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.

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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 (Cr⁶⁺) 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/m³ [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 Cr⁶⁺ 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 Cr⁶⁺ emissions [23]. However, these Cr⁶⁺ specific technologies have little to do with the other metals in the fume emissions.
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 fume particles 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).
A welding machine (Lincoln Power MIG 140C, Cleveland, OH) was used in the study. The voltage and wire speed were kept at 19.5 V and 100 inches per minute (ipm) throughout the study. The welding wires used were ER 308L stainless steel of 0.035 inch diameter, with a nominal composition of 19.5–22.0% Cr, 9.0–11.0% Ni, and 1.0–2.5% Mn. Studies such as Gonser and Hogan [36] showed over 95% of the welding fume originated from filter material. In other words, the choice of the base metal should not affect the composition and toxicity of the welding fume. In this study, mild steel base metal was used to minimize costs instead of stainless steel. The base metal plates were placed on a rotating turntable (MK Products Aircrafter T-25, Irvine, CA) at the bottom of the chamber (as seen in Fig. 2). A stand was used to hold the welding gun and to keep the torch at a constant height relative to the base metals. The trigger of the welding gun was modified to allow remote control from outside the welding chamber. The chamber study simulated welding on the rotating plates for 1.5 min per sample. The length of the sampling period was based on those used in previous studies to ensure sufficient fume particles were collected for analysis.

An IDST replaced the conventional welding torch to allow separate flows of the primary shielding gas and the TMS carrier gas. The TMS carrier gas (argon) flowed through a Teflon impinger (Apex Instruments T507G, Fuquay-Varina, NC) filled with TMS liquid at the bottom. The impinger was immersed in an ice bath at 0 °C to lower the vapor pressure of TMS for controlling the amount of vapor entering the carrier gas. The TMS-saturated carrier gas was delivered to the welding arc zone through the outer shroud of the IDST. A mixture of 75% argon and 25% carbon dioxide was chosen as the primary shielding gas, based on the low power capacity of the welding machine. The flow rates of the primary shielding gas and the TMS carrier gas (listed in Table 1) were respectively controlled by a rotameter (Radnor HRF-1425-580, Radnor, PA) and a mass flow controller (Omega FMA5500, Stamford, CT).

The welding fume particles collected on the filter were gravimetrically measured before and after sampling, using an analytical scale (Sartorius MC210S) with a readability of 10 μg. Each sample was weighed three times and the mean value was calculated.

### 2.2. Analysis of silica encapsulation

Determination of SCE followed the methodology developed in a previous study [34], which used the acid resistance ability of the silica shell to measure SCE. Glass fiber filters loaded with welding fume particles were cut into two halves. One half was digested using 9 mL nitric acid (HNO₃, 68%) and 1 mL hydrofluoric acid (HF, 48–51%), which were aggressive enough to dissolve all the metals regardless of their coating conditions. The other half was digested using 10 mL aqua regia, a mixture of HNO₃ and hydrochloric acid (HCl, 38%) (1:3 v/v), which only dissolved metals not encapsulated in the silica shell. The SCE was thus calculated by using the differences in measured metal mass in the following equation:

\[
SCE = \frac{\sum_{i=1}^{N} C_{NF,i} - \sum_{i=1}^{N} C_{AR,i}}{\sum_{i=1}^{N} C_{NF,i}} \times 100\%
\]

where SCE is in percentage (%), \(N\) is the number of metals involved (three in this study), \(C_{NF,i}\) is the measured concentration of the \(i\)th metal digested by HNO₃/HF mixture, \(C_{AR,i}\) is the measured concentration of the \(i\)th metal digested by aqua regia. In other words, SCE represents the ratio of encapsulated metals to total metals measured.

The digestion was done using a microwave digestion system (CEM MDS 81D, Matthews, NC) following the eight-step protocol described in the previous study [34]. The digests were cooled, filtered, and diluted. Measurement of the mass of each metal in diluted solutions was conducted with inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Perkin–Elmer.

<table>
<thead>
<tr>
<th>Primary shielding gas (Lpm)</th>
<th>TMS carrier gas (Lpm)</th>
<th>Mass of collected fume particles (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (low)</td>
<td>0.16</td>
<td>12.3 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>13.1 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>11.7 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>12.4 ± 0.6</td>
</tr>
<tr>
<td>25 (medium)</td>
<td>0.16</td>
<td>13.6 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>12.8 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>14.2 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>13.0 ± 1.2</td>
</tr>
<tr>
<td>30 (high)</td>
<td>0.16</td>
<td>17.6 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>16.5 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>19.2 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>21.4 ± 2.3</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic diagram of the TMS feeding apparatus and the welding fume chamber.
Plasma 3200, Norwalk, CT). Two atomic emission spectral lines for each metal (Cr, Ni, and Mn) were used simultaneously to reduce spectral interference introduced by other co-existing elements in the welding fume. The operating conditions and spectral lines selected are listed in Table 2. The concentration of each metal in a sample was determined by averaging the results of five reading replicates.

Transmission electron microscopy (TEM, JEOL 2010F, Peabody, MA) was used to observe the morphology and silica encapsulation conditions of the welding fume particles. The JEOL 2010F has an ultrahigh spatial resolution below 1 nm. A specialty grid (Pelco 300 mesh, Ted Pella, Redding, CA) was inserted into the welding chamber, as shown in Fig. 2. The grid was held for 30 s in the welding fume stream drawn upwards by the pump. Fume particles thus attached to the ultrathin lacy carbon film on the grid. Images of both the baseline and the ASE samples were captured. The microscopic image is a supplemental tool for determining the effectiveness of the ASE technology. However, TEM only focused on a fraction of the welding fume particles and was limited to a two-dimensional plane.

### 2.3. Mechanical property tests

It is difficult to generate welds of high quality using the chamber system due to problems of the welder’s access to the enclosed environment. The welds for mechanical property tests were generated at an industrial facility that regularly conducts welding activities. The modification to the conventional welding system in the facility for the IDST was similar to the laboratory chamber setup, except with a different welding machine (Miller Invision Plasma 3200, Norwalk, CT). The IDST was designed to compare the performance of welds generated from the baseline and ASE technology.

### 2.4. Quality control and statistics

All chemicals used were analytical grade or higher in purity. DI water used for dilution and cleaning was deionized and purified by a Nanopure system (Barnstead Nanopure D11901, Thermo Fisher Scientific, Waltham, MA) to a conductivity of 18.2 mΩ cm. All acid solutions (Acros Organics, Morris Plains, NJ) were at their original concentration and not diluted. All the shielding gases used were ultra-high purity and certified by the manufacturers (Airgas and Air Liquide). The glassware used in the study was cleaned in an ultrasonic cleaner (FS220, Thermo Fisher Scientific, Waltham, MA) for 4 h, and dried in an Isotemp oven (FS230G, Thermo Fisher Scientific, Waltham, MA) in a laminar flow hood. The tubing in the sampling system was Polytetrafluoroethylene (PTFE) or Tygon, and air leaking tests were performed regularly.

The calibration curve for chemical analysis was obtained from external standards. Standard solutions were prepared by diluting high-purity stock solutions with DI water: 1000 mg/L Ni and 1000 mg/L Mn (SpeX Certiprep, Metuchen, NJ) and 1000 mg/L chromate (CrO32−) (Acros Organics, Morris Plains, NJ).

All the samples were pentaplicate per each combination of the primary shielding gas flow rate and the TMS carrier gas flow rate. t-test was used to examine the results from different combinations using a significance level of p = 0.05. Statistical analyses were performed using the statistical software SAS 9.3.

### 3. Results and discussion

#### 3.1. Silica encapsulation

Fig. 3a–c shows SCEs under different combinations of primary shielding gas and TMS carrier gas flow rates. Overall, the SCE ranged from 31–76%, which was a significant improvement from the SCE of 14–38% with premixed gases in the previous study [34]. Furthermore, the TMS carrier gas feed rate was below 1 Lpm (compared to over 2 Lpm when the gases were premixed.) Inspection of the welding gun revealed few deposits of white silica powder, verifying a lower degree of premature decomposition of the TMS. These pieces of evidence prove that the IDST design can deliver silica precursor to the welding arc zone more effectively and efficiently than the premixed gas method while decreasing the costs associated with feeding excessive TMS.

Under the low and medium shielding gas flow rates, the highest SCEs were similar at 64%. The highest SCE for 20 Lpm (low) primary shielding gas flow was 64 ± 6.1%, feeding with only 0.16 Lpm TMS carrier gas, and there was no statistical difference in SCE among 0.32–0.96 Lpm TMS carrier gas flow rates (p > 0.1). The SCE of the 25 Lpm (medium) primary shielding gas flow reached a maximum of 64 ± 9.4% at 0.32 Lpm TMS carrier gas flow rates, and no statistical difference for the rest of TMS carrier gas flow rates. The 30 Lpm (high) shielding gas flow showed a different trend. The SCEs were low at 31 ± 4.9% and 38.3 ± 2.8% at 0.16 Lpm and 0.32 Lpm TMS carrier gas flow rates, respectively. Although a maximum SCE of 76 ± 7.9% occurred at 0.64 Lpm TMS carrier gas flow, it decreased to 43 ± 9.0% after further increase of the TMS carrier gas flow rate.

Table 1 lists the mass of collected fume particles under the different conditions tested. The gravimetric measurements of collected fume particles under low and medium primary shielding gas flows were significantly lower than those of high shielding gas flow (p < 0.01). Hence, the ASE technology was able to deliver enough in situ generated silica to coat the relatively low amount of welding fume particles under low and medium primary shielding gas flows. However, coating under high primary shielding gas flow (30 Lpm) was less effective with low TMS feed rates, at least...
partially due to the high mass of welding fume generated. At very high TMS feed (0.96 Lpm), both the primary and the TMS carrier flows might disperse the silica vapor and metal particles to a larger mixing zone and therefore reduce the time of interaction. The chaotic condition at high gas flow was confirmed by the TEM images later, with a large quantity of uncoated metal particles and the formation of stand-alone silica particles.

By delivering TMS into the effective mixing area using the IDST technology, it was hoped that the SCE would be near 100% and all metal particles would be fully encapsulated. However, the welding process naturally contains a high intensity of ultraviolet (UV) light emitted from the welding arc. TMS inevitably undergoes photolysis under UV [38] in undesirable locations such as inside the welding gun. This was confirmed by the trace amount of silica powder deposits in the torch. To further improve SCE, aerosol dynamic modeling of the welding fume system will be needed to provide helpful insights into the effects of the UV and other influential factors. These insights can be used to optimize the silica precursor delivery setup.

The calculation of SCE was done by summing up the differences in mass of individual metals. The mass of iron (Fe) was excluded from the calculation due to its insignificant toxicity, even though Fe is a major component among the metals in welding fume particles. Other trace metals present only in extremely low amounts in the welding fume particles were also disregarded. Hence, SCE as calculated was toxicity-weighted with Cr, Ni, and Mn. In addition, SCE measurements only counted particles fully enclosed in a hermetical silica shell (i.e., partially encapsulated particles were not

![Fig. 3. SCE as a function of TMS carrier gas flow rate at: (a) 20 Lpm; (b) 25 Lpm and (c) 30 Lpm primary shielding gas flows.](image)

![Fig. 4. TEM images of: (a) baseline welding fume particles without any coating; (b) welding fume particles agglomerate with a distinct silica layer; (c) 2 × magnification view of the fume particles and silica layer in (b) and (d) welding fume particles with excessive silica particles formed.](image)
counted as encapsulated). In short, SCE measurements conserva-
tively quantify the reduction in the bioavailable mass of selected
toxic metals (Cr, Ni, and Mn) caused by encapsulation of these
toxic particles in amorphous silica shells.

3.2. TEM Imagery

Fig. 4a–d displays the TEM imagery of welding fume particles
under various conditions. Because of the penetration ability of
electrons when interacting with the particles, metals with a high
electron density are typically darker on a bright-field TEM image
while silica is lighter with its low electron density [39].

Fig. 4a depicts the welding fume particles generated from
30 Lpm primary shielding gas without the introduction of TMS.
The diameter of the welding fume particles ranged from
10–100 nm. From the 2D image, it was difficult to determine if
the particles were chain-like agglomerates or overlapped at differ-
ent planes.

Fig. 4b and c show welding fume particles generated from
30 Lpm primary shielding gas and 0.64 Lpm TMS carrier gas flow
with SCE of 76 ± 7.9%. The images showed a silica-encapsulated
metal agglomerate, with a clear boundary between the amorphous
silica layer and its metal components. By comparing with Fig. 4a, it
was observed that the primary particle size was smaller than that
in the baseline case. The result suggests that the silica coating pre-
vented sintering of metal particles. Fig. 4c also showed that encap-
sulated metal particles have different shapes, from spherical to
polygonal. The nano-sized primary metal particles were bound to
an agglomerate particle with a larger equivalent diameter through
the inter-coagulation mechanism [40]. This resultant increase in
particle size can effectively reduce respiratory tract deposition,
due to the low deposition of particles around 200–300 nm [41].

Fig. 4d shows the welding fume particles generated from
30 Lpm primary shielding gas and 0.96 Lpm TMS carrier gas flows
with SCE of 43 ± 9.0%. The particles are more randomly arranged,
due to the high amount of welding fume particles generated and
possible poor mixing interaction between silica vapor and metal

Table 3

<table>
<thead>
<tr>
<th>Standard material/Welds</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Si</th>
<th>Mo</th>
<th>Cu</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER 310 stainless steel welding wire specification [46]</td>
<td>25.0–28.0</td>
<td>20.0–22.5</td>
<td>1.0–2.5</td>
<td>0.30–0.65</td>
<td>N/A*</td>
<td>N/A*</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Baseline</td>
<td>26.5</td>
<td>20.0</td>
<td>1.19</td>
<td>0.47</td>
<td>0.14</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>ASE technology</td>
<td>26.0</td>
<td>19.7</td>
<td>1.21</td>
<td>0.47</td>
<td>0.14</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* No standard values for the elements Mo and Cu in the specification.
particles. In the situation of excessive TMS feed, the silica vapor was more likely to form stand-alone silica particles than to condense on the surface of metal particles. The same phenomenon was also observed at the 0.96 Lpm TMS carrier gas flow with 20 and 25 Lpm primary shielding gas. Some metal particles were trapped in the silica matrix, but a high level of excess silica particles formed from feeding a high amount of TMS warrants investigation of the health effects. Some studies showed that amorphous silica particles may cause phagocytosis but the mechanism by which this occurs is not clear [42–44]. Meanwhile, our previous study showed amorphous silica itself produced in welding process exhibited no toxicity to *E. coli* [45]. TEM imagery supports the idea that there is an optimal TMS carrier gas flow rate for applying the ASE technology, i.e., a rate to allow sufficient silica vapor for the amount of metal particles, without causing an overflow of excess silica particles.

3.3. Mechanical properties

The chemical compositions of the welds in weight percentage (wt%) from the baseline and the ASE technology are listed in Table 3. Cr, Ni, Mn, and other elements in both conditions were almost identical to the specification of standard ER 310 stainless steel listed in AWS standard [46]. It was also noted that the ASE technology did not introduce extra Si content into the welds, while extra Si could adversely affect weld quality [47].

The macrostructures of the welds are shown in Fig. 5. The weld metal and base plate are labeled as WM and BP, respectively. The welds of the baseline technology revealed typical columnar grains adjacent to fine grains of the base plates. The welds from the ASE technology were identical to the baselines in macrostructure with no weld defect.

Fig. 6a displays the microstructure of one particular baseline weld. The baseline weld was comprised of grains within the hundreds of micron range, adjacent to the fine grains in the heat-affected zone (HAZ) and the fusion line (FL). The microstructures of the baseline weld showed the presence of intermetallic particles onto which the grains nucleated. The microstructures of one particular weld generated by the ASE technology are shown in Fig. 6b. The weld was generally similar to that of the baseline, except for a tiny crack at the interface of the HAZ and weld metal (WM). It is possible that the addition of gas (TMS/Ar) created a gas pocket that coalesced into a crack. However, no crack was found in other welds from the ASE technology.

The results of the tensile tests of the welds are shown in Fig. 7a, and the detailed data are in Table S-1. The yield strength (YS) of the welds from the baseline and the ASE technology were identical, 44 ± 1 kilo-pounds per square inch (ksi). Meanwhile, the ultimate tensile strength (UTS) of the welds from the baseline and the ASE technology were 83 ± 4.3 ksi and 77 ± 8.1 ksi, respectively, with no statistical difference (*p* > 0.1). Fig. 7b shows the comparison of average elongation of welds from the baseline and the ASE technology. Again, the elongation values showed no statistical difference (*p* > 0.1). The AWS requirement [46] for ER 310 stainless steel is also displayed. It should be noted that the AWS minima for UTS and elongation are established for standard materials with uniform composition, not for welds involving a combination of welded metal, HAZ, and base metal. Hence, these AWS minima are included for reference only. As both the baseline and the ASE samples were lower than the AWS minimum, welder inexperience working with a new welding shielding gas additive likely is a major factor contributing to the imperfect welds. If not from the statistical aspect, the result indicated that the ASE technology reduced tensile strength in some samples. While the ASE technology did not statistically deteriorate the mechanical quality of the welds, optimization of different welding parameters to achieve better tensile property certainly should be considered.

4. Conclusions

The ASE technology applied to the stainless steel welding process is an emerging method for effective minimization of welder exposure to toxic nano-sized welding fume particles. Overall, 31–76% of Cr, Ni, and Mn in the welding fume particles were completely encapsulated in a layer of amorphous silica by feeding the TMS carrier gas into the welding arc zone through the IDST. At low and medium primary shielding gas flow rates, the SCE was similar and reached a maximum of 64% at a moderate TMS carrier gas flow rate. At the high primary shielding gas flow rate, the SCE was 76% at 0.64 Lpm TMS carrier gas flow rate, and much lower at other TMS carrier gas flow rates. The high amount of welding fume generated at high primary shielding gas flow rate likely contributed to the low SCE. The high gas flows possibly caused a poor mixing, reduced the exposure time, and resulted in a low SCE and the formation of more stand-alone silica particles, which was confirmed by the TEM images. On the other hand, the TEM images also showed a distinct silica layer on the primary metal particles and agglomerates at the optimal gas flow rate.

The result also showed that introducing TMS as an additive to the shielding gas did not change the metal and Si contents in the welds. The metallography of welds generated from the baseline and the ASE technology were similar. A tiny crack was found in the microstructure of one particular weld from the ASE technology. The yield strength, ultimate tensile strength, and elongation of
welds from the baseline and the ASE technology showed no statistical difference. The ASE technology may be further optimized to achieve both a higher SCE and mechanical properties through tools such as computational fluid dynamic simulations combined with aerosol dynamics. Toxicological studies are also essential to help fully realize the potential health benefits brought by the ASE technology.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.matdes.2013.08.002.

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