Ice Particles Study For Ice Jet Machining

by

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Abstract

This research was undertaken at the Industrial Research Institute of the Swinburne University of Technology (IRIS), Melbourne, Australia. The aim of this research work was to study the effects of parameters such as temperature and flow rate of water, on the phenomenon of ice particle formation. The shape, size and the percentage of ice produced from water were studied. The ice particles can be used for water jet applications such as cleaning, degreasing and cutting. The concept is based on the convective heat transfer between a cold cryogenic gas and atomised water droplets. . Ice particles are formed inside the system by transferring latent heat of water droplets to liquid nitrogen. The results show that the ice particles obtained were linearly proportional to the water droplets atomised.

1. Introduction

Abrasives are used for many applications including cleaning, depainting and cutting operations. There are, however, some applications where the use of abrasives is not possible. These applications include, for example, the processing of meat products and cleaning of sensitive surfaces. An ice jet is a non-destructive, non-abrasive, residue-free, and environmentally friendly way of machining. The ice jet can be used for either initial or final cleaning, and for numerous critical and non critical cleaning applications in the semiconductor, disk drive, vacuum technologies, surface science, surface analysis, optical, medical, automotive, analytical instrument, and manufacturing industries.

An important consideration was to get particles as small as possible so that these ice particles, when entrained with high velocity water, can produce a very fine surface finish, because the smaller the particles size the better the surface quality. Some research had already been carried out in the field of ice jet processing. Galecki and Vickers (1982) performed cleaning and abrading surfaces with an ice-blasting technique in which ice-particles of approximately 3mm diameter were produced by crushing (mechanically) 30mm ice cubes which were then accelerated by a compressed air jet. They produced ice particles by refrigeration of 3cm blocks, which were then transferred to a container of liquid nitrogen where the ice cubes were further cooled. They were then transferred to a mechanical crusher where they were crushed and subsequently entrained into a nozzle where the high velocity compressed gas was flowing in an air/ice venturi nozzle. Geskin *et al.* (1999) applied ice particles for precision cleaning of sensitive surfaces. Ice particles of smaller diameter were formed by mechanical crushing of large block of ice. The FIDAP software package was used to determine the probability of particles surviving in the course of the jet formation. The operating nozzle diameter was 5mm and the ice particles were 2 to 5mm in diameter. They carried out various cleaning and degreasing applications on printed circuit boards and on compact discs. Settles (1998) developed an apparatus for producing ice particles. The apparatus consisted of a pressure reservoir, a mixing chamber, a flow spreader, a pneumatic atomiser and a freezing chamber. This apparatus was basically designed for cleaning applications. Hisasue *et al.* (1994) developed another apparatus for polishing surfaces of an article having a relatively low hardness. They focused on the visualisation study of the size and shape of fine powder particles, which were formed as a result of entraining liquid metals with liquid nitrogen. Geskin *et al.* (2000) experimented with an icejet for decontaminating surfaces. Various electronic devices were disassembled and their electronic boards were contaminated by grease and metal powder. They then tried to clean them with ice blasting. These were then reassembled in order to study whether they would work normally. The study indicated that at sufficient kinetic energy ice particles could be used for cleaning ceramics and composites.

2. Industrial Implications

The significance of this research lies in design development of an ice jet system capable of cleaning, degreasing, depainting and cutting applications. The research so far has gone through the process of the design and development stage of the system, and experiments were conducted to determine the feasibility of the formation of ice particles. Here, a visualisation study of the ice particle structure was conducted to determine the diameter of the ice particle, its shape and percentage of water droplets converted to ice particles. Further research is now under way on simulation studies to determine the extent of its compilation with the experimental data and to modify the analytically developed design. The later stage of this research is focussed on the actual limitations of the developed prototype for cutting, cleaning and depainting applications.

3. Experimental Apparatus and Procedures

Figure 2.1 shows the schematic representation of the ice particle formation system that was constructed in this project. The ice particle formation system consists of an ultrasonic atomiserm, mounted on the ice particle system, and capable of producing fine water droplets. Liquid nitrogen was supplied to the system from the storage tank, which was specially insulated, through a transfer hose in which the temperature was measured to be -196°C. The ultrasonic atomiser consumes little energy, because liquid is supplied without pressure and requires less electric power. The selected atomiser can produce uniform droplets, ranging from 45 to 90 microns. The liquid was dispensed to the atomising probe (nozzle) by both gravity feed and by small low-pressure metering pump, and atomised continuously. The amount of material atomised can vary from 2 litre/hr to 12 litre/hr. Since the velocity of the droplets generated was very low, the probe was mounted with the tip facing downward.

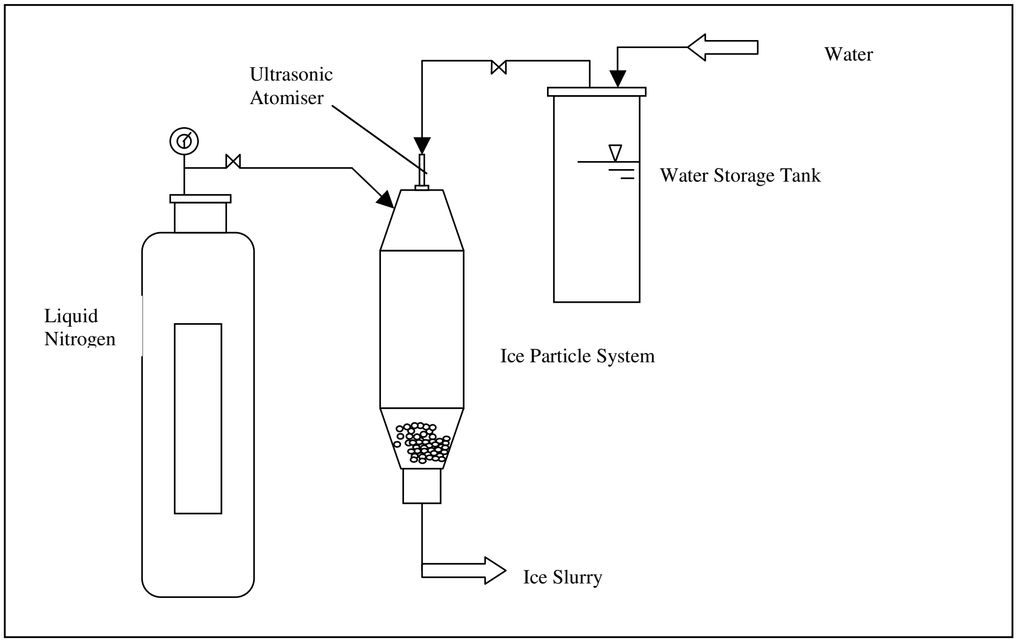

Figure 2.1 Schematic diagram of the Ice particle formation system

A microscopic study of the size and shape of ice particles and the percentage of water droplets converted into ice particles was experimentally performed. The temperature of water and the amplitude of the ultrasonic atomiser were used as variable parameters. A full factorial experiment that consisted of 18 runs was performed, including one repeat. The temperature range was kept from 8 °C upto 20 °C, and the amplitude of the vibration was kept from 60 μm to 100 μm. An imaging camera, with a magnification of 25 mm, was used with a 15mm spacer to capture the micro droplets formed from the prototype. The camera was connected to the computer in real time and the image obtained from the camera was stored in the computer for further analysis. The only known factor was the size of the abrasive particles that had a mean diameter of 180 microns. The ice particle images captured were embossed with grids and the size of the grid was calculated with the given abrasive diameter. The weight of the ice particles flowing out was measured with a physical balance with an accuracy of 0.1 grams. Each measurement was performed after 2 minutes for a period of 2 minutes after opening the liquid nitrogen valve. This was performed to bring the liquid nitrogen to atmospheric pressure while flowing.

4. Results and Discussion

The shape of the ice particles was found to be spherical although the size varied as shown in Figure 4.1. From a sample of 50 abrasives it was found that one grid corresponds to 90 microns. This grid size was then used to calculate the diameter of ice particles. The generated ice particles were under 100 microns so that this can later be mixed with high velocity water for cutting and cleaning very fine surfaces. The images taken from the camera was analysed with a analysis software called V++. The edges of the ice particles were detected and the intensity increased to view the ice particles clearly. 50 clear ice particles were randomly selected for each temperature and amplitude and the diameter measured with reference to the grids. A normality test was carried out using MINITAB to find out whether the mean diameter for different temperature and amplitude lies within the normal range. It was found that the plot of mean diameter verses the probability is linear and about 80.8% of the particles lie within the range as shown in Figure 4.2.

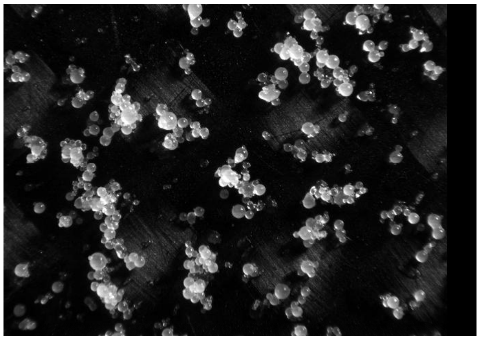

Figure 4.1 - Ice particles formed at 8 °C and 80 μm

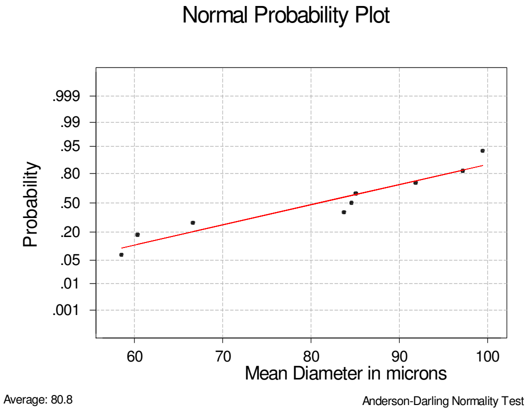

Figure 4.2 - Plot of Mean Diameter against Probability

A qualitative analysis was performed over the formation of ice particles with respect to the inlet water temperature and the amplitude of the ultrasonic probe. As it is shown for example at 8 °C and at 60 μm the mean diameter was 91.8 microns and at the same temperature and at 100 μm the mean diameter was 58.5 microns. It was observed from the readings that when the amplitude increases the mean diameter decreases even as the temperature remains constant. The amplitude verses mean diameter plots are shown in the Figure 4.3. Another analysis was made to compare the effect of temperature over the size of the ice particles. For example at 14 °C and 60 μm the mean diameter was 97.2 microns and at 20 °C and 60 μm the mean diameter was 99.45 microns. From the above readings it was observed that as the temperature increased the mean diameter increased. The plot temperature verses mean diameter is shown in Figure 4.4.

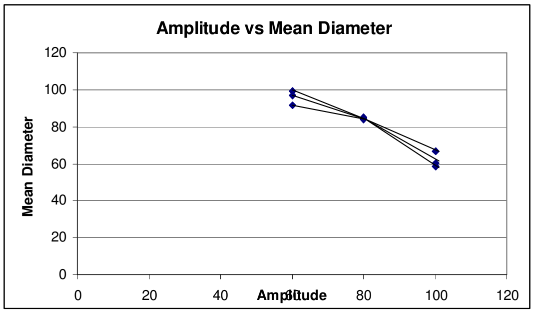

Figure 4.3 - Plot of amplitude against mean diameter

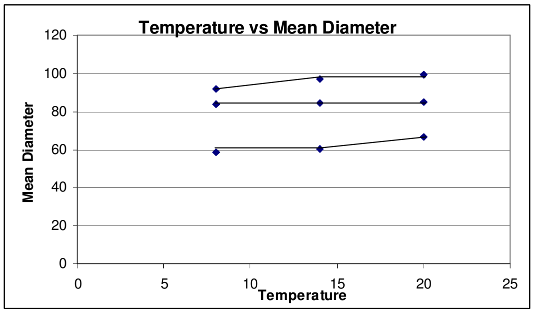

Figure 4.4 Plot of temperature against mean diameter

Regression analysis was also performed from MINITAB for calculating the relationship among the size of the ice particles, inlet water temperature and the amplitude of the ultrasonic atomiser. The response factor here was the size and the predictors were temperature and amplitude. The relationship is shown in Equation 1.

$$\text{Mean Diameter} = 143 + 0.475\ \text{Amplitude} - 0.859\ \text{Temperature}. \quad (1)$$

From the equation it was observed that the mean diameter was directly proportional to the amplitude and inversely proportional to the temperature of the inlet water. Further R^2, which is the proportion of the variation in the response data, is calculated. The larger the R, the better the model fits the data. The calculated R^2 value was 95.8% and the calculated R^2 (adjusted) value was 94.4% from the analysis made from MINITAB. Thus from the values it is evident that 94.4% of the data fits the model.

Experiments were also conducted to find out the percentage of atomised water droplets converted into ice particles. Full factorial design was performed with a total of 18 runs with inlet water temperature and amplitude as factors with one centre point for each variable. Figure 4.5 shows the plot of amplitude against the mean diameter.

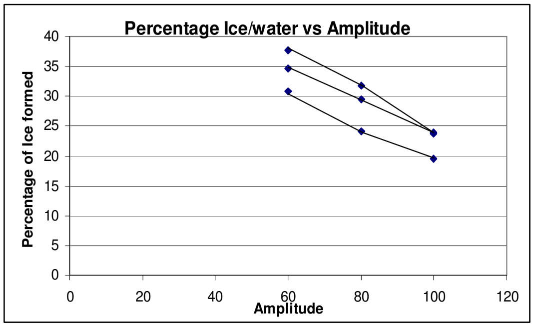

Figure 4.5 - Plot of amplitude against mean diameter

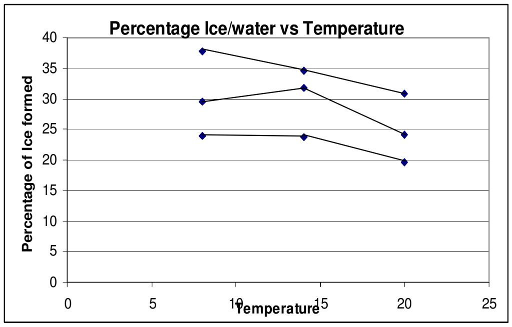

Figure 4.6 - Plot of temperature in °C mean diameter in microns

From the obtained results it was observed that as the amplitude increased the percentage of the ice formed decreased, for example the ice formed was 62.92% at 8 °C and 60 μm and the percentage was 39.93% at 8 °C and 100 μm. It was observed that as the amplitude increased, the focal angle of the ultrasonic atomiser increased, which resulted in ice particles being held to the inner surface of the prototype. Another observation was that as the temperature increased the percentage of water droplets converted to ice particles decreased, as for example the ice formed at 14 °C and 60 μm was 57.75% and 51.42% at 20 °C and 60 μm. The reason might be as the temperature was increased the flow rate of liquid nitrogen was also increased in order to compensate the temperature difference and that increase in the liquid nitrogen flow rate caused the water droplets to clog on to the surface. The regression analysis was also obtained using MINITAB and is given in Equation 2.

$$\text{Percentage of ice} = 98.1 - 0.500\ \text{Amplitude} - 0.764\ \text{Temperature.} \tag{2}$$

As from the equation it is quantitatively proven that the amplitude and temperature are inversely proportional to the percentage of ice formed. The R^2 adjusted value is 90.2% so about 90.2% of the data fits the model.

5. Conclusion

From the experiments performed the mean diameter is directly proportional to the amplitude and inversely proportional to the temperature. The percentage of ice formed is inversely proportional to the amplitude and inversely proportional to the temperature. Although the experiments performed gave quantitative results, these are preliminary in terms of temperature and amplitude only. There are a few more parameters, such as the flow rate of water and flow rate of liquid nitrogen and their effects on the formation of ice particles which are yet to be studied. There are problems in terms of clogging which have to be eliminated. Although these are experimental, numerical simulations of the same are yet to be conducted to study the behaviour of the ice particles. Further studies are focussed in entraining these ice particles into stream of water cleaning and cutting operations.

6. Acknowledgement

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7. References

Galecki G., and Vickers G. W., "The development of Ice-Blasting for surface cleaning", Jet cutting technology, pp59-79, 1982.

Geskin E. S., Shishkin D., and Babets K., "Application of ice particles for precision cleaning of sensitive surfaces", Proceedings of the 10th American Waterjet Conference, Houston, Texas, Vol. 22, pp315-333, 1999.

Settles G. S., "Supersonic abrasive ice blasting apparatus", United States Patent: 5785581, July 28, 1998.

Hisasue A., Kanno I., and Fukumoto T., "Apparatus for polishing an article with frozen particles", United States Patent: 5283989, February 8, 1994.

Geskin E.S., Goldenberg B., Shishkin D., Babets K., and Petrenko O., "Ice-based decontamination of sensitive surfaces", Proceedings of the 15th International conference on Jetting technology, pp219-228, Sweden, 2000.