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Effectiveness of amorphous silica encapsulation technology on welding fume particles and its impact on mechanical properties of welds

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ABSTRACT

Stainless steel welding generates nano-sized fume particles containing toxic metals which may cause serious health effects upon inhalation. The objective of this study was to investigate the effectiveness of an amorphous silica encapsulation (ASE) technology by evaluating its silica coating efficiency (SCE), particle morphology, and its impact on the weld's mechanical properties. Tetramethylsilane (TMS) added to the welding shielding gas decomposed at the high-temperature arc zone to enable the silica coating. Collected welding fume particles were digested by two acid mixtures with different degrees of silica solubility, and the measured mass differences in the digests were used to determine the SCE. The SCEs were around 48–64% at the low and medium primary shielding gas flow rates. The highest SCE of 76% occurred at the high shielding gas flow rate (30 Lpm) with a TMS carrier gas flow of 0.64 Lpm. Transmission electron microscopy (TEM) images confirmed the amorphous silica layer on the welding fume particles at most gas flow rates, as well as abundant stand-alone silica particles formed at the high gas flow rate. Metallography showed that welds from the baseline and from the ASE technology were similar except for a tiny crack found in one particular weld made with the ASE technology. Tensile tests showed no statistical difference between the baseline and the ASE welds. All the above test results confirm that welding equipment retrofitted with the ASE technology has the potential to effectively address the toxicity problem of welding fume particles without affecting the mechanical properties of the welds.

1. Introduction

Stainless steel contains alloying metals such as chromium (Cr), nickel (Ni), and manganese (Mn) [1]. These metals in welding filler material such as wires and electrodes can vaporize during the welding process due to the high temperature of the welding arc. The metals are oxidized and subsequently form nano-sized particles as the temperature drops [2,3] which may stay airborne in welders' breathing zones [4]. Among all the metals in welding fumes, hexavalent chromium (Cr^{6+}) and nickel are known human carcinogens [5], while manganese (Mn) is a neurotoxin that can induce neurological symptoms such as recognition dysfunction [6,7]. Numerous toxicological studies have shown that welders inhaling fume particles are exposed to these toxic metals and bear the risk of respiratory diseases, neurological symptoms, and cancer [7–11]. Because of their nanometer to submicron size, the inhaled particles can penetrate deeply into the human respiratory tract [12,13]. Upon contact with human organs, these metals can be released from the particles, absorbed, distributed, and metabolized [14].

Although the Occupational Safety and Health Administration (OSHA) does not currently regulate total welding fumes, the National Institute for Occupational Safety and Health (NIOSH) considers welding fumes to be potential occupational carcinogens and has set the recommended exposure limit (REL) at the lowest feasible concentration [15]. The American Conference of Governmental Industrial Hygienists (ACGIH) has also assigned welding fumes an 8-h time weighted average (TWA) threshold limit value (TLV) of 5 mg/m^3 [16].

There are various ways to mitigate the emission of welding fume particles and reduce fume exposure [17]. The most effective methods are personal protective equipment (PPE) such as respirators [18] and local exhaust ventilation [19,20]. Control technologies targeting Cr^{6+} have also been developed. For example, shielding gases [21], and shielded metals [22] have been used to protect metals from oxidation by oxygen species in the welding arc zone. Replacing Cr in stainless steel with other materials can also reduce the Cr^{6+} emissions [23]. However, these Cr^{6+} specific technologies have little to do with the other metals in the fume

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particles, and none are well received yet by the industry. In addition, none of these technologies has addressed their potential impact on the welds' mechanical properties.

Coating an amorphous silica layer on particle surfaces to insulate engineered nanoparticles from degradation from exposure to the surrounding environment has been reported in various studies [24–27]. It has also been demonstrated to be an effective measure for controlling nano-sized metal particle emissions from combustors and incinerators [28–30]. This concept, when implemented in welding (as shown in Fig. 1), has been labeled amorphous silica encapsulation (ASE) and presents a potential solution that can reduce the toxicity of welding fume particles provided the silica coating layer is in the amorphous phase. Indeed, X-ray diffractograms (XRD) of the coated fume particles confirmed that the in situ generated silica was all in the amorphous phase [31], hence eliminating the potential hazard of crystalline silica. The amorphous silica layer on metal particles can insulate the metal species from absorption when inhaled. Additionally, silica thus formed yields a web-like network structure that effectively increases the size of the particles. Furthermore, the decomposition of the silica precursor scavenges oxygen species, thus suppressing the oxidation of Cr to Cr^{6+} [31–33].

A previous study on silica coating efficiency (SCE) used welding as an example [34]. The results using a premixed shielding gas containing a silica precursor showed the SCE to be about 14–38%, depending on the flow rate used. The relatively low SCE resulted from the premature decomposition of the silica precursor, i.e., the spatial and temporal mismatch of metal vapor's nucleation and silica condensation. At low shielding gas flow, when the gas could not effectively disperse the heat, thermal energy induced the decomposition of the silica precursor and the formation of silica particles inside the nozzle and outside the welding arc zone, before welding fume particles had even formed. Recently, a newly designed insulated double shroud torch (IDST) was developed to address this premature decomposition issue [33]. The IDST design involves a ceramic wall in the torch to insulate the heat between the primary shielding gas and the silica precursor carrier gas (as shown in Fig. 1), thus preventing the premature decomposition of the silica precursor that occurs when the gases are premixed. While the testing showed reduction of airborne Cr^{6+} concentration to below the detection limit, the impact on SCE and the mechanical properties of the weld remained unknown. Knowledge of SCE is imperative due to the fact that uncoated fume particles still come into direct contact with human organs. Verification that the mechanical properties of the weld had not been altered by the addition of the silica precursor is critical, if the technology is to be accepted and adopted by the industry.

The objectives of this study were to assess the effectiveness of the ASE technology with IDST feeding to encapsulate the welding fume particles and to characterize the mechanical properties of welds. Both quantitative analysis of SCEs and qualitative TEM images were acquired for evaluating the conditions of encapsulation. The weld generated from the ASE technology underwent a series of mechanical property tests to validate the applicability of the ASE technology to welding practices.

2. Experimental method

2.1. Welding fume generation

Sampling of welding fumes (Fig. 2) followed the American Welding Society (AWS) fume hood design [35]. Welding fumes were generated in an enclosed conical chamber of 36 inches in diameter at the base, 8 inches in diameter at the top, and 36 inches in height. A high-volume flow pump (General Metal Works GL-2000H, Cleves, OH) was mounted on top of the chamber. The welding fume particles generated were collected onto a glass fiber filter (Whatman 90 mm GF/B 1821-090, Maidstone, Kent, UK).

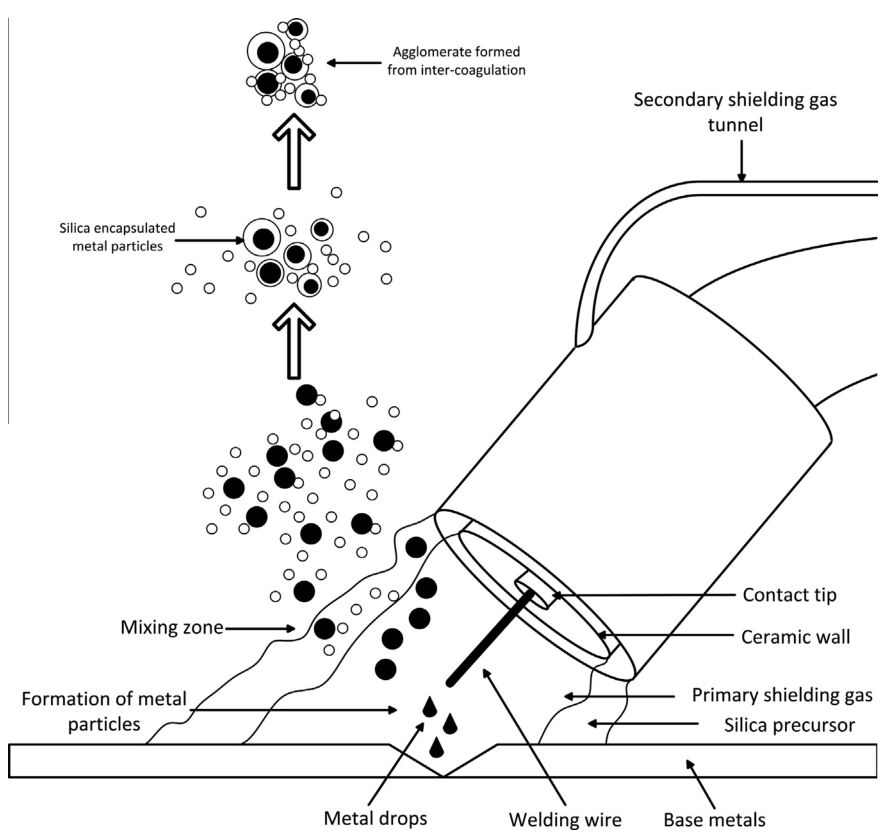

Fig. 1. Mechanistic illustration of the ASE technology in welding application.