [4] have reported work that increases the experimental accuracy in measuring total fume from GMAW. The work of Castles & French [5] and French, Tyagi & Brooks [6] provided an important initial impetus to set up the CRC project group working on understanding fume formation. The group has published a number of papers [7 to 15] related to fume formation, of which reference [7] is a summary of the earlier work of the group. This paper is intended to summarise the most recent work.

Diagram 1 is a sketch of the important processes that are taking place during the formation of fume from GMAW. The identification of these processes is important for understanding the role of each, and the contribution they make to the production of welding fume. Previous work has shown there to be two types of fume formed:

- Microspatter and,
- Fine fume

The microspatter is formed from small droplets (greater than about 1 micron) breaking up from the main droplet as it detaches from the wire. Microspatter has been found to consist mainly of metal, with small amounts of oxide on the surface. In general, the fraction of microspatter in fume is small. It is thought that the fraction of microspatter in fume will be highest in dip transfer mode.

Fine fume is formed by the condensation of metal vapour as it is rapidly cooled by mixing of the metal vapour enriched welding gas with cold air. A fine fog is formed of mixed metal oxides, which have condensed to form sub-micron particles from a few nanometres to about 500 nanometres in diameter. These particles agglomerate later to form long branched chains.

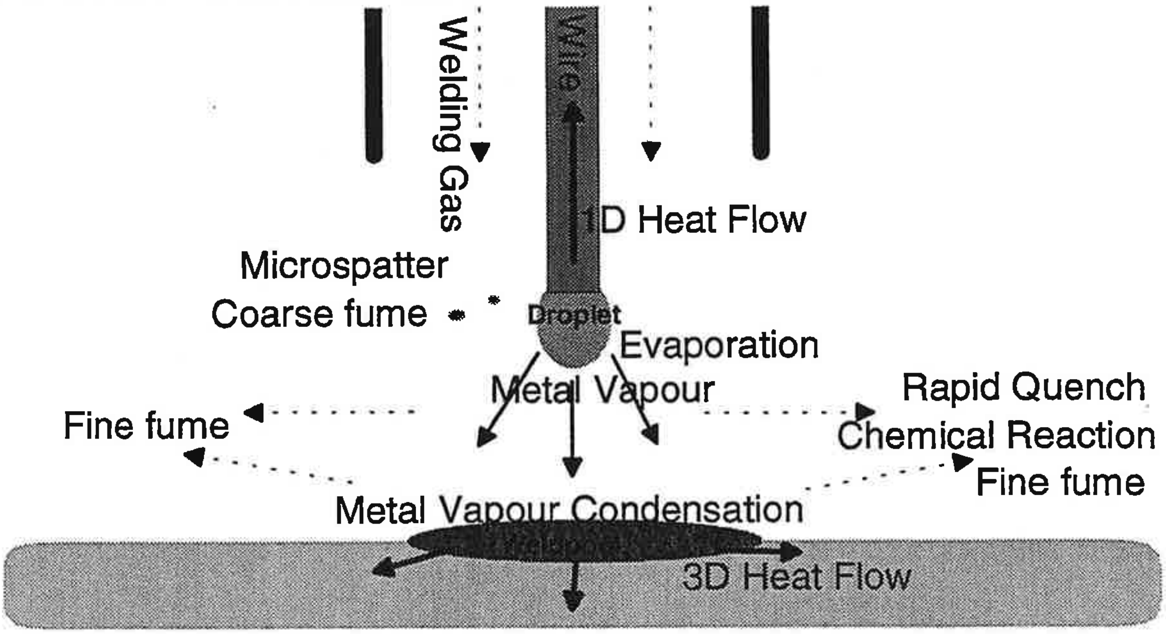

Figure 1: Sketch of Fume Formation Processes

A significant fraction of the metal vapour in the welding gas is condensed onto the weldpool. This is called metal vapour transfer. The droplet at the end of the electrode is much hotter than the weldpool. This makes the droplet a source of metal vapour and the weldpool a sink. The reason that the droplet is much hotter than the weldpool is that heat conduction from the droplet is via the wire electrode and therefore one dimensional heat flow is a reasonable approximation. By contrast the weldpool is cooled by at least two dimension heat flow, (3D heat flow for a weldpool that does not penetrate the workpiece). Two or three dimensional heat flow is very much more effective at cooling than one dimensional. This also explains why GTAW generates very much less fume than an equivalent GMAW procedure.

This paper will concentrate on the fine fume formation mechanism, which makes up most of the fume. Probably the part of the fume generation process that has caused the most excitement of the past year, is understanding the chemistry that occurs in the rapid quench region. This is where chemical kinetics becomes extremely important, as well as the "cloud physics" of nucleation and formation of the fine fume. The study of the particle size distribution should be predictable from the concentrations of the metal vapour and the quench rate.

3. CHEMICAL COMPOSITION

3.1 Experimental measurements

Experimental measurements of the fume morphology and chemical composition have been carried out. The fume generated from plain carbon steel wire was studied using, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM) and Energy Dispersive Spectroscopy (EDS). A range of metal transfer modes were studied; dip transfer, globular transfer, drop spray transfer and streaming spray transfer. The results show that both the total fume formation rate and fume particle size distribution depends on the metal transfer mode, globular transfer having the largest mean particle size and total fume formation rate. The majority of the fume particles were much smaller than 1 micron, typically lying within the range 10 to 200 nanometres. The chemical composition of the particles is that of complex oxides of iron, silicon, and manganese, reflecting the composition of the wire used, but enhancing the fractions of silicon and manganese. Silicon and manganese have higher vapour pressures than iron at the same temperature. The chemical composition of the fume formed from mild steel wire is close to predictions made from chemical equilibrium models. This is not the case for fume formed from stainless steel wire, which suggests that chemical kinetic effects are important. This work is reported by Brooks et al. [9] and Zhou, Norrish & Chen [12].

3.2 Chemical Kinetic Modelling & Cr (VI)

Experimental measurements of Chrome (VI) in the fume from stainless steel GMAW have been made. These studies used different power supplies with different welding parameters at the same wire feed speed. The total amount of Cr (VI) produced varied from 10 to 65 mg/hr. No clear empirical trend could be found. The connection between Cr (VI) content and power supply characteristics was first identified in the earlier study by Brooks et al. [9]. This inexplicable connection of fume composition to power supply characteristics is what first led to the investigation of the kinetics of Cr (VI) formation.

A chemical kinetic model of the formation of the different oxidation states of chromium has been formulated. The formation of CrO, Cr_2O_3,CrO_2, and CrO_3 are considered in the model. The model is built around the assumption that the Cr (VI) is formed when chromium vapour is oxidised when it enters the plasma arc, the welding gas being Argon with 1.5% Oxygen. Equilibrium calculations show that the maximum amount of Cr (VI) is formed between temperatures of 2,500 K and 3,000 K, under the welding conditions considered. Since the Cr (VI) state is not an equilibrium product below about 2,200 K, chemical kinetics must "freeze" the composition as the gases are rapidly cooled. The region of rapid quench, when the chromium oxides in the plasma welding gas mix with air, is the heart of the model. A quench rate of 10^6 K per second (calculated from computer prediction of the welding gas flow [16]) was found to give reasonable agreement with experiment. The amounts of Cr (VI) depended on the amount of chromium vapour generated from the droplet, and the oxygen concentration in the plasma gas. This would imply that accurate predictions will only be possible if the amount of chromium vapour can be predicted for the particular welding condition. It would seem that the chemical kinetic model has all the correct ingredients, but must await more accurate values for the amount of chromium vaporised.

3.3 Future chemical modelling work

The chemical kinetic model may be further checked against existing experimental data. For example, the addition of small amounts of zinc has been reported to reduce the levels of Cr (VI) in welding fume [17]. The mechanism controlling this reduction could be understood using the chemical kinetic model developed. This might point the way to other and improved methods for reducing Cr (VI) in welding fume.

4. EVAPORATION & CONDENSATION

4.1 Computer model

The aim of developing a computer model of the GMAW process is to be able to predict the amount of fume generated using just material properties and welding parameters as input data to the model. Further refinements to the model have been reported [10, 11]. This has enabled predictions of the amount of metal evaporation from the droplet [14]. The model predicts the droplet growth and size at detachment from the wire. These calculations originally led to the realisation of how important metal vapour transfer is in GMAW. Other researchers in the field have noted the significant fraction of metal vapour that is produced, see page 227 (1st edition) of Lancaster's book [18], Levchenko [3] and Perrott [19]. The measured amount of fume produced in GMAW is between 1.5% to 0.2% of the wire feed.

Measurements have shown that less than half of the metal vapour generated ends up as fume, see section 4.2 below.

The next development of the computer model will be to include condensation at the workpiece. This would enable a complete fume formation rate calculation to be carried out from first principles. The drawback is that the computer code takes a long time to run. Predicting fume levels over a range of conditions may be very time consuming. This has led to the development of the semi-empirical model described in section 4.4.

4.2 Metal Vapour Transfer experiments

Some innovative experimental work has been carried out to help quantify the amount of metal vapour transferred to the weldpool. The reason for doing this work is that if Metal Vapour Transfer is as important as the model predicts, then understanding the condensation mechanisms could possibly be more important to the development of fume reduction strategies than reducing the vapour generation rate.

Welds were made using a steel wire, over a fast moving copper substrate. The vapour trails between the droplets were analysed and the amount of vapour condensed on the copper was measured. The results are presented below in Table 1, (MVT stands for Metal Vapour Transfer and FFR for Fume Formation Rate).

Table 1: Measured Metal Vapour Transfer

GMA Welding Conditions	Wire Feed Rate (m/min)	Measured Metal Vapour Transfer (% Wire Feed)	Measured Fume Formation Rate (% Wire Feed)	(MVT)/(MVT+FFR) or fraction Condensed
Non-Pulsed	2	0.9	1.2	43%
Pulsed	5	2	0.8	72%

This interesting work is more fully reported by Bosworth and Farmer [15]. A further experimental programme may be undertaken to quantify the amount or fraction of Metal Vapour Transfer over a range of wire feed speeds and welding conditions. This would allow the theory of metal vapour condensation from the arc to the workpiece to be developed and checked against experimental data.

4.3 Droplet measurements

The computer model developed predicts the amount of metal vapour generated. To do this many parameters have to be calculated. One of the more important is the droplet diameter, which needs to be checked against experimental data. Measurements have been made by Simpson [20] of the droplet size distribution (at detachment from the wire), for a range of wire feed speeds and wire diameters. Figure 2 below, shows the average measured detached droplet diameter for 1.2 mm mild steel wire over a range of wire feed speeds. A laser shadow graph technique was used to measure the droplet sizes. The averages are taken over hundreds of readings.

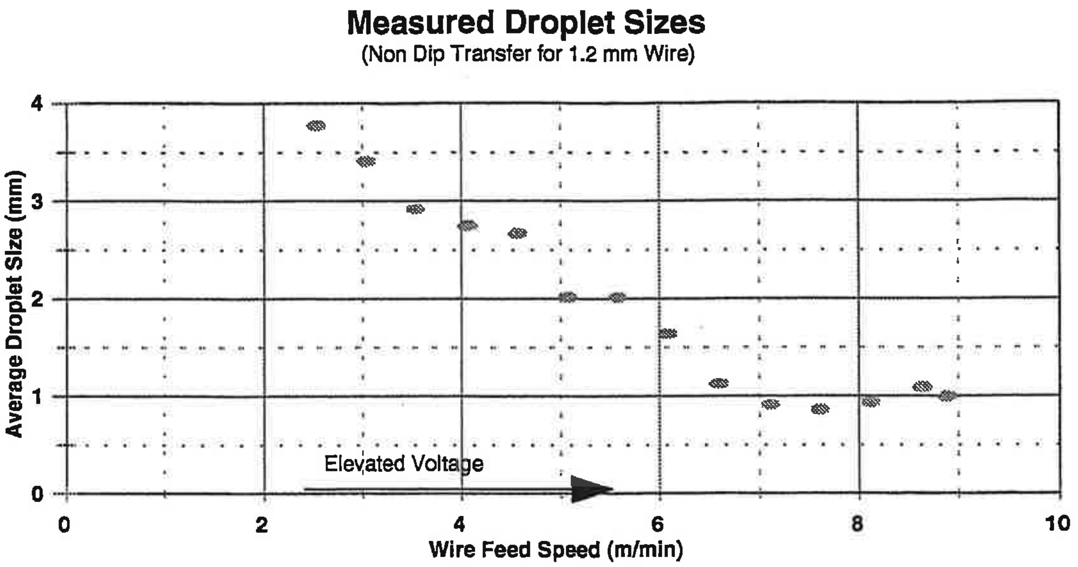

Figure 2: Measured Droplet sizes from GMAW using 1.2 mm mild steel wire

These droplet diameters were measured in flight, in other words, after the droplet had detached from the wire. The measurements were made ensuring that the welding conditions used were not in dip transfer mode, by using a relatively high operating voltage of 30 V. Measurements made for wire feed speeds in the indicated range from about 2 to 5.5 m/min, were made at an elevated voltage, compared to the normally used dip transfer welding procedures. Similar measurements will need to be made in dip transfer mode, to measure the maximum droplet size, just before dipping occurs.

4.4 Semi-empirical model

A semi-empirical model has been formulated to attempt to capture the essential features of fume generation in GMAW. The model is relatively simple and has few adjustable parameters. In particular, the complicated prediction of the maximum droplet size has been removed. Experimental droplet size data is used. The Fume Formation Rate (FFR) is calculated assuming that the fume is generated solely from the metal vapour mechanism (microspatter is ignored). A further simplification is that the fume is generated only from the droplet formed at the end of the wire. At present, dip transfer mode is not considered in the model. The steps to calculate the Fume Formation Rate in Gas Metal Arc Welding, from the vapour mechanism are:

1. Predict the liquid (droplet) surface temperature at anode,
2. Calculate the gas flow velocities,
3. Calculate the metal evaporation rate,
4. Calculate metal vapour condensation rate at the work piece,

The Fume Formation Rate is the evaporation rate minus the condensation rate.

The liquid droplet temperature is predicted, knowing the wire feed speed, the droplet size and the engineering heat transfer correlation that allows the heat flow through the droplet to the wire to be calculated. This is an important point, because it allows the elimination of the heat flux and relates the maximum droplet temperature to the wire feed speed and droplet size.

The metal evaporation rate is calculated using the relationship between the equilibrium metal vapour pressure and the temperature at the surface of the droplet; plus an engineering correlation for the mass transfer of vapour from the droplet's surface, across the boundary layer, to the bulk plasma flow. The engineering mass transfer correlation allows for convection to thin the boundary layer around the droplet. This increases the Sherwood number that would be expected, if the mass transfer process was dominated by diffusion alone. The mass transfer is also affected by the partial pressure of oxygen in the plasma gas surrounding the droplet. This effect is yet to be included. Any concentration gradient of alloying elements within the liquid droplet is ignored. At present the model predictions are for a single element wire composition (iron).

The vapour condensation rate on the workpiece is calculated assuming a potential flow model. A stagnant flow is modelled (flow directed at the workpiece), assuming that any metal vapour that comes into contact with the workpiece, within a set distance from the arc, is completely condensed onto the workpiece. The remaining metal vapour forms fine fume in the gas. The slower the quench rate of the plasma gases from the arc, the larger the distance from the arc that condensation on the workpiece can occur. This is the one free variable of the potential flow model, and is fitted to the experimental data from the metal vapour transfer measurements.

Figure 3 shows the result of the predicted vapour generation rates; for different size droplets against wire feed speed.

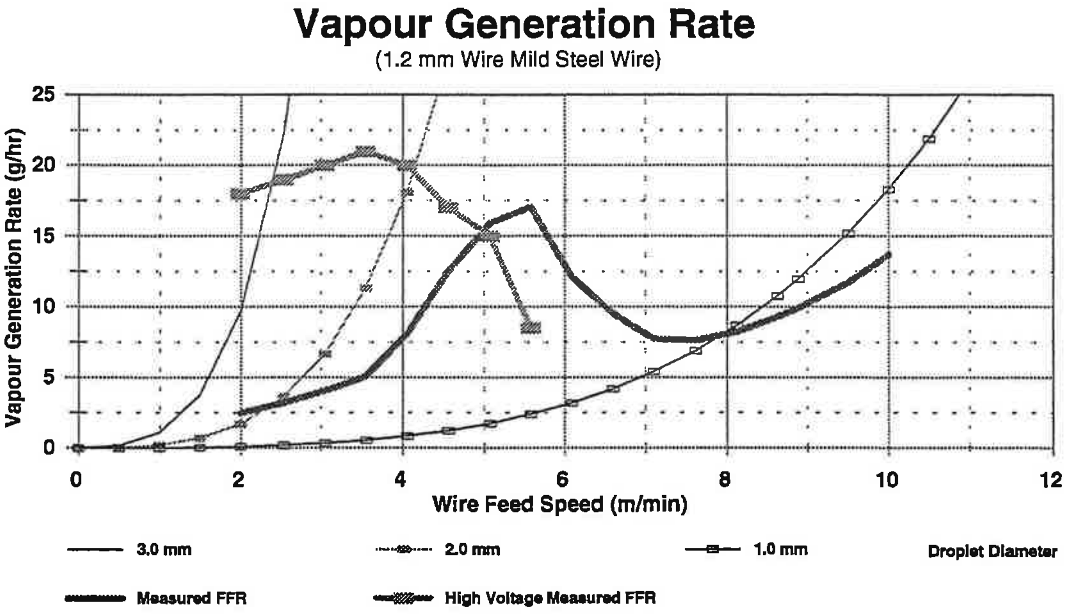

Figure 3: Predicted Vapour Generation Rates for different droplet sizes, and measured Fume Formation Rates

These data can be used in conjunction with the measured droplet sizes, to predict the fume formation rate. This is shown in figure 4. The predictions are only valid away from dip transfer at higher voltages, which corresponds to the upper envelope of the experimental data shown in figure 4, (the fume measurements made at high voltage).

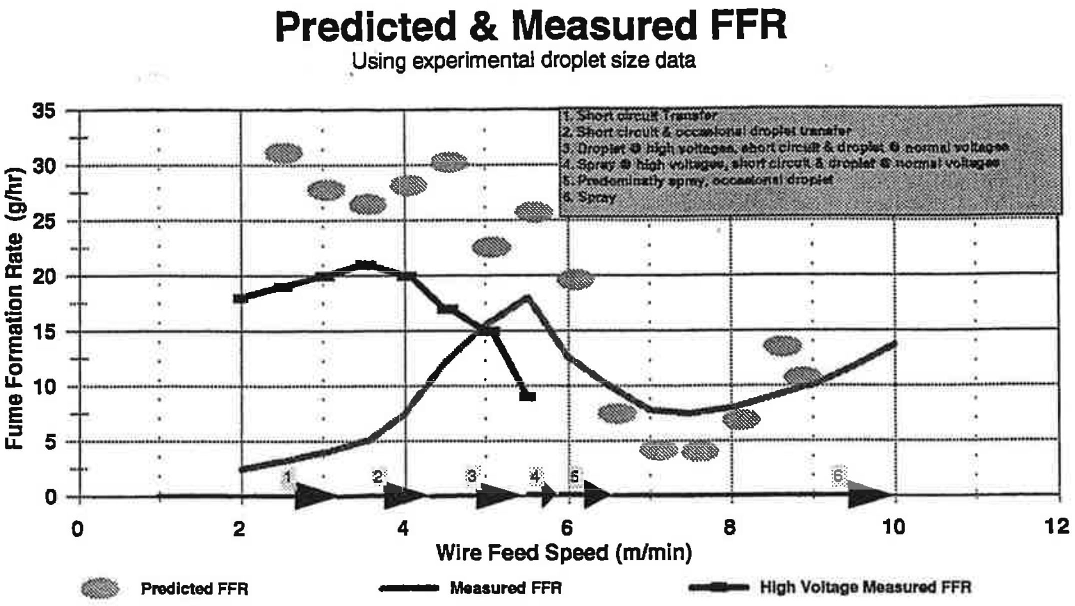

Figure 4: Predicted Fume Formation Rate, using measured droplet sizes

This simple model of fume generation predicts that the fume formation rate depends on the wire feed speed and droplet diameter at detachment. The model predicts that the smaller the detached droplet size, the lower the Fume Formation Rate. A more detailed description of the model is in preparation [21]. Further modelling to include dip transfer is planned in the next stage of the investigation. This would predict the Fume Formation Rate to be compared with the lower line of the experimental data in figure 4.

5. DISCUSSION

An understanding of the metal vapour mechanism for fume formation has been developed, for non dip transfer GMAW. Droplet size and wire feed speed control the fine fume formation rate. The understanding developed so far, indicates that the smaller the detached droplet size, the lower the total Fume Formation Rate. The physics behind this is twofold:

1. The smaller the droplet, the smaller the temperature drop across the droplet, for the same wire melt off rate. This means that the vapour pressure of the metal is lower for smaller droplets.

2. The total mass transfer of metal vapour from the droplets increases with droplet size. Thus smaller droplets have lower metal vapour generation rates.

Point 2 seems counterintuitive. It must be borne in mind that the main assumption of the semi-empirical model was that the fume is generated only from the droplet formed at the end of the wire. It does not matter how quickly the droplets are formed and leave the end of the wire. There is always a growing, heated droplet attached to the wire. Therefore the bigger the droplet, the greater the surface area and the more the fume it will produce. Although the mass transfer coefficient falls with increasing droplet size, the overall effect is that the total vapour generation rate increases with the droplet diameter raised to a power between 1 and 2. The power index is 2 for no gas flow (diffusion only into the gas phase), and falls towards one as the flow past the droplet increases. The time dependent calculations of Haidar [14], also reported by the group [7], clearly show the vapour generation increasing as the droplet attached to the wire grows.

There must be a practical limit to the minimum size of droplet that can be detached from the wire. The models developed should be extended to pulsed GMAW to explore the possibility of defining a practical minimum Fume Formation Rate for pulsed GMAW.

More experimental Metal Vapour Transfer work is needed to validate the models and understand fully the interplay between condensation on the workpiece and Fume Formation Rate. It is not yet clear if the condensation rate could be increased by the welding procedure in some way to reduce fume formation. Also, further work needs to be carried out to extend the modelling to dip transfer GMAW, both for the metal vapour and the microspatter mechanisms of fume formation.

A most interesting aspect of this research concerns what happens in the rapid quench region, where fine fume is formed. The study of the size distribution of the fine fume particles could be used, together with chemical composition predictions of the chemical kinetics model, to double check the quench rate calculations. The chrome (VI) calculations and particle size distribution measurements made so far, should form the basis for work in this area.

6. CONCLUSIONS

Models of fume formation by GMAW have now been developed and compared with experimental measurements of total fume formation rate, fume composition and the fraction of Chrome VI in the fume from stainless steel GMAW. These models give an insight into how process modification might be used to control fume at source.

An understanding of the physics indicates that smaller detached droplets will lead to lower Fume Formation Rates.

The quench rate experienced by the fume vapour has a controlling effect on the size distribution of the fume particles and the chemical composition of the fume. The formation of Chrome (VI) in fume has been shown to be entirely a kinetic effect, and thus controlled by the quench rate as well as the species concentrations.

Since control at source is believed to be the most cost effective and energy efficient technique for dealing with welding fume, it is anticipated that the understanding gained from this project, will be applied to determine the practical limits for the control of welding fume at its source.

7. ACKNOWLEDGEMENTS

The work reported herein was undertaken as part of a Research Project of the Cooperative Research Centre for Welded Structures. Contributions were made to the project by CSIRO Manufacturing Science and Technology, CSIRO Division of Telecommunications and Industrial Physics, the University of Wollongong, the University of Sydney and also WTIA's Panel 14. The Cooperative Research Centre for Welded Structures was established by and is supported under the Australian Government's Cooperative Research Centres Program.

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