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Pressure build-up at the metal delivery tube orifice in ultrasonic gas atomization

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The effects of geometry (diameter and tip design) and position (relative to the gas nozzles) of the metal delivery tube in an ultrasonic gas atomization (USGA) device on the pressure condition in the gas–metal interaction zone at the tube orifice have been studied. Simulation of ultrasonic gas (argon or nitrogen) atomization has been conducted, both at low (3.5 to 14 atm) and high (15 to 75 atm) atomization pressures. Low gas atomization pressures are generally used in spray deposition processes such as liquid dynamic compaction (LDC), while high pressures are used for powder production. Depending on the experimental conditions, i.e. the shape and angle of the taper at the metal delivery tube orifice or its position with respect to the nozzles' gas exit common plane, either partial vacuum (equivalent to downward aspiration of the melt) or overpressures (equivalent to back-pressurization of the melt) at the metal delivery tube was detected. Underpressure and overpressure effects were found to increase with gas atomization pressure. The maximum pressure differences measured with respect to the atomization chamber pressure were about 0.15 to 0.25 atm for the low-pressure experiments, and 0.50 to 0.60 atm for the high-pressure experiments. Underpressures or overpressures of these magnitudes have a large effect on the metal flow rate during gas atomization, either enhancing or reducing it, and thus changing significantly the gas to metal flow ratio. Because this is a crucial parameter for both the USGA and the LDC processes, the state of pressure at the delivery tube's orifice has to be monitored carefully, in order to ensure optimal processing conditions.

1. Introduction

The benefits associated with the rapid solidification of metals and alloys have been documented extensively [1–3]. Of the numerous rapid solidification techniques that are available today, gas atomization is the one most widely used, because it offers a large degree of processing flexibility with the potential for high tonnage production. The cooling rate obtained during gas atomization depends, among other factors, on the droplet size. The droplet size can be readily decreased, and the correspondingly cooling rate increased, by increasing the ratio of gas to metal flow rates [4–6]. In turn, the gas to metal flow ratio can be enhanced by raising the gas atomization pressure, and/or increasing the gas exit area at a given pressure. The metal flow rate depends on the metallostatic pressure head in the crucible (or tundish) and on the area of the metal delivery tube. Hence, during experiments in which the melt is not pressurized, as the metallostatic pressure head lowers, the metal flow rate decreases and the ratio of gas to metal flow rate increases.

Additionally, it has also been reported [6–9] that the metal flow rate depends upon the relative position of the metal delivery tube. For certain atomization conditions, a low-pressure zone is formed at the tip of the metal delivery tube that effectively causes an aspiration effect and increases the metal flow rate. Alternatively, for other atomization conditions, a high-pressure zone can form that effectively reduces the metal flow rate and in some cases even blocks it completely, or, in the extreme case, causes back-pressure on the melt [7]. Furthermore, the magnitude of the underpressure (aspiration) or overpressure (pressurization) at the tip of the metal delivery tube also depends on the atomization pressure [7, 8].

However, care must be exercized when selecting the position of the metal delivery tube with respect to the exiting atomization gas jets, as variations in position of the metal delivery tube have a strong effect on the atomization efficiency. When the position of the metal delivery tube is such that the atomization gas partly impacts the periphery of the tube instead of disintegrating the molten metal stream, large amounts of energy are wasted, and the resulting atomization efficiency is decreased.

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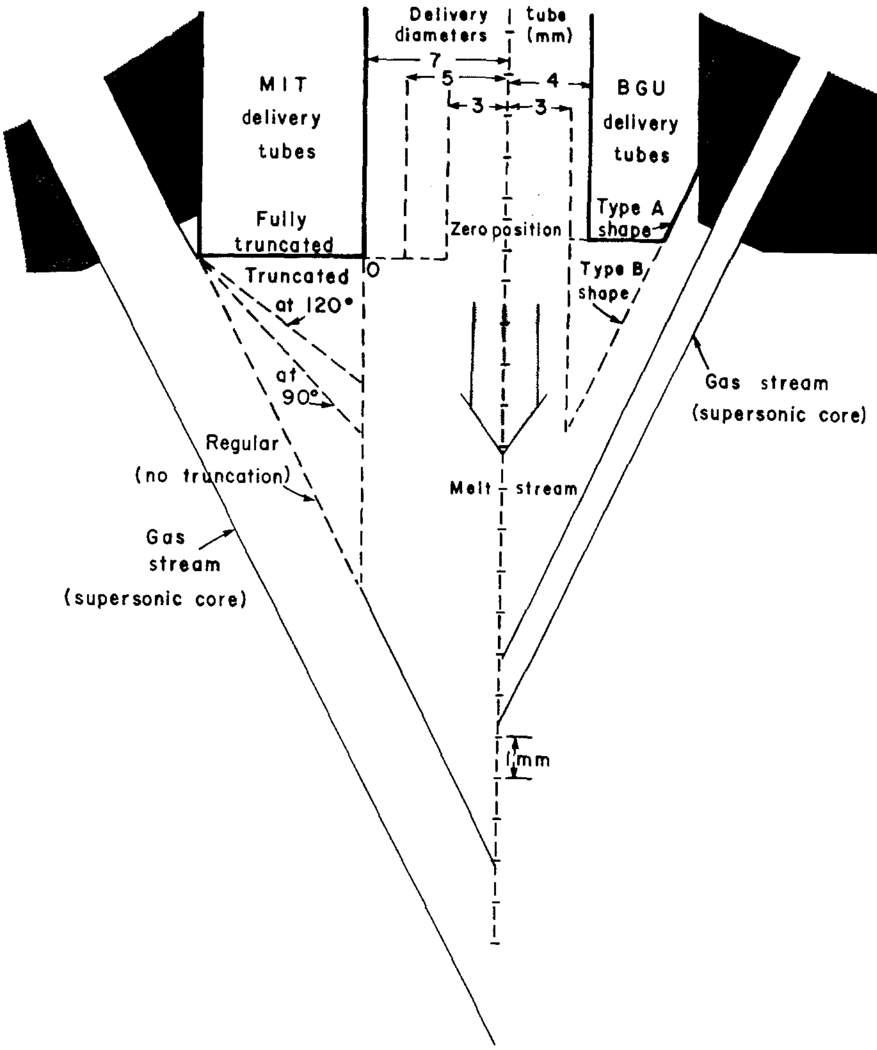


Figure 1 Schematic drawing of the metal delivery tube tip shapes.

The purpose of this investigation was to understand what factors affect the pressure levels at the exit end of the metal delivery tube during ultrasonic gas atomization (USGA), with emphasis on the geometry, position and dimensions of the metal delivery tube.

2. Experimental procedure

The simulated gas atomization experiments were done using two atomization chambers (at the Ben-Gurion University (BGU) and at MIT) of different dimensions but identical gas delivery systems. A detailed description of the USGA device is given elsewhere [9]. The atomizers used in this study were ultrasonic gas atomizers with total gas-exit areas of about 9.0 and 57 mm^2 at BGU and MIT, respectively. Gas atomization pressures varied from 3.5 to 14 atm (at MIT) and 15 to 75 atm (at BGU), using either nitrogen or argon as the atomization gas. The experiments at MIT were performed in an open chamber while those at BGU were performed under both open and contained (closed chamber) atomization conditions. Pressure changes with respect to ambient pressure at the tip of the metal delivery tube were measured with a pressure transducer at MIT [8] and with a mercury manometer at BGU [7].

A schematic drawing of geometries of the various delivery tubes used in these studies is shown in Fig. 1. The supersonic core part of the atomizing gas streams is shown for both devices used in these experiments. The outer diameters of the delivery tubes were 15 mm for the MIT device and 9.5 mm for the BGU device. The inner diameters for the delivery tubes were 3, 4, 5 and 7 mm. As shown in Fig. 1, the metal delivery tube tips were machined to various shapes, some with varying (90 and 120°) truncation angles. Various lengths (between 27 and 35 mm, not shown in Fig. 1) were used for the metal delivery tube. The position of the tubes was varied, upwards and downwards with respect to the common circle of the gas atomization ports, selected as the zero position (see Fig. 1). The tube's positions were monitored in millimetres, below (positive values) or above (negative values) the zero position. It is important to note that the amount of screening (blockage) of the gas flow by the delivery tube depends upon its position, as well as upon the shape of the tip at the tube's end. The parameters studied in these experiments were

(i) the dynamic inlet pressure of the atomizing gas,
(ii) the shape of the tip at the metal delivery tube's orifice, and
(iii) the inner diameter of the delivery tube.

3. Results and discussion

The effect of the atomization gas inlet pressure on the local pressure at the metal delivery tube's orifice is depicted in Fig. 2. Fig. 2a shows results for the low gas inlet pressure experiments; Figs 2b and c are high gas inlet pressure results for open and closed atomization chambers, respectively. In these and in the following

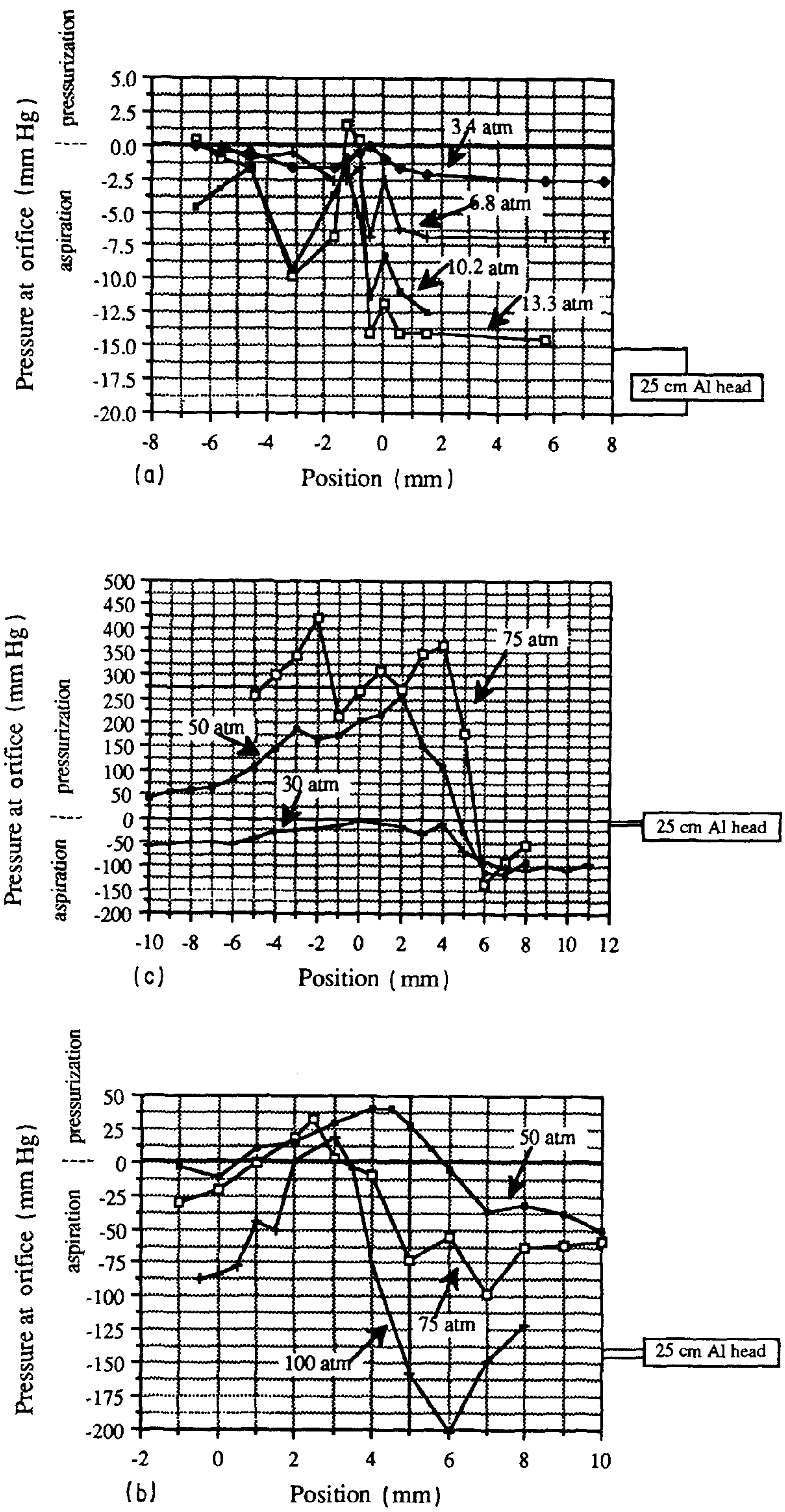


Figure 2 The effect of the atomization gas inlet pressure on the pressure condition at the metal delivery tube orifice: (a) nitrogen, low gas inlet pressures, open chamber, delivery tube diameter 7 mm; (b) nitrogen, high gas inlet pressures, open chamber, delivery tube diameter 3 mm; (c) argon, high gas inlet pressures, closed chamber, delivery tube diameter 3 mm.

figures a common under- or overpressure range is marked for reference, representing the pressure equivalent to a metallostatic head of 25 cm (10 in.) of aluminium in the casting crucible. With the open-chamber condition, the trend is an upward shift, towards less negative (aspiration), more positive (pressurization) values of the pressure at the delivery tube's orifice, as the gas inlet pressure decreases. The opposite holds for the closed-chamber situation, where high gas inlet pressures result in strong pressurization effects, which are weakened as the inlet pressure lowers, as seen in Fig. 2c. At 30 atm, the pressure condition shifts from pressurization to aspiration for the whole range of positions of the delivery tube which were studied. The local pressure variations at the tube's orifice depend also on the gas inlet pressure, both pressures increasing together (notice changes of scale for the pressure at the orifice in the three parts of Fig. 2). A closed-chamber condition generates higher under- and overpressures (for equal gas inlet pressures). Low gas inlet pressures generally yield an aspiration mode for all tested positions of the metal delivery tube: however, the amount of back-pressure at the orifice varies considerably when the position of the orifice is raised or lowered. In the closed-chamber mode, the measured pressure

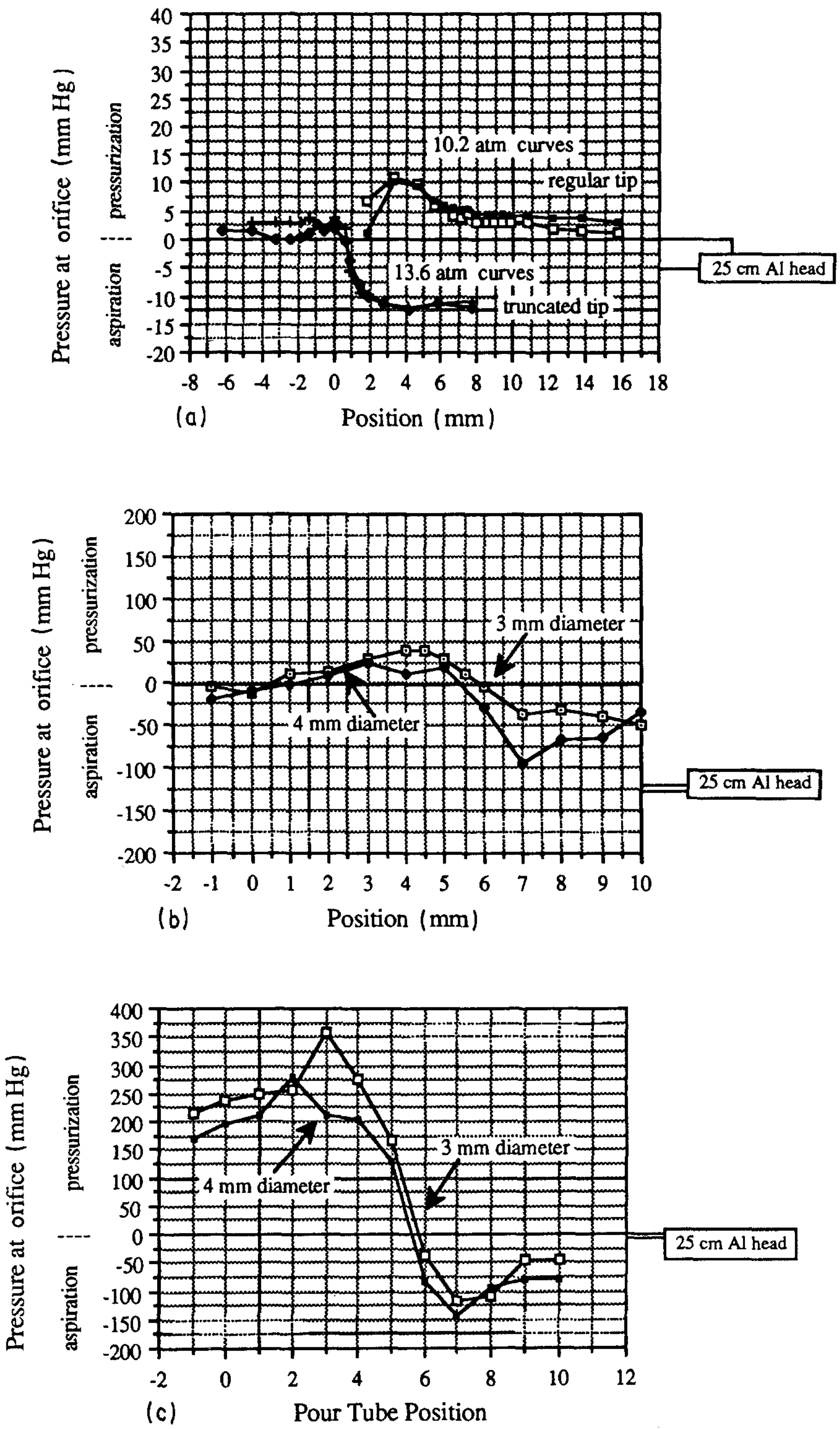


Figure 3 The effect of inner tube diameters on the pressure conditions at the metal delivery tube orifice: (a) argon, low gas inlet pressures, open chamber, delivery tube diameters 3 and 7 mm; (b) nitrogen, 50 atm gas inlet pressure, open chamber, delivery tube diameters 3 and 4 mm, Type A tip shape; (c) nitrogen, 50 atm gas inlet pressure, closed chamber, delivery tube diameters 3 and 4 mm, Type A tip shape.

variations reached values of (+420, −138) mm Hg for 75 atm and (−8, −109) mm Hg for 30 atm inlet pressures. In the open-chamber mode, the measured pressure variations are less pronounced, ranging from (−202, +19) mm Hg for 100 atm to (−50, +40) mm Hg for 50 atm and to (−14.5, +1.5) mm Hg for 13.3 atm gas inlet pressure. A general trend observed in Figs 2a to c is that as the delivery tube is moved upwards, the aspiration effect decreases steeply. The position where the transition from the aspiration mode to the pressurization mode occurs at gas high inlet pressures is the 5 to 6 mm down position. At this position, the atomization gas impacts the delivery tube, causing a screening (blockage) effect.

The effect of the inner diameter of the tube on the local pressure at the orifice is depicted in Fig. 3. Fig. 3a shows results for the low gas inlet pressure experiments, for diameters of 3 and 7 mm. Figs 3b and c are high gas inlet pressure results for open and closed chambers, respectively, for 3 and 4 mm diameters. The general trend shown in these figures is that the inner diameter of the metal delivery tube has an insignificant effect on the pressure condition at the orifice. Neither the magnitude of an aspiration or pressurization effect, nor the position of the tube for the transition from aspiration to pressurization, are practically affected by the diameter of the delivery tube. It should be remembered however that the metal flow rate is increased by a factor of 5.4 as the inner tube's diameter changes from 3 to 7 mm, for example.

The most striking result of the present investigation is the strong effect that the delivery tube tip shape has

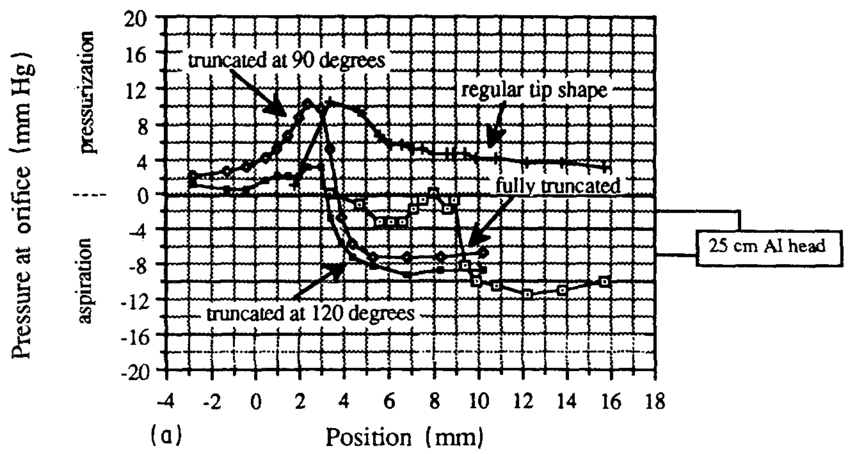
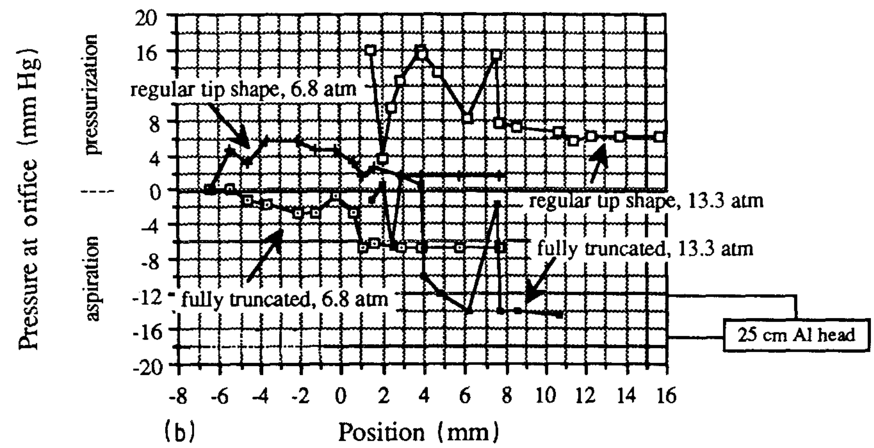
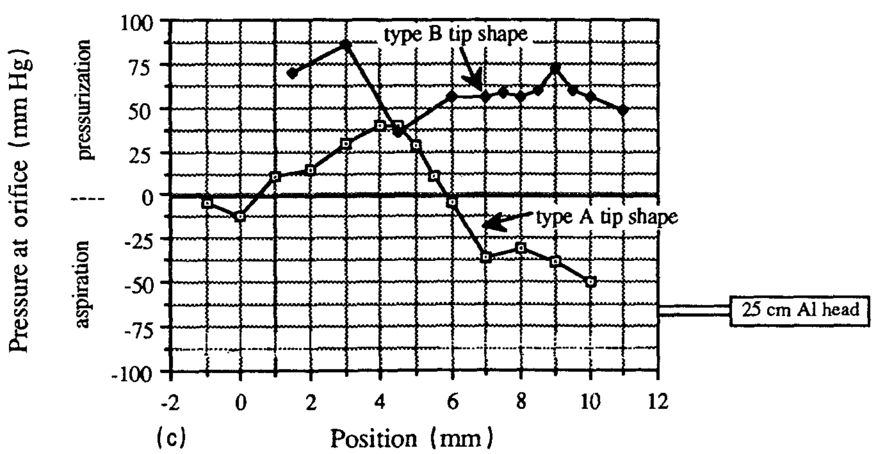


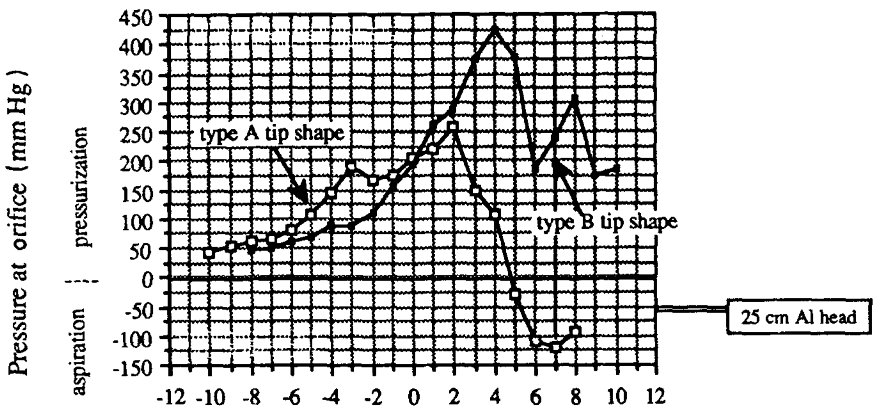
Figure 4 The effect of tip shape on the pressure conditions at the metal delivery tube orifice: (a) argon, 10.2 atm gas inlet pressure, open chamber, delivery tube diameter 7 mm; (b) nitrogen, low gas inlet pressures, open chamber, delivery tube diameter 7 mm; (c) nitrogen, 50 atm gas inlet pressure, open chamber, delivery tube diameter 3 mm; (d) argon, 50 atm gas inlet pressure, closed chamber, delivery tube diameter 3 mm; (e) argon, 30 atm gas inlet pressure, closed chamber, delivery tube diameter 3 mm.





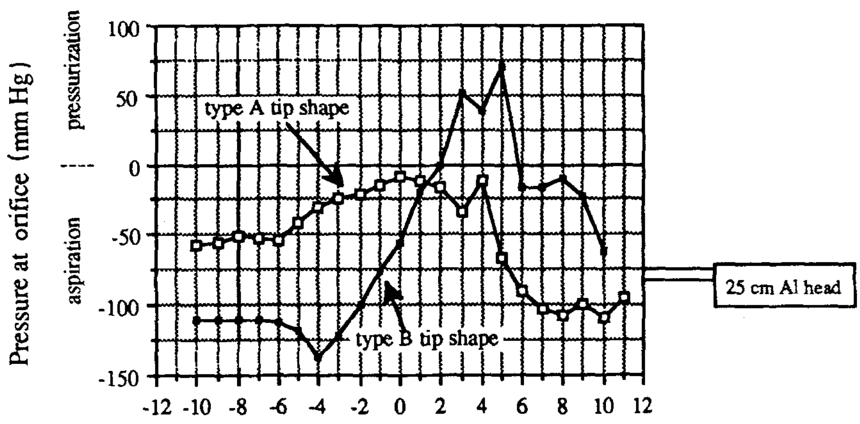
on the pressure condition in the gas–metal interaction zone at the tube's orifice. The various tip geometries used are shown in Fig. 1. The effect of the tip geometry of the metal delivery tube on the local pressures at the orifice is depicted in Fig. 4 (see also Fig. 3b). Figs 4a and b show the results for low (6.8, 10.2 and 13.3 atm) inlet pressure experiments in the open chamber condition. In Fig. 4a, four tip geometries are compared, namely the regular (fully tapered, not truncated), the fully truncated, and shapes truncated at 120 and 90° (see Fig. 1). Fig. 4b shows the behaviour for the regular and fully truncated shapes. Fig. 4c shows one high (50 atm) gas inlet pressure experiment in an open chamber, for the A and B taper types (see Fig. 1). Figs 4d and e show the pressure condition changes at the delivery tube orifice for the high gas inlet pressure (30 and 50 atm) experiments, run with A and B tip shapes, in a closed chamber.

As can be seen from the figures for the open-chamber experiments, the aspiration mode prevails as long as the delivery tube is positioned from the initial screening position down to lower positions, which means further screening. The amount of aspiration increases as the tube is placed lower down (see Fig. 4a). As soon as the tube is moved to a position in which a gap is created between the ultrasonic core of the gas stream and the tube, a pressurization situation develops, and back-pressures increase as the tube is raised further. As shown in Fig. 4b, the pressure condition at the orifice becomes erratic at low gas inlet pressures, and small changes in the position of the



(d)

Figure 4 Continued.



(e)

metal delivery tube result in relatively sharp variations in local pressure at the orifice. But there too, as the truncation provides free space between the gas stream ultrasonic core and the tube, a pressurization situation is developing again, at positions where the regular (not truncated) shaped tube resulted in aspiration. Fig. 4c shows that the pressurization situation prevails for Type B taper at all positions, while the Type A geometry condition transits from pressurization to aspiration only when total screening of the gas stream ultrasonic core by the tube is achieved. Figs 4d and e add further insight into an understanding of the pressure conditions in the gas–metal interaction region. The grazing (tangential) positions for the supersonic core of the gas stream with the metal delivery tubes are 2 and 7 mm, respectively, for the A and B tip shapes (see Fig. 1). At these positions, the pressure condition is the pressurization mode for both inlet pressures practiced, but the back-pressures in the tube are the same: +250 mm Hg for the 50 atm runs, and +75 mm Hg for the 30 atm runs. Transition from pressurization to aspiration at 50 atm occurs only when an A-type tip shape is used, at the 5 mm position, i.e. a full screening position. The transition at 30 atm occurs for Type B this time, at the 2 mm position, whereas Type A yields an aspiration mode at all positions, in accordance with the trend already observed of a downward (towards lower pressurization or higher aspiration) shift when the gas inlet pressures are decreased.

The numerous experimental conditions studied in this investigation demonstrate that the pressure condition at the metal delivery tube orifice in a USGA device does not depend solely upon the gas atomization pressures. The local configurational and geometrical conditions prevailing in the atomization chamber also have a pronounced effect on the pressure condition at the delivery tube orifice. Pressures at the metal delivery tube orifice have been shown to vary from as high as 450 mm Hg (0.59 atm) in the pressurization mode to as low as 200 mm Hg (0.26 atm) in the aspiration mode (at high atomization pressures, in a closed chamber), depending on the shape of the metal delivery tube tip and the tube's position relative to the atomization ports.

Similar localized effects have been reported in the theory for the mode of operation of the Hartman air jet generator [10] and in several studies of the fluid dynamics in supersonic gas nozzles [11–13]. The Hartman air jet generator has many features in common with the USGA nozzle design. It is made of an axially symmetrical convergent nozzle and a resonator. Resonators of various sizes and forms can be used. It has been shown experimentally [10] that the frequency and the acoustic power of a generator are affected by the resonator type and dimensions, the distance from nozzle to resonator, and of course the magnitude of the pressure supply. The presence of vortices in the mixing region of a supersonic flow at some distance downstream from the nozzle orifice has been reported

[12]. These vortices are the result of downstream travelling disturbances in the jet, generated by upstream propagating sound waves emitted by the supersonic jet itself [13]. The disturbance train is reported [12] to develop to a long vortex whose axis is a helix enclosing the flow. As the sound-waves travelling upstream interact with the eddies travelling downstream, a standing pattern is formed (and well seen on schlieren photographs taken in a visualization experiment of ultrasonic gas atomization [14]). This *acoustic feedback effect* on supersonic jets has been largely documented [12, 13]. The most interesting result of experiments reported [13] is that any sound-reflecting material in the vicinity of the gas jet can alter or reduce the acoustic feedback, which in itself is also influenced by the inlet pressure and/or the spread angle. It has been shown that acoustic feedback effects significantly reduce the impact pressure of supersonic jets, as well as increasing the downstream turbulence [13].

In the presently reported experiments, the geometry of the reflecting material surrounding the jet is altered every time the tip geometry or the position of the delivery tube is changed. The intensity and the rate of occurrence of the acoustic feedback-generated vortices and eddies are varied for each combination of atomization pressure, metal delivery tube tip shape and position, thus yielding the observed pressurization effects. However, when the position of the metal delivery tube with respect to the supersonic core of the gas stream is such as to screen the gas stream, the resulting effect at high atomization pressures in a closed chamber is an aspiration effect, instead of pressurization. Further, at low atomization pressures in an open chamber, pressurization occurs when a regular tip shape (see Fig. 1) is used, whereas each change in tip shapes yields aspiration at the delivery tube orifice, as space is available for the vortices to develop. The results of this investigation suggest that the acoustic feedback effect has to be accounted for to understand the observed pressure variations at the metal delivery tube orifice, in addition to turbulent mixing, shock-wave formation and reflection, and other related gas dynamics phenomena.

USGA and liquid dynamic compaction (LDC) are alloy processing techniques that take advantage of the high cooling rates achieved during solidification of atomized powders. The cooling rate obtained during gas atomization depends, among other factors, on the droplet size. The droplet sizes can be decreased, and cooling rates therefore improved by increasing the ratio of gas to metal flow rates. On one hand, this can be achieved by controlling the gas atomization pressure and/or the gas exit area. On the other hand, control of the metal flow rate also contributes to the ratio of gas to metal flow rates. The metal flow rate depends on the metallostatic pressure head in the crucible, on the area of the metal delivery tube, and on the amount of aspiration or pressurization. During experiments in which the melt is not pressurized the metallostatic pressure head decreases. Minimal variations in the gas to metal flow ratios can be achieved by selecting the proper geometry and position of the metal delivery tube to provide either for pressurization (to counteract the progressive loss of head) or for aspiration (to ensure stable metal flow rates).

4. Conclusions

In the present study the effects of the geometry and position of the metal delivery tube on the conditions which determine the metal flow rate in ultrasonic gas atomization were studied, in open and closed chambers, for various atomization pressures. For the geometries used in this work, overpressures (leading to a pressurization effect) or underpressures (leading to an aspiration effect) were measured at various positions of the metal delivery tube. It is proposed that these effects can be partly explained as due to vortices which result from an acoustic feedback phenomenon. The acoustic feedback is active whenever space is left between the metal delivery tube and the supersonic core of the atomization gas stream, generating backpressures, i.e. pressurization, in the tube. In the cases where the metal delivery tube screens the supersonic core of the atomization gas stream, an aspiration mode is generated, i.e. underpressure at the tip of the delivery tube. Overpressures and underpressures were found to increase with the gas atomization pressure, and to change drastically according to the type of the delivery tube taper shape. These phenomena have to be taken into account whenever optimization of the gas atomization process is sought.

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