ABSTRACT

Both powder particle size control and efficient use of gas flow energy are highly prized goals for gas atomization of metal and alloy powder to minimize off-size powder inventory (or “reverb”) and excessive gas consumption. Recent progress in the design of close-coupled gas atomization nozzles and the water model simulation of melt feed tubes were coupled with previous results from several types of gas flow characterization methods, e.g., aspiration measurements and gas flow visualization, to make progress toward these goals. Size distribution analysis and high speed video recordings of gas atomization reaction synthesis (GARS) experiments on special ferritic stainless steel alloy powders with an Ar+O₂ gas mixture were performed to investigate the operating mechanisms and possible advantages of several melt flow tube modifications with one specific gas atomization nozzle. In this study, close-coupled gas atomization under closed wake gas flow conditions was demonstrated to produce large yields of ultrafine (dia.<20 µm) powders (up to 32%) with moderate standard deviations (1.62 to 1.99). The increased yield of fine powders is consistent with the dual atomization mechanisms of closed wake gas flow patterns in the near-field of the melt orifice. Enhanced size control by stabilized pre-filming of the melt with a slotted trumpet bell pour tube was not clearly demonstrated in the current experiments, perhaps confounded by the influence of the melt oxidation reaction that occurred simultaneously with the atomization process. For this GARS variation of close-coupled gas atomization, it may be best to utilize the straight cylindrical pour tube and closed wake operation of an atomization nozzle with higher gas mass flow to promote the maximum yields of ultrafine powders that are preferred for the oxide dispersion strengthened alloys made from these powders.

INTRODUCTION

Powder particle size distribution control, both average particle size and standard deviation, are critical for a powder producer to remain globally competitive, especially for high cost alloy powders to minimize inventory and for special purposes that demand tailored distributions. Improved designs of close-coupled gas atomization nozzles and melt feed tubes can help achieve these goals. Close-coupled gas atomization
under open wake gas flow conditions was demonstrated [1] to provide robust powder particle size control for the production of Al powder over the size range of about 50 to 500 µm and with a narrow standard deviation as low as 1.53 (for d_{50}/d_{84}). Open wake gas flow (see Fig. 1b) offers only a singular atomization mechanism (liquid surface shear that follows the wave acceleration model) with the most intense effect at the melt orifice periphery, tapering off downstream. The robust size control demonstrated for Al powder also was enabled by stabilized pre-filming of the melt due to a slotted trumpet bell melt pour tube which promoted enhanced primary atomization [1].

![Diagram of gas flow features](attachment:image)

Figure 1. Schematic illustrations of the gas flow features of the gas-only flow field of Ar or N₂ flow from a close-coupled gas atomization nozzle, where the flow patterns are: a) closed wake and b) open wake, adapted from [2].

In the particular case of this investigation, it is most desirable to generate a powder particle size distribution that has a greatly enhanced yield of ultrafine (dia.< 20 µm) powders, similar to the most favored particle sizes for metal injection molding. More specifically, the challenge is to generate precursor powders of Fe-Cr-Y-(Ti,Hf) for oxide dispersion strengthened (ODS) ferritic stainless steel alloys that offer improved high temperature strength and creep resistance [3,4,5]. As such, these alloys are being considered for high temperature applications within future generation power reactors [6,7,8]. The improved mechanical properties associated with ODS alloys stems from interactions between nano-metric oxide dispersoids and dislocations within the alloy microstructure [7,8]. Consequently, the resulting ODS grain or sub-grain structure is dependent on the size, distribution, and volume fraction of the dispersoid phase and its thermal stability [6,7].

As a modification of the typical close-coupled inert gas atomization process, gas atomization reaction synthesis (GARS) was employed in this study as an economic alternative to the traditional high cost mechanical alloying (MA) processing route for the production of agglomerated/alloyed particulate that is used to make oxide dispersion forming ferritic stainless steel [9,10]. During the GARS process, a reactive atomization gas (i.e., Ar+O₂) is used to oxidize the surface of nascent molten metal droplets in situ during primary break-up and rapid solidification of the alloy. This rapid solidification process promotes the
formation of an ultra-thin kinetically favored metastable Cr-enriched surface oxide layer, which is used as a vehicle to transport a prescribed amount of solid-state oxygen into the consolidated microstructure along each prior particle boundary (PPB). Elevated temperature heat-treatment can promote an internal O-exchange reaction between the metastable Cr-enriched PPB oxide and Y-enriched intermetallic compound (IMC) phases that are within each former powder particle. This results in the formation of Y-enriched nano-metric oxide dispersoids throughout the alloy microstructure [11,12]. The size and distribution of the resulting Y-enriched dispersoids is controlled by the length-scale of microsegregation that occurs upon rapid solidification within the powders (i.e., particles with increased amounts of solute trapping or highly refined solidification structures result in smaller and more evenly distributed nano-metric oxide dispersoids) [12]. Thus, there is a preference to maximize the yield of ultrafine powders for this purpose.

With the single-minded purpose of maximizing the ultrafine powder yield, past research has concluded that it is best to utilize a nozzle that is designed to achieve wake closure. Although it can only be fully realized at one pressure with a compatible nozzle, the closed wake pattern (see Fig. 1a) offers two effective atomization mechanisms, i.e., the intense primary melt shear that follows the acceleration wave model and the shock disruption effect that is associated with the Mach shock disk [2]. As Fig. 2 shows, nozzle aspiration measurements permit the selection of a gas atomization nozzle with either a 30 or 45 degree apex angle for the discrete jets and a 45 degree nozzle was chosen for this study.

With the lessons of the open wake atomization study as a motivation, it was decided to test whether the enhanced melt flow stability and pre-filming effect of the slotted trumpet bell melt pour tube design [1] could increase the yield of ultrafine powders of a closed wake nozzle, in a similar way to its beneficial effect on control of open wake atomization. Thus, the intention is to promote more uniform and efficient atomization (presumably to finer sizes) by using the energetic action of all of the available gas jets, instead of overloading a small portion of jets at most times during the process [13].

From this knowledge base, the challenge of the current project was to determine the most effective combination of gas atomization system parameters, especially comparing two different melt pour tube designs, for generation of high yields of Fe-Cr-Y-X powder as fine to ultrafine spherical powder by the GARS process. Powder yield results and high speed video observations of simulated melt flow and real

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**Figure 2.** Summary of aspiration results that were collected for a set of identical gas atomization nozzles that varied only in the apex angle of the gas jets, where the figure was adapted from [2].
gas atomization experiments will be presented to investigate the operation and effectiveness of melt flow tube modifications with a selected close coupled nozzle that was intended to utilize closed wake flow conditions.

EXPERIMENTAL PROCEDURE

Gas Atomization Reaction Synthesis: For these gas atomization experiments [MPC ref.], the nominal atomization charge chemistry for the 4 “chemical reservoir” (CR) alloy powders is displayed in Table 1. The charge components were pure (99.9%) Fe (all) and Cr (CR-160, -162) or Fe-Cr master alloy (CR-164, -166), added to Fe-Y and either Fe-Ti (CR-160, -162, -166) or Fe-Hf (CR-164), provided by the Materials Preparation Center [14]. Each charge was loaded into the experimental gas atomization system and the atmosphere in the melting chamber and (connected) atomization system was evacuated with a mechanical pump to < 26.6 Pa prior to backfilling to 111 kPa of ultrahigh purity (UHP grade) Ar. Melting was performed in a yttria (Y$_2$O$_3$) painted yttria-stabilized zirconia (YSZ) bottom pour crucible and superheated to 1700-1725°C before pouring. The melt pour was initiated by raising a pneumatically actuated stopper rod, composed either of yttria painted alumina (CR-160) or of a composite (YSZ/W/hard fired Al$_2$O$_3$) design [16], which allowed the molten alloy to flow through a plasma arc sprayed pour tube, composed either of monolithic YSZ (CR-160) or of Y$_2$O$_3$ lined YSZ (CR-162, -164, -166).

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Charge Size (g)</th>
<th>Fe (balance)</th>
<th>Cr (at.%)</th>
<th>Y (at.%)</th>
<th>Hf (at.%)</th>
<th>Ti (at.%)</th>
<th>O$_2$ in Ar (vol.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-160</td>
<td>6,000</td>
<td>Bal.</td>
<td>16.0</td>
<td>0.21</td>
<td>-</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>CR-162</td>
<td>5,000</td>
<td>Bal.</td>
<td>16.0</td>
<td>0.21</td>
<td>-</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>CR-164</td>
<td>4,500</td>
<td>Bal.</td>
<td>16.0</td>
<td>0.21</td>
<td>0.12</td>
<td>-</td>
<td>0.19</td>
</tr>
<tr>
<td>CR-166</td>
<td>4,500</td>
<td>Bal.</td>
<td>16.0</td>
<td>0.21</td>
<td>-</td>
<td>0.12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

As one of the main features of this study, the internal design of each pour tube (see Fig. 3) was varied from straight cylindrical (GA-160, -162) to trumpet bell profile with either 4 slots (GA-164) or smooth with no slots (GA-166), all with a metering orifice of 2.8 mm. It should be noted that the exit orifice of the trumpet bell pour tube for CR-166 was only partially flared (due to machining error) with a blunt tip, having ~1.5 mm of flat base extending to the periphery. The melt exited the pour tube and was atomized with the Ar+O$_2$ gas mixture at a pressure of 6.55 MPa from a 45-30-029 close-coupled gas atomization nozzle (or die), having a jet apex angle of 45 degrees with 30 cylindrical gas jets, each with diameter of 0.737 mm (or 0.029 inches), arrayed around the axis of a 10.4 mm central bore [15].
Figure 3. Schematic of pour tubes with different interior designs, a) straight cylindrical, b) trumpet bell with no slots, and c) slotted (4 slots) trumpet bell.

The atomization gas supply pressure of 6.55 MPa was set to operate in a closed wake condition (see Fig. 1) slightly above the apparent wake closure pressure of about 6.2 MPa (see Fig. 2) that was measured on the test bench to account for slight additional pressure drop in the atomization system. It should be noted that constrictions of the regulator, valves, and tubing in the test bench system resulted in a pressure drop of about 2.2 MPa for this nozzle, since a manifold pressure of 4.0 MPa was determined by schlieren imaging to produce wake closure [15]. Secondary gas halos of Ar also were added to the interior of the spray chamber at downstream locations for additional cooling of the atomized droplets to inhibit sintering of the resulting powder.

Atomization Process Observations: High-speed cinematography was performed with self-illumination from the molten alloy, using a Phantom 7.1 high-speed video camera from Vision Research with a Nikon 85mm f/1.8D AF Nikkor lens set to f/16. Resolution was set to maximize the active pixels at framing rates, between 2,000 and 8,000 frames per second (fps), that were appropriate to capture the motion of the molten metal, starting with the onset of atomization, i.e., after a full stream had been established and the first evidence of attack by the atomization gas became apparent.

Resulting Powder Characterization: Powder size analysis started with screening of the full powder yield through a 106 µm ASTM sieve to eliminate atomization debris (splits and fibrous remnants of the non-steady state startup period) and riffling of the undersize spherical powder to divide the yield randomly into representative samples. A random sample from one of the rifflle tubes was taken for dispersal and automated characterization of the size distribution in a Microtrac unit (Nikkiso Co., Ltd.). A similar sample was also mounted with carbon paint for SEM observation to provide some confirmation of the particle size, along with useful analysis of shape, and “satellite” content.

RESULTS

A summary of the powder size analysis results from the 4 gas atomization trials is given in Table 2, below. It is apparent that the range of d50 results, from 43 to 29 µm, certainly demonstrates that this close-coupled gas atomization method is effective for atomizing significant yields of fine powder, dia.<45µm, i.e., at least about 50% by weight. Although there were systematic changes in the charge
quantity for the runs, the actual run times variations did not scale with the charge quantity due to several
types of experimental occurrences during each atomization trial, e.g., incomplete melting and/or pouring
for CR-160 and CR-166. Thus, the results for mass flow of gas and melt are not reported and no analysis
of the influence of gas/melt mass flow ratios on the resulting powder size distribution will be attempted.
It should be noted that the CR-164 trial was accomplished under full compliance with all of the intended
parameters, making future comparative experiments desirable. All things considered, the size analysis
results in Table 2 are considered to be reasonable indications of the effects of the pour tube variations, but
future atomization experiments that closely follow the CR-164 parameters (with similar gas and melt flow
rates) are needed to definitively rank the effectiveness of the straight cylindrical pour tube vs. the slotted
trumpet bell pour tube.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>d16 (µm)</th>
<th>d50 (µm)</th>
<th>d84 (µm)</th>
<th>Standard Deviation (d84/d50)</th>
<th>Run Time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-160</td>
<td>23.0</td>
<td>43.3</td>
<td>70.0</td>
<td>1.62</td>
<td>95</td>
</tr>
<tr>
<td>CR-162</td>
<td>13.4</td>
<td>30.6</td>
<td>60.8</td>
<td>1.99</td>
<td>65</td>
</tr>
<tr>
<td>CR-164</td>
<td>14.0</td>
<td>29.4</td>
<td>56.6</td>
<td>1.93</td>
<td>100</td>
</tr>
<tr>
<td>CR-166</td>
<td>16.7</td>
<td>35.8</td>
<td>63.5</td>
<td>1.77</td>
<td>42</td>
</tr>
</tbody>
</table>

The set of 6 still images in Fig. 4 are from a high speed (2,000 fps) video of the self-illuminated spray
from the CR-160 atomization experiment. The single frames show, in order; a) the onset of gas flow
acting on the free-falling stream and the clearest image of the extended interior ceramic tube from an
accidental fracture event [16], b) the start of melt transport across the flat base of the tip from the gas
recirculation force (see Fig. 1), c) further melt transport across the tip, d) nearly complete melt tip
transport and a brief truncation of stream, e) complete melt filming at the tip periphery and start of the full
atomization process, and f) a later spray image of stream/film wandering to the backside of the pour tube
periphery.
Figure 4. Set of 6 still images (in time sequence, but not sequential frames) from a high-speed (2,000 fps) video of the self-illuminated spray from the CR-160 atomization experiment, proceeding in chronological order from a) through f).

The images in Fig. 5 are a set of 6 still images from a high-speed (2,000 fps) video of the self-illuminated spray from the CR-162 atomization experiment. The sequence of single frames show: a) the onset of gas flow acting on the free-falling stream, b) the start of melt transport across the flat base of the tip in response to the force of the gas recirculation, c) further melt transport across the tip, d) nearly complete melt tip transport and brief truncation of the stream, e) complete melt filming at the tip periphery and the start of the full atomization process, and f) a later spray image of minor stream/film wandering away from the front of the pour tube periphery.
Figure 5. Set of 6 still images (in time sequence, but not sequential frames) from a high speed (2,000 fps) video of the self-illuminated spray from the CR-162 atomization experiment, proceeding in chronological order from a) through f).

Although only qualitative information can be obtained from SEM micrographs about the size distribution of the two runs with the straight cylindrical pour tubes, it can be useful to at least survey the powder morphologies and apparent differences. Thus, Fig. 6 presents SEM micrographs of representative samples of screened (dia.<106µm) powder from CR-160 and CR-162. First, it should be noted that both of the powder samples show very few satellite particles and are quite spherical in shape. It also is apparent after careful study that the CR-160 (see Fig. 6a) has a lack of the finest powers that are easily seen in Fig. 6b and that Fig. 6a also has the largest particles of the two micrographs.
Figure 6. SEM micrographs of representative samples of screened (dia.<106µm) powder from the two runs with the straight cylindrical pour tube.

From the automated size analysis on the screened and riffled powder samples, you will find the cumulative size distributions for all of the resulting powders in Fig. 7. In good agreement with the qualitative observations made about the micrographs in Fig. 6, the dashed lines in Fig. 7 show the difference between the d50 for the two runs with the straight cylindrical pour tube. This evidence provides quantitative measurement of the significantly smaller particle size that was generated by the CR-162 experiment.

Figure 7. Cumulative size distributions for all of the resulting powders, with dashed lines to show the difference between the d50 for the two runs with the straight cylindrical pour tube.

Fig. 8 exhibits a set of 6 still images from a high speed (4,000 fps) video of the self-illuminated spray from the CR-164 atomization experiment, showing; a) onset of gas flow acting on the free-falling stream, b) start of melt transport within the trumpet bell recess from the gas recirculation force of the closed wake mode (see Fig. 1), c) further melt transport within the recess, d) nearly complete melt tip transport within
the recess and a brief truncation of the stream flow, e) complete melt filming at the tip periphery and the start of the full atomization process, and f) a later spray image of illustrating near-uniform film ligamentation and breakup around the pour tube periphery.

Figure 8. Set of 6 still images (in time sequence, but not sequential frames) from a high speed (4,000 fps) video of the self-illuminated spray from the CR-164 atomization experiment, where the chronological order proceeds from a) through f).

In Fig. 9 a set of 6 still images from a high speed (8,000 fps) video of the self-illuminated spray from the CR-166 atomization experiment can be found that shows; a) the onset of gas flow acting on the free-falling stream, b) the start of melt transport within the trumpet bell recess from the gas recirculation force, c) further melt transport within the recess, d) nearly complete melt tip transport of liquid metal within the recess and across a part of the flat base and a brief truncation of the stream, e) complete melt filming at the tip periphery and start of the full atomization process, and f) a later spray image of near-uniform extended film and ligament breakup around the pour tube periphery.
Figure 9. Set of 6 still images (in time sequence, but not sequential frames) from a high speed (8,000 fps) video of the self-illuminated spray from the CR-166 atomization experiment, where the frames are in chronological order from a) through f).

With the same caveat about the qualitative information that can be obtained from SEM micrographs about the size distribution of the two runs with the trumpet bell interior profile, it is useful to at least survey the powder morphologies and apparent differences. Thus, Fig. 10 presents SEM micrographs of representative samples of screened (dia.<106µm) powder from CR-164 and CR-166. Again, it should be noted that both of the powder samples show very few satellite particles and are quite spherical in shape. It also is apparent immediately that the CR-166 sample (see Fig. 10b) has a near total lack of the finest powers that are easily seen in Fig. 10a and that Fig. 10b also has the largest particles of the two micrographs.
From the automated size analysis on the screened and riffled powder samples, the cumulative size distributions for all of the resulting powders are repeated in Fig. 11. In good agreement with the qualitative observations made about the micrographs in Fig. 10, the dashed lines in Fig 11 reveal the difference between the $d_{50}$ for the two runs with the trumpet bell pour tube profile. While showing far less of a difference in particle size than Fig. 10 seems to indicate, the data in Fig. 11 provides quantitative measurement of a smaller particle size that was generated by the CR-164 experiment compared to CR-166.

DISCUSSION

In general, the size distribution results from the four GARS experiments of this study indicate that the selected discrete jet close-coupled gas atomization nozzle operating in the closed wake mode is effective
for atomizing significant yields of fine powder, dia.<45µm, of at least about 50%. For ultrafine powder, dia.<20µm, at least about 11% and up to about 32% was produced, which compares very favorably to the best industrial yields, although full industrial particle size yield characteristics are closely guarded and typically not published. The fine and, especially, ultrafine yield of the fully developed gas atomization process for producing chemical reservoir (holding available oxygen) precursor powders will have a profound effect on the prospects for large scale commercialization of this attractive approach for low cost production of ODS ferritic stainless steel alloys that have extensive possible uses for both fossil energy [6] and nuclear (fission and fusion) energy [7] applications. Thus, it is important to examine the influences of the two types of melt flow guidance that can be offered by different designs of the melt flow tube orifice.

For the case of the straight cylindrical pour tube, it can be said that the first experiment (CR-160) was a non-ideal trial, since the pour tube cracked across its axis and slipped down slightly within the nozzle insert sleeve, as described in another report [16]. As the schematic in Fig. 12 shows, this extent of interference with the gas path can have a significant effect on the closed wake gas flow pattern (see Fig. 1) that was intended, effectively turning the operation of this nozzle into a degraded type of open wake flow. In other words, the sharp change of direction of the gas flow from the jets when they encounter the interfering tip surface would eliminate the Mach disk and decrease the momentum of the jets [2]. Also, after rebounding away from the interference, the maximum possible effective gas velocity (available for primary atomization) would be Mach 1, due to the formation of linked shock structures, e.g. Prantl-Meyer fans [17]. Therefore, it was expected that the resulting powder particle size of CR-160 was significantly (about 12 µm) larger than the companion run of CR-162 that performed in a much more ideal mode for this type of pour tube. The ideal mode is when a tip insert and ceramic pour tube are arranged to match the extended gas flow path (apex angle and position) of the inner wall of the jets, preserving the momentum of the gas and confining the interior of the free expansion of each jet without interference [2].

Figure 12. Schematic of the gas path interference effect (pictured as a simple collision reflection) of the straight cylindrical pour tube that broke and slipped down (about 1 mm) past the projected edge of the nozzle insert sleeve, where the apex angle (included total angle) of the jets is indicated by the arrows pointing to extension lines.
For the case of the two versions of the trumpet bell pour tube, it is clear that the intention of a test of slotted vs. non-slotted (smooth wall) trumpet bell designs was not met, since a machining error truncated the non-slotted trumpet bell and prevented a more direct comparison. Therefore, the true comparison is between a fairly ideal version of the slotted trumpet bell pour tube (CR-164) vs. a smooth wall type of trumpet bell profile with a truncated end (CR-166) that has a short (~1 mm doughnut) section of flat base that the melt must traverse radially (see Fig. 10d) before reaching the periphery. In terms of the effect of the truncation feature compared to the ideal “sharp” edge of the trumpet bell, Fig. 9e-f and 10e-f show that the melt film and the resulting ligaments may be thicker in the case of the truncated tip. This is consistent with the detectable reduction (7 µm) in the average particle size (d50) of the CR-164 run compared to the CR-166 results. Certainly, this type of tentative conclusion awaits a direct test of the reproducibility of the ideal slotted trumpet bell pour tube design before it can be said that this is a significant effect, i.e., leading to setting of closer tolerances on machining of the end of the trumpet bell tubes.

When operating in the closed wake (or with slight over-pressure for CW) condition, both types of high energy atomization mechanisms are activated, i.e., surface acceleration wave shear and shock disruption, and it appears that fine powder can be produced effectively in these experiments. However, the goals of higher yields of ultrafine (dia.<20µm) powder and further improved size control by use of the slotted trumpet bell pour tube to stabilize and pre-film the melt clearly was not demonstrated in the current experiments, as evidenced (see Table 2) by the nearly identical d50 and standard deviation for the two “best” experiments with both types of pour tubes. One of the lessons of the previous study [1] on size control over a wide range with a consistent open wake nozzle, achieved by use of a low (14˚) jet apex angle, as shown in Fig. 2, was that a large increase in gas flow was very useful for producing the most uniform particle size distribution, with standard deviations of 1.53-1.56. The increased gas flow was achieved by a 4X increase in gas nozzle exit area (over the companion nozzle that was being studied) without an increase in the gas jet interior circle (central axis bore diameter).

While atomization nozzles studied in the previous work had a large central axis bore (19.5 mm) to promote melt pre-filming and uniform melt disintegration, the current findings [18] on GARS processing of these ODS ferritic stainless steel alloys, argue against (at least raise a caution about) the use of a nozzle with an enlarged central bore. This is due to the tendency for enhanced oxidation of the pre-filmed melt in the interior recess of the slotted trumpet bell orifice (see Fig. 4c) in the current small bore nozzle that could be accentuated by the use of an enlarged nozzle, certainly for the case of a trumpet bell pour tube. It is suspected that excess oxidation of the pre-filmed melt before it is subject to atomization, i.e., after transport from within the interior recess to the periphery, would increase the melt viscosity and inhibit breakup into the finest possible droplets. Within the limits of the present experiments, this suspicion was confirmed tentatively by the failure to generate a significantly finer d50 in the CR-164 compared to the CR-162, in spite of the visually improved tendency (compare Fig. 6f to Fig. 8f) to thinner and more uniform melt filming and finer melt ligamentation. The thinner melt film is expected to produce finer droplets, according to the acceleration wave model [1], so increased melt viscosity from oxygen incorporation in the pre-filming recess is a likely suspect for preventing finer powder from being produced.

Therefore, if the most important goal is the highest yield of ultrafine Fe-Cr-Y-X powders from this GARS (oxidative) approach, it can be postulated that a significant increase in gas mass flow (e.g., from a 2-4X increase in gas jet exit area) is required, along with continued use of a straight cylindrical pour tube design. These changes to a gas atomization nozzle that may retain the same central bore diameter would boost the intensity of the Mach shock disk by adding gas mass and prevent any significant bypass of the shock disruption mechanism for melt fragments by further closing of the seams in the gas “curtain” (by additional gas expansion) that are due to the spacing of the discrete jets. This strategy of maintaining the compact size of this highly energetic closed wake gas atomization nozzle also may be attractive for
industrial use for the GARS process since the total gas consumption could still be lower than common types of annular slit close-coupled nozzles that are operated in closed wake condition. Of course, experimental proof must be generated to prove this extension of the analysis of the current results.

CONCLUSIONS

Close-coupled gas atomization under closed wake gas flow conditions was demonstrated to produce large yields of ultrafine powders (up to 32%) with moderate standard deviations (1.62 to 1.99).

The increased yields of fine powders is consistent with the dual atomization mechanism of closed wake gas flow patterns, with both intense atomization effects in the near-field of the melt orifice, tapering off downstream.

Enhanced size control by stabilized pre-filming of the melt with a slotted trumpet bell pour tube was not clearly demonstrated in the current experiments with closed wake gas flow, perhaps due to the confounding influence of the melt oxidation reaction that occurred simultaneously with the atomization process.

For this GARS variation of close-coupled gas atomization, it may be best to utilize the straight cylindrical pour tube and closed wake operation of an atomization nozzle with higher gas mass flow to promote the highest yields of fine and, especially, ultrafine powders.

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