final report

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Preliminary study of cutting meat with ultra-high pressure icejet

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1. Preamble

Water jet technology uses a pump to generate ultrahigh pressure water which passes through a fine orifice and nozzle to form a high pressure water jet. The commonly used water jet systems can produce a water pressure of up to about 400MPa and the newly marketed technology by Flow Corporation in the USA can generate water pressures to 600MPa. Because of the various advantages of this technology, such as heat free, it has found wide applications such as in meat processing, thin plastics cutting, and cleaning of sensitive surfaces often in the electronic and medical fields.

Owing to the limited processing capability of the pure water jet technology, abrasive particles are often mixed with the water to form water-abrasive slurry jet, i.e. abrasive water jet (AWJ). Fig. 1 is a schematic of an AWJ cutting system. The commonly used abrasives include garnet, silicon carbide and aluminium oxide particles. AWJ technology has a number of distinct advantages over the other cutting technologies, such as no thermal effects on the material, high cutting versatility to cut virtually any materials, high flexibility to cut in any direction, small cutting forces, and high process efficiency. As a result, it increasingly replaces the conventional mechanical techniques, such as sawing, jack-hammering and milling. AWJ technology is particularly used in cutting 'difficult-to-cut' materials such as ceramics and marbles, layered composites and in pattern cutting.

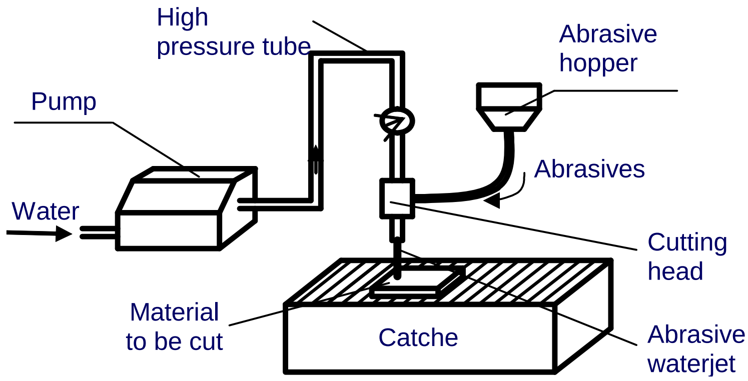

Fig. 1. Schematic of an abrasive waterjet cutting system.

After consulting with the meat processing industry, it is believed that AWJ will be very attractive as a non-contact, low meat-loss cutting technology for this industry. While the water jet technology using a pure water jet has been used for meat processing, such as trimming off the fat from a slice of meat, it is unable to effectively cut the bone inside the meat. The cutting rate is expected to be too low for a production environment. By contrast, the AWJ cutting technology offers an effective means for this purpose. A challenging question is that the abrasives used must not contaminate the meat and such abrasives are to be found in the use of ice particles. Such a technology is therefore called ice water-jet or icejet technology. The icejet cutting technology has a number of advantages. For instance, it does not bring any foreign contaminations into the process except water, is heat free, dust free, environmentally-friendly and safe to operate, can yield high cutting rate and low meat loss (by cutting narrow kerfs of about 1mm), eliminates bone chips, and does not require to freeze meat for shape cutting (such as slicing and dicing). In addition, the technology is flexible to operate in a production environment by delivering the cutting head to a product line. However, while the concept of icejet is not new, an extensive international patent search has not revealed any significant resemblance to the proposed technology that is suitable for meat cutting.

Before a large scale research and development effort is carried out to develop the proposed icejet cutting technology, a preliminary study to assess the cutting capability of the technology, such as the cut or kerf quality, kerf width or meat loss, depth of cut or meat thickness that it can cut, and cutting rate etc. has been carried out. Because of the unavailability of the technology anywhere in the world to generate ice particles in the sizes and hardness suitable for cutting applications, salt particles were used as the substitutes to simulate the icejet cutting process. Ice particles have lower density, but are much harder than salt particles. It is believed that these two types of particles will generate comparable cutting performance for meat. This report highlights the outcomes of this preliminary study.

2. Experimental work

The experiment was conducted on a Flow abrasive waterjet system equipped with a model 5X-60 single intensifier water pump (up to 415 MPa) and an ABB 6-axis robot positioning system to manipulate the cutting head. The major components of the system are shown in Fig. 2. The cutting head components were selected in the range of cutting applications and considering the abrasive sizes, i.e. a ϕ0.254mm sapphire orifice and a ϕ1.016mm carbide nozzle. Meat was placed on a supporting fixture made of aluminium which was clamped on the metal gratings of 3mm thickness at the top of a water catching tank. There might be very slow wear on the gratings by the abrasive jet, but there was no damage to the water tank.

(a) Water pump and cooling system. (b) Robot cutting head.

Fig. 2. Major components of abrasive waterjet system.

In this study, meat specimens of beef, pork and lamb with and without bones were selected from leg, spine and ribs. Attempts were also made to cut pure meat, meat with bone and pure bone (with little meat). More attention was paid to the cutting of beef spine and beef ribs. Cooking salt particles whose sizes were sieved to less than 0.4mm were used as the abrasives to form abrasive waterjet. In addition, pure waterjet was tested to compare the cuts with the abrasive waterjet. It was found that the addition of abrasive particles increased the depth of cut and cutting rate with improved cut quality.

The process parameters were selected with the assistance of statistical experimental design principles which included water pressure, nozzle traverse speed, salt mass flow rate, and the standoff distance between the nozzle exit and the meat top surface. The water pressure was varied with its maximum at 400MPa and the standoff distance was maintained at approximately 4mm throughout the experiment to accommodate the irregularity of the meat top surface. In addition, meat temperature varying from 5^{o}C to 20^{o}C was considered. For the test conditions in this study, the maximum water consumption was within 1.9 litters per minute.

The assessment of cut quality was carried out by observing the cut specimens and photos taken at different combinations of process parameters. A clear cut without bone/meat chips or debris and meat tearing was considered as an acceptable cut. The depth of cut or jet penetration was measured immediately following each cut using a feeler gauge sliding from the top to the bottom of cut, whereas the kerf width was measured at the top of cut using a variable thickness feeler gauge.

3. Highlight of outcomes

3.1 Quality of cuts

The meat quality after cut was analysed qualitatively by observing the cutting walls or kerf quality. Some selected cut samples are shown in Fig. 3. It has been found that a pure waterjet was unable to satisfactorily cut through bones at acceptable cut quality and cutting rate; even when cutting pure meet, the process parameters for a pure waterjet had to be carefully selected in order to produce good quality of cuts while maximising the cutting rate. By contrast, the AWJ could generate cuts that were of high quality throughout the surface and did not show any marks of meat destruction or tearing. The cut surfaces were clear without bone chips or debris. This result was obtained for not only ribs, spine and legs for beef, pork and lamb, but also for cutting the bovine bones of beef that is considered as the hardest part to cut by AWJ amount all beef bones.

Fig. 3. Meat surfaces after cutting by abrasive waterjet.

3.2 Effect of meat temperature

The effect of meat (with and without bone) temperature on the quality of cut and cutting performance (depth of cut and nozzle traverse speed) was studied by varying the temperature from 5^{o}C to 20^{o}C. It has been found that while meat temperature did not shown discernible effect on the cut quality, a higher meat temperature was favoured for increasing the depth of cut at a given nozzle travel speed, or for increasing the nozzle traverse speed for a given meat thickness. However, too high a meat temperature may be not appropriate for meat storage and processing, and room temperature in the meat processing plant may be used. This finding is significant in that this cutting technology can eliminate the cost for meat freezing or chilling.

3.3 Process capability (meat thickness and cutting rate)

The process capability in terms of the cutting rate (or nozzle traverse speed) and meat thickness (or depth of cut) has been assessed with variations of the other process variables while yielding good kerf quality. With the meat/bone temperature of 20^{o}C and within 400MPa of water pressure, the process capability achieved can be shown by the following examples:

- The maximum meat thickness tested for pure meat was 150mm at the nozzle traverse speed of 4000mm/min, while that for beef spine was 90mm (bone thickness was approximately 70mm) at the nozzle traverse speed of 300mm/min.
- For typical beef ribs of 40-50mm thickness, the nozzle traverse speed of 900-1200mm/min may be used to achieve good kerf quality. Similarly, 800-900mm/min of nozzle traverse speed may be selected for cutting 40-50mm beef spine.

It is expected that the process capability of the AWJ technology can be significantly increased when the commercially available hyper-pressure (600MPa) waterjet system is used. It can be further increased if multiple nozzles are used along with a mechanised and automated system to increase the operation efficiency.

3.4 Assessment of meat loss

Kerf width is the measure of meat loss and, for this purpose, the top kerf width at the jet entrance was investigated. It has been found that the top kerf width varied from 0.3mm to 1mm. The maximum kerf width was approximately equal to the nozzle diameter, which was mostly found from the cutting of bones. In many cases of cutting meat, the top kerf width was much smaller than the nozzle diameter, possibly because of the elastic deformation of the meat during the cutting process. The kerf width normally reduces as the jet cuts into the meat, so that the kerf width at the lower portion is smaller than that at the upper portion of the cut. The worst-case scenario to estimate the meat loss would be to take the maximum kerf width that is approximately equal to the nozzle diameter of 1mm in this study.

A smaller nozzle may be used to obtain a smaller kerf width, and hence less meat loss; however, because of the jet energy and abrasive size restrictions, nozzles in the vicinity of 1mm is considered appropriate for this application.

4. Safety considerations of the cutting system

The operation of the machine requires safety protection for the operator, including ear masks, protective clothing, and protective footwear. The operator must be familiar with the standard operating and safety procedures provided by the machine supplier. In our operations, the operator kept about 0.5-3m away from the cutting head. The cutting head must be placed towards the catcher tank before switching on the waterjet and remain so for the entire operation. If operated with a robot, a protective enclosure around the robot is required and must be closed while the machine is in operation. The Australian Standard AS2939-1987 gives the detailed codes and practices to operate a robot. The programmed robot paths must be tested without switching on the high pressure waterjet before actual cutting operations. With due precaution, the abrasive waterjet cutting system is considered safe to operate.

> *Disclaimer: The above comments are indicative only of the procedures used in the experiment, and do not intend to be a comprehensive list of safety procedures to be followed for operating an abrasive waterjet machine. Professional OH&S advice should be sought in case of any further experiment by any other party or operations in an industrial environment.*

5. Concluding remarks

This preliminary study has shown that abrasive waterjet is a feasible technology for cutting meat with bone with good cut quality and acceptable cutting rate. It is associated with less meat loss than sawing processes, and can cut meat at room temperatures, thus eliminating the cost for meat freezing or chilling. The operating cost including consumables and machine maintenance when using salt particles as abrasives is less than $20 per hour of continuous operation, which is considered to be economical, and a new waterjet machine system costing from less than $200,000 is affordable. Before a suitable icejet technology becomes available, salt particles may be used for cutting meat with the waterjet technology, subject to a further study of salt contamination in meat and its effect on meat properties.

For applications at an advanced level, the proposed icejet technology should be very attractive to the meat processing industry for a clean, hygienic, non-contact cutting process. The development of the icejet technology is seen as a major and challenging initiative that will place the Australian meat industry in the forefront of world, but requires considerable time and effort for the research and development.

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