Final report

Project: Att minimera hälsorisker av svetsrök genom att anpassa svetselektrodens kemi [Adjustment of the chemistry of a welding electrode to minimize health risks caused by welding fume]

Project number: 19-323

Summary

One of the main purposes of this project was to investigate how different chemical compounds in the welding electrodes influence the toxicity of welding fume. We investigated fluorides, sodium, potassium, and worked closely with welding electrode manufacturers to tune the welding electrode formulation towards a safer composition. In total 34 welding electrodes were produced and welded to collect welding fume for further analysis. We then used many spectroscopic, microscopic, and electrochemical methods to characterize the welding fume nanoparticles and investigate their solubility in different surrogate body fluids and industrially relevant extraction solutions. We also used different cell tests to investigate DNA damage, cell death, and inflammatory markers simulating a risk to induce inflammation. We found that fluoride salts, which often are added to some welding electrodes (flux-cored wires), cannot directly, but indirectly, increase the solubility of hexavalent chromium, which is the toxic form of chromium and responsible for cell death and DNA damage in our cell tests. Sodium and potassium are also linked to increased solubilty of hexavalent chromium, but not necessarily in a direct way. We were able to produce welding electrodes that minimized health risks in our cell tests to almost zero, which was a very big difference to the commercially available versions. However, the weldability of these welding electrodes was not ideal and they produced a welding fume that still contained and released relatively high amounts of manganese, which can cause inflammatory conditions. Our final part of the project involved the development of welding electrodes that are both acceptable from a health and a commercial perspective. We were able to develop some for one type of stainless steel. These had no negative health effects, as determined by several cell tests, and had an acceptable weldability. This has been confirmed in a round robin test of three different labs and these electrodes will now be made available on the market. In all, the project has not only been successful in developing welding electrodes that minimized negative health outcomes but also developed safer welding electrodes that are currently placed on the market.

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Involved researchers and collaborators, and their role in the project

- Docent Yolanda Hedberg (Surface and Corrosion Science, KTH, and Assistant Professor at University of Western Ontario, Canada): Project leader, supervisor and researcher
- Docent Hanna L. Karlsson (Institute of Environmental Medicine, Karolinska Institutet - KI): Researcher and supervisor for the toxicity studies
- Sarah McCarrick (Institute of Environmental Medicine, KI): Ph.D. student, focus on toxicity investigations
- Zheng Wei (Surface and Corrosion Science, KTH, and University of Western Ontario, Canada): Ph.D. student, focus on release testing and particle characterization
- Juliette Theodore (KTH Royal Institute of Technology): Internship student, focused on release testing and particle characterization
- Lila Laundry-Mottiar (Department of Chemistry, University of Western Ontario, Canada): Internship student, focus on release testing and particle characterization
- Professor Inger Odnevall Wallinder (Surface and Corrosion Science, KTH): researcher focused on surface characterization
- Dr. Kjell-Arne Persson (Swerim): researcher focused on welding methods
- Klara Trydell (Swerim): leading discussions and organizing meetings, researcher
- Richard Andreas Wagner (AGA Gas): planning and welding, collection of welding fume, delivery of shielding gas, researcher
- Dr. Elin Westin (Voestalpine Böhler): planning of welding methods and electrodes, development of welding electrodes, researcher
- Dr. Mark Biesinger (Surface Science Western, University of Western Ontario, Canada): Researcher, X-ray photoelectron spectroscopy
- Ivan Barker (Surface Science Western, University of Western Ontario, Canada): Researcher, scanning electron microscopy
- Dr. Valentin Romanovski (KTH Royal Institute of Technology, MiSIS, Russia): Researcher, transmission electron microscope, X-ray diffraction
- Mathias Lundin (Swedish Welding Commission): participation in reference group
- Gustaf Bäck (Swedish Work Environment Agency): participation in reference group

Communication, reference group, and societal use

This project was partially supported by Vinnova (Metallic Materials) and involved therefore several companies, authorities, and a reference group. Each month from October 2018 until now, phone meetings were arranged between all involved partners, collaborators and the reference group. In addition to this, the project leader (Y. Hedberg) participated in the working group 32 (health and safety) of the Swedish Welding Commission two times per year, and also in the intermediate and annual meetings of Commission IIX (health and safety) of the International Institute of Welding twice per year.

The project resulted in the following publications and planned publications:

Published work resulting from previous studies

- Thesis work: Nanxuan Mei, *"Characterization of Stainless Steel Welding Fume Particles. Influence of Stainless Steel Grade, Welding Parameters and Particle Size":* Download: http://www.diva-portal.org/smash/get/diva2:944365/FULLTEXT01.pdf
- Internship report: Laure Belleville*,"Welding project: Characterization of stainless steel welding fume particles":*
- Popular science article in Swedish: Y. Hedberg, K.-A. Persson, I. Odnevall Wallinder, *"Pilotstudie: sexvärt krom",* **Svetsen**, 2: 35, 2017. http://www.svets.se/download/18.274ebf1415b8cd45d5228547/1504794254865/Svetsen2.2017_tema.pdf
- Scientific publication: N. Mei, L. Belleville, Y. Cha, U. Olofsson, I. Odnevall Wallinder, K.-A. Persson, Y. Hedberg, *"Size-separated particle fractions of*

stainless steel welding fume particles – a multi-analytical characterization focusing on surface oxide speciation and release of hexavalent chromium", **Journal of Hazardous Materials**, 342: 527-535, 2018.

- Video presentation of the above article: http://audioslides.elsevier.com//ViewerLarge.aspx?source=1&doi=10.1016/j.jhazmat.2017.08.070
- K.-A. Persson, A. Lundstjälk, Y. Hedberg, I. Odnevall Wallinder, H. Karlsson, P. Bengtsson, R. A. Wagner, E. Siewert, N. Hussary, P.-O. Oskarsson, G. Säwemark, L.-Å. Bylund, E. Westin, A. Saric, M. Lundin, G. Bäck, J. Surakka, "*Minimized risk for exposure and release of harmful substances when welding stainless steels"*, **Final report, Vinnova, Metalliska Material**, 2018-04-13.
- Y. Hedberg, *'A focus on surface oxide speciation and release of hexavalent chromium from welding'*, **International Welding Institute Commission IIX intermediate meeting**, 20-21 February 2019, invited speaker, Cambridge, UK.
- S. Mc Carrick, Z. Wei, N. Moelijker, R. Derr, K.-A. Persson, G. Hendriks, I. Odnevall Wallinder, Y. S. Hedberg, H. L. Karlsson, *"High variability in toxicity of welding fume nanoparticles from stainless steel in lung cells and reporter cell lines: the role of particle reactivity and solubility"*, **Nanotoxicology**, 13:1293-1309, 2019. Download: https://www.tandfonline.com/doi/full/10.1080/17435390.2019.1650972
- Y. Hedberg, H. L. Karlsson, R. A. Wagner, P. Bengtsson, I. Odnevall Wallinder, K.-A. Persson, K. Trydell, E. Westin, M. Lundin, *"Forskning om skadliga metaller i svetsrök - Nya rörelektroder avger mindre sexvärt krom [Research on hazardous metals in welding fume – new welding electrodes emit less hexavalent chromium]"*, **Svetsen** 3: 21, 2020.
- Press release from Karolinska Institute: https://nyheter.ki.se/stor-skillnad-i-skadlig-effekt-av-partiklar-i-svetsrok [Big difference in harmful effects of welding fume]
- Z. Wei, S. McCarrick, V. Romanovski, J. Theodore, N. Mei, K.-A. Persson, O. Runnerstam, H.L. Karlsson, I. Odnevall Wallinder, Y. Hedberg, *"Minimized risk for exposure and release of harmful substances when welding stainless steels"*, 23-25 October 2019, poster presentation, **Materials and Formulations at Biointerfaces**, a symposium on surface chemistry and materials science, Malmö, Sweden Sweden.
- Y. Hedberg, *"Physicochemical characteristics of welding fume nanoparticles determine their adverse health impact"*, 23-25 October 2019, Nouryon invited speaker, Nouryon Nordic Prize session, **Materials and Formulations at Biointerfaces**, a symposium on surface chemistry and materials science, Malmö, Sweden.

Publications from this study

Scientific articles

- S. McCarrick, V. Romanovski, Z. Wei, E. M. Westin, K.-A. Persson, K. Trydell, R. Wagner, I. Odnevall, Y. S. Hedberg, H. L. Karlsson, *"Genotoxicity and inflammatory potential of stainless steel welding fume particles – an in vitro study on standard vs Cr(VI)-reduced flux-cored wires and the role of released metals"*, **Archives of Toxicology**, DOI 10.1007/s00204-021-03116-x. Download: https://link.springer.com/article/10.1007/s00204-021-03116-x
- Y. S. Hedberg, Z. Wei, S. McCarrick, V. Romanovski, J. Theodore, E. M. Westin, R. Wagner, K.-A. Persson, H. L. Karlsson, I. Odnevall Wallinder, *"Welding fume nanoparticles from solid and flux-cored wires: solubility, toxicity, and role of fluorides"*, **Journal of Hazardous Materials**, 413(5 July): 125273, 2021. Download: https://www.sciencedirect.com/science/article/pii/S0304389421002363

Popular science and magazine articles

- Y. Hedberg, *News within health and safety from commission VIII of the International Institute of Welding*, **Weld Magazine**, Fall 2021, 70.
- Y. Hedberg, *Nytt inom Hälsa, Säkerhet och Miljö - International Institute of Welding (IIW)*, **Svetsen**, in press.
- Y. Hedberg, H.L. Karlsson, *Praktiska råd angående mangan och krom i svetsrök [Practical advice regarding manganese and chromium in welding fume]*, **Svetsen**, in press.
- Y. Hedberg, *"Schadstoffe beim Schweißen und bei verwandten Verfahren – Expositionen, Gefährdungen und Schutzmaßnahmenkonzept" (Spiegel-Ciobanu, DVS-Media GmbH, Düsseldorf, 2020)*, **Schweisstechnik Soudure**, 2021, 21 (1): 7.
- Y. Hedberg, H.L. Karlsson, *Practical advice related to manganese and hexavalent chromium in welding fume*, **Weld Magazine**, Spring 2021, 022-024. ***Attached as appendix to this final report***
- D. Hisey, Y. Hedberg, J. Galloway, *Recommended Protocols for Secondary School Welder Training Programs during Covid-19 Pandemic - Updated*, **Weld Magazine**, Winter 2020, 036-043.
- Y. Hedberg, *Nytt inom hälsa, säkerhet och miljö - International Institute of Welding [News on health, safety, and environment – International Institute of Welding]*, **Svetsen** 3: 21, 2020.

Conference contributions

- S. McCarrick, V. Romanovski, Z. Wei, E. M. Westin, K.-A. Persson, K. Trydell, R. Wagner, I. Odnevall, Y. S. Hedberg, H. L. Karlsson, *"Genotoxicity and inflammatory potential of stainless steel welding fume particles – an in vitro study on standard vs Cr(VI)-reduced flux-cored wires and the role of released metals"*, oral presentation by K. Trydell, **Joint Commission II and VIII meeting**, International Institute of Welding, virtual conference, July 7-21, 2021.
- E. M. Westin, S. McCarrick, Z. Wei, V. Romanovski, R. Wagner, K.-A. Persson, K. Trydell, I. Odnevall, H. L. Karlsson, Y. S. Hedberg, *"New weldable 316L stainless flux-cored wire with reduced Cr(VI) fume emissions"*, oral presentation by Y. S. Hedberg, **Joint Commission II and VIII meeting**, International Institute of Welding, virtual conference, July 7-21, 2021.
- Y. Hedberg, *"On the search for culprits of the high solubility of hexavalent chromium in some welding fume particles"*, International Institute of Welding document number VIII-2296-20, invited speaker, **73rd International Institute of Welding annual assembly and international conference**, 19-24 July, 2020, virtual conference.
- Y. Hedberg, *"The solubility of hexavalent chromium and manganese of welding fume determine their adverse health impact"*, 19 February 2020, invited speaker, **Commission VIII intermediate meeting**, International Welding Institute, Versailles, France.

Upcoming publications from this study

- E.M. Westin, S. McCarrick, L. Laundry-Mottiar, Z. Wei, M.C. Biesinger, I. Barker, R. Wagner, K.-A. Persson, K. Trydell, I. Odnevall, H.L. Karlsson, Y.S. Hedberg, *"New weldable 316L stainless flux-cored wires with reduced Cr(VI) fume emissions Part 1 – Health aspects of particle composition and release of metals"*, submitted as invited paper to Welding in the World, July 2021.
- E.M. Westin, S. McCarrick, L. Laundry-Mottiar, Z. Wei, R. Wagner, K.-A. Persson, K. Trydell, I. Odnevall, H.L. Karlsson, Y.S. Hedberg, *"New weldable 316L stainless flux-cored wires with reduced Cr(VI) fume emissions Part 2 – Round robin creating fume emission data sheets"*, submitted as invited paper to Welding in the World, July 2021.

For more information, please see the appendix, which contains one of our popular science articles. For more detailed information, please see any of our scientific articles, all of which are open access.

On behalf of the whole project group, I would like to thank ÅForsk for the financial support.

Yolanda Hedberg

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on behalf of the entire project group

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PRACTICAL ADVICE

RELATED TO MANGANESE AND HEXAVALENT CHROMIUM IN WELDING FUME

Occupational hygiene limit values in environments where welding fumes are generated can be challenging to meet for manganese (Mn) and hexavalent chromium Cr(VI). The amount of Mn and Cr(VI) in welding fume, and whether they find their way to the welder's breathing zone and are potentially released and induce acute toxicity, depends on many factors. Advanced and expensive measurements are required to make accurate estimations.

Our project investigated welding fume generated from different stainless steels, welded by active gas shielded metal arc welding (spray arc and short arc – high current and low current) using different electrodes; solid wire, flux-cored wire (FCW), metal-cored wire (MCW), and FCW developed to reduce Cr(VI). Some general advices are presented below which can be helpful to improve the daily safety work.

In Sweden, one part of the overall risk management is often based on measurements of the mass of welding fume and information in the safety data sheets (SDS) of the welding electrodes. However, the SDS information, which includes information on the electrode composition and possible hazards, is normally not correlating with either the amount of Mn and Cr(VI) in the welding fume or their solubility. For stainless steels, between 10 and 35 weight-% of chromium (Cr) and between 0.01 and 2.5 weight-% of Mn are declared in the SDS for the welding electrodes. The actual amount in the welding fume varies between 0.3 and 8 weight-% for Cr and between 2 and 14 weight-% for Mn, Figure 1. This means that Mn would be strongly underestimated based on information of the SDS only.

The solubility of the more hazardous form Cr(VI) in welding fume depends mainly on the type of welding electrode, Figure 1. Everything else is of minor importance. We have demonstrated that welding with solid wire results in a low solubility of Cr(VI), independent of other conditions, Figure 1. MCW shows the same behavior. Welding fume from FCW welding contains less metals in total, but is characterized by a very high solubility of Cr(VI) and Mn. An exception is FCW electrodes developed to reduce Cr(VI), which generated very low amounts of Cr(VI) at maintained or elevated levels of Mn. The special electrodes used in this study are, however, not yet commercially available.

In this work, 308L, 316L, 2209 and 2307 type of fillers have been investigated. Most Cr(VI) was released from welding fume generated from FCW spray arc welding of duplex stainless steels (independent of shielding gas composition). The solubility of Mn was lowest for welding fume generated from solid wire and MCW welding, Figure 1.

We measured the release of Mn and Cr(VI), in addition to other metals, into phosphate buffered saline (PBS) under conditions relevant for the human lung environment. Cr(VI) release in PBS correlated well with adverse effects in cultured human lung cells such as cytotoxicity (cell death) and DNA damage. Release of Mn correlated better with the ability of the particles to generate reactive oxygen species. It should be noted that our PBS release test correlated well with the ISO 16740 / ISO 15011 test method, which is testing the soluble Cr(VI) content in welding fume by an extraction method in alkaline conditions.

Based on our findings, we can give the following practical advice:

- All welding methods generate welding fumes. The amount can vary for different welding parameters, shielding gases, and wire material. It is always important to protect the welder with proper fume extraction equipment. This becomes increasingly important when welding with FCW due to the high concentration of either Cr(VI) or Mn.
- The fraction (relative amount) of Mn in welding fume is normally larger than what is specified in the SDS.
- The solubility and hazard of Mn and Cr in welding fume depend primarily on the type of the welding electrode. Welding electrodes of alloys containing higher amounts of Cr, such as duplex stainless steel, result in most soluble Cr(VI) in the fume.
- ISO standards 15011 (for collecting welding fume) and 16740 (for measuring soluble Cr(VI) in welding fume) can be used to estimate risks induced by Cr(VI) in welding fume. These measurements correlate well with our measurements and are directly linked with cytotoxicity and DNA damage.
- Stainless steel welding that generates a lot of fume is generally of higher risk due to more soluble Cr(VI) in the fume and due to increased risk for exposure.
- Welding in the short arc mode (low current), which is possible for some electrodes (solid and metal-cored wires), results in fumes with lower amounts of Cr(VI) and higher amounts of Mn as compared to spray arc (high current). W

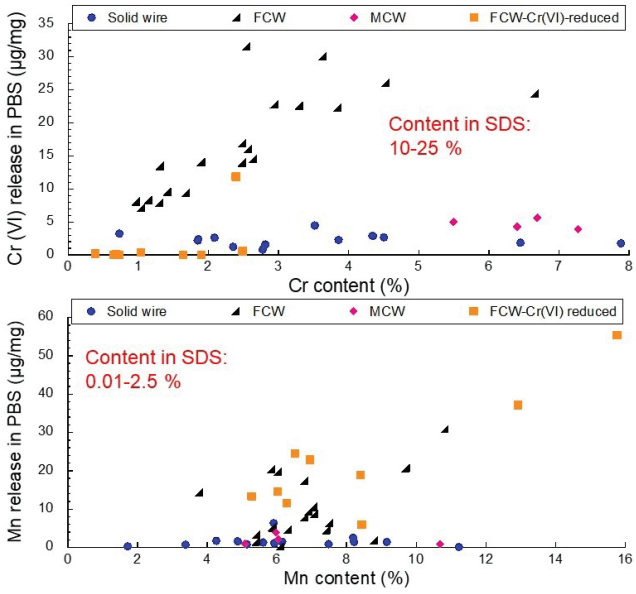

Fig. 1: Content of chromium (Cr) and manganese (Mn) in welding fume in weight-%, and release of Cr(VI) and Mn into phosphate buffered saline (PBS) at 37 °C and pH 7.4 after 24 hours. The information on the safety data sheet (SDS) is included for comparison.

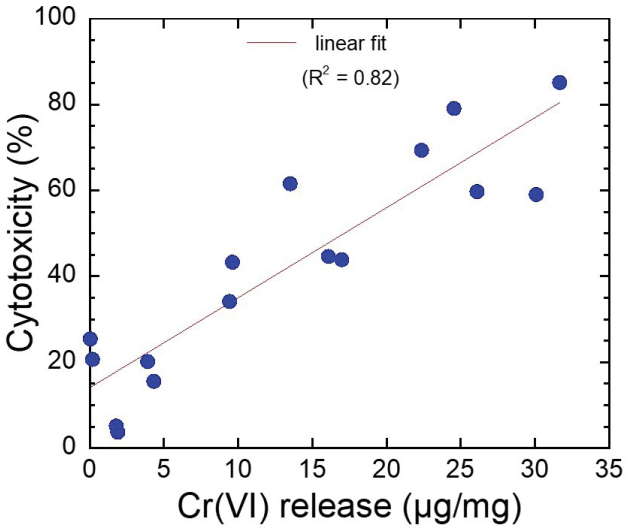

Fig. 2: Correlation between release of Cr(VI) from welding fume in PBS (37 °C, pH 7.4, 24 hours) and cytotoxicity induced in human epithelial lung cells (dose: 50 µg/mL, 24 hours).

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Read more:

S. Mc Carrick, Z. Wei, N. Moelijker, R. Derr, K.-A. Persson, G. Hendriks, I. Odnevall Wallinder, Y. S. Hedberg, H. L. Karlsson, High variability in toxicity of welding fume nanoparticles from stainless steel in lung cells and reporter cell lines: the role of particle reactivity and solubility, **Nanotoxicology**, 13:1293-1309, 2019. https://doi.org/10.1080/17435390.2019.1650972

N. Mei, L. Belleville, Y. Cha, U. Olofsson, I. Odnevall Wallinder, K.-A. Persson, Y. Hedberg, Size-separated particle fractions of stainless steel welding fume particles – a multi-analytical characterization focusing on surface oxide speciation and release of hexavalent chromium, **Journal of Hazardous Materials**, 342: 527-535, 2018. https://doi.org/10.1016/j.jhazmat.2017.08.070