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Research Paper

CUTTING IMPROVEMENTS BY ADDING DILATANTS FLUID

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Effect of addition of viscoelastic additive on the stability and precision enhancement of the abrasive waterjet is studied. Cornstarch is chosen to be added to the mixture of water and abrasive for it is readily available in large quantities at low cost. Yet it shows major nonlinear properties valuable for waterjet machining. It is shown that the normal stresses developed in the nonlinear viscoelastic cornstarch remain substantially unchanged throughout effective jet length resulting in an almost completely prismatic jet, most desirable for precision and straight machining. Furthermore, the jet becomes more stable upon increasing the cornstarch percentage. The additive also causes the jet to produce less friction with the surrounding air avoiding possible jet disintegration. Clearly, due to the increase of elastic as well as viscous effects, there is restriction to the pump delivery upon adding the dilatant cornstarch. Different percentages of the additive are therefore examined. It is found that, a 22% additive results in the best performance based on the precision, available pump power and stability of the jet. The experiment was carried out on three products; marble, aluminum and glass. In all cases, kerf angle was reduced significantly. Simulation of the problem is in good agreement with the experimental observations.

Keywords: Viscoelastic additive, Abrasive waterjet, Kerf angle

INTRODUCTION

The abrasive waterjet (AWJ) technology is a main approach to machining hard-to-cut, thermally sensitive and delicate materials as well as surface treatments such as polishing and peening (Sadasivam *et al.*, 2009). The plain "high-pressure" waterjet cutting was first proposed by N Franzin in 1968, which later in 1971 it was commercially used to cut laminated paper tubes. In 1980, Hashish added abrasives to the plain waterjet to improve the cutting process and to cut materials such as steel, glass and concrete. In 1983, more delicate materials such as automotive glass were commercially cut by means of abrasive waterjet technology.

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Addition to the degrees of freedom in motion of the nozzle together with better control techniques made the abrasive water jet a favorite option for cutting a wide range of geometries (Janet, 2009). In AWJ cutting, unlike traditional machining techniques such as milling and grinding in which solid forms of cutting tools are used to machine products, the cutting accuracy and efficiency depend mainly on the flow and stability of the jet (Hashish, 1989; Momber and Kovacevic, 1998; Wang, 2003; and Janet, 2009). This fact has been the main driving force for preparation the current paper.

Similar to any manufacturing technique, the AWJ comes with difficulties improving which has been subject of research studies. Major problems that limit AWJ application are the width of cut and kerf quality (Shanmugam *et al.*, 2008). A great deal of research has been carried out to improve the cutting performance and also to enhance the cutting capacity of AWJ technology, including studies of the mechanism of the AWJ cutting process (Hollinger *et al.*, 1989, for instance) and modeling for process control and optimization (Miller, 2004). It is reported that the process of waterjet cutting and machining may be improved by tilting the nozzle at a small angle [6], use of high pressure nozzle discharge (Susuzlu *et al.*, 2004), introduction of oscillation in the nozzle (Wang, 2007) and application of prestress in the material to be cut (Sadasivam *et al.*, 2009), to name a few. The idea of polymeric (otherwise known as viscoelastic) additive to improve the cutting quality has also been introduced (Zakin and Summers, 1976; Howells, 1990; Chacko *et al.*, 2003; and Louis *et al.*, 2003), however no reference is made to the effect of the rheology of viscoelastic materials in the improvement of cutting technology. Rather in the present study however, the effect of additive on the jet has been examined to observe the improvement on the jet stability, widening effective jet width power of the jet.

Cornstarch was chosen as the viscoelastic additive to provide desired normal stresses to help strengthen the effective length of jet, and to maintain a prismatic geometry of the jet. Unmodified cornstarch is a consistent mixture of two biopolymers, amylose, a straight-chain molecule, and amylopectin, a larger, branched molecule of the basic repeating unit anhydroglucose (Sudhakar *et al.*, 1995; and Lii *et al.*, 1996). This mixture provides complicated nonlinear properties of the cornstarch such as shear thickening at higher shear rates and normal stresses upon application of shear or axial stresses. Although cornstarch is actually shear thinning in low shear, within the applicable range of shear rates in waterjet cutting it becomes shear thickening or dilatant (Bischoff *et al.*, 2010). It was observed that very fragile material such as glass could be machined with no breakage with Viscoelastic Abrasive Waterjet (VAW). When applying this jet in the cutting of various materials with the hardness ranging from ceramic to rubber, an increase in the effectiveness of the standard abrasive waterjet by producing straight kerf widths, and by improving the cutting performance at lower stand-off distances was achieved. The experiment was carried out on three products, marble, aluminum glass to observe the cutting improvement especially for the kerf angle and stand-off distance. A dimensional analysis is then undertaken to develop the mathematical relationship between the jet stability measure and the jetting parameters to provide a practical means for quantitatively predicting the jet stability. Finally, It is known that three cutting zones exist in the processing of ductile and brittle materials under abrasive waterjets, namely, the primary cutting zone at shallow angles of attack, the secondary cutting zone at large angles of attack, and the jet upward deflection zone (Hashish, 1984 and 1991). It is projected that the viscoelastic additive affects all three zones.

EQUIPMENT

The experiments were conducted on an abrasive waterjet system with a model 5X-60 single intensifier high output pump (up to 500 MPa) schematically shown in Figure 1. The water pressure was controlled by an air-driven Haskel pump with an accumulator to stabilize the pressure. The pressurized water was then injected into a cylinder where it pushed a piston to pass the pressure to the working fluid on the other side of the piston. The abrasive and cornstarch was delivered from two compressed air feed hoppers to the cutting head and were regulated using a metering

Figure 1: General Layout of the Viscoelastic Abrasive Waterjet Cutting System with Cornstarch Supply Tank

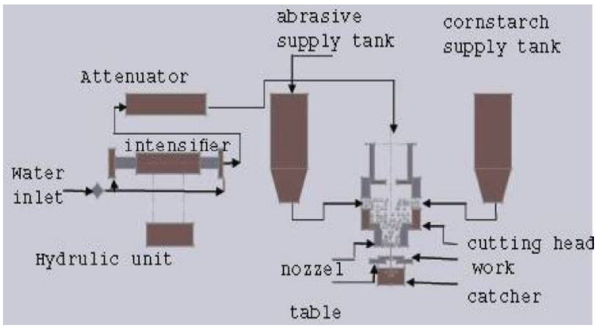
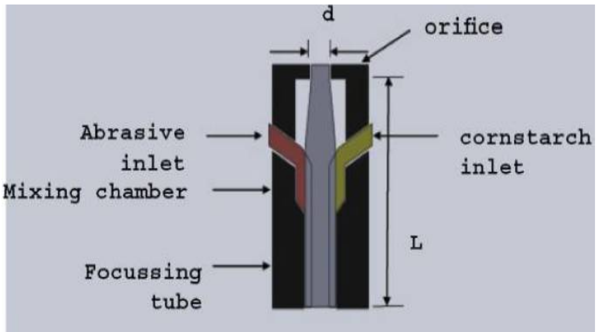


Figure 2: Inlet Galleries of Abrasive and Cornstarch in the Cutting Head (Mixing Chamber)

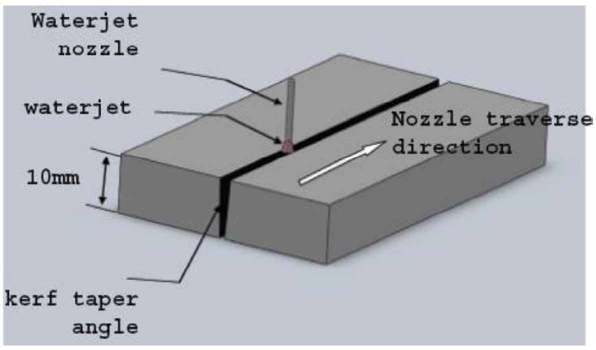


disc. The water and cornstarch in the cylinder were mixed in cutting head mixing chamber, Figure 2, which was mounted on a 6-axis manipulator. The primary components of the cutting head for this study consisted of a 0.31 mm diameter orifice that delivered the water to a the jet, abrasive and cornstarch inlet tubes, abrasive and cornstarch mixing chamber, and a 1.02 mm internal diameter nozzle. The orifice and nozzle combination is the common one used for cutting applications and suitable for the abrasive particles together with the viscoelastic agent used. The mixing is carried out so that the composition and concentration of the working fluid could be maintained uniformly during the cutting process. The nozzles were constructed from circular stainless steel tubes. The nozzle aspect ratio (nozzle length to diameter, l/d) has a significant effect on the initial jet velocity profile (McCarthy and Molloy, 1974). It should be assured that the ratio is sufficiently large so that the boundary layer fills the entire tube, resulting in a fully developed pipe flow. A catcher tank collected the slurry comprised of abrasive and cornstarch flowing out of the nozzle, absorbed the jet residual energy, and collected the debris of the product.

EXPERIMENT

The AWJ cutting involves a large number of variables that affect the main cutting results, i.e., cut depth, kerf width and kerf quality (Hashish, 1984 and 1991). In the present study, five major dynamic variables are considered on three samples; glass, marble and aluminum. These include water pressure, nozzle traverse speed, abrasive and additive flow rates, the standoff distance, and the additive concentration. A dimensional analysis of the jet hydrodynamics can also aid to determine the significance of each variable. For the first stage, the water pressure and abrasive and additive flow rates, and standoff distance were selected according to the common range of applications, shop floor practice and equipment limitations. The approach to selecting the appropriate levels of traverse speed was such that at the predetermined maximum standoff distance, minimum abrasive flow rate and minimum water pressure, the traverse speed was adjusted for a through cut while at its maximum possible rate. Lesser traverse speeds were then selected at an appropriate spacing. This approach would therefore ensure that all the combinations of parameters selected would produce through cuts for evaluation. In fact, higher traverse speeds for through cut may be possible at the high level of settings for abrasive and additive mass flow rates and water pressure and the low level of standoff distance used in the present study. The traverse speeds selected in this experiment were to ensure that through cuts could be achieved in all tests for comparison purpose. The optimum combination of the parameters for good quality through cuts can only be accurately evaluated when a great number of experiments are carried out. Here however, three levels of waterjet pressure (200, 250 and 300 MPa), three levels of traverse speed (400, 600 and 800 mm/min, and so on), three levels of additive concentration (0%, 10% and 22% by mass) and three levels of standoff distances (2, 3 and 4 mm) were tested using a single jet impact angle of 90°. The parameters which were kept constant included the orifice diameter (0.31 mm), the mixing tube (chamber) diameter (1.35 mm), the length of mixing tube (95.5 mm), the nozzle diameter (1.02 mm), the nozzle length (76.0 mm), and the abrasive which was 80 mesh almandite garnet sand flowing at the rate of 0.4 kg/min. Consequently, a total of 81 cuts (slits) were undertaken in this experiment. Figure 3 shows the schematic of the cutting process on sample of 10 mm width.

Figure 3: Viscoelastic Abrasive Waterjet Cutting



RESULTS AND DISCUSSION

Results of the experiments carried out on the three samples are given here. The primary interests in waterjet processing are the kerf shape (kerf width and kerf taper) and kerf quality (cut surface roughness) as well as burrs which may be formed at the jet exit. As the aim of the study is the improvements achieved upon using the viscoelastic agent, the effect of this agent on the effective jet width and a kerf taper angle are brought to attention.

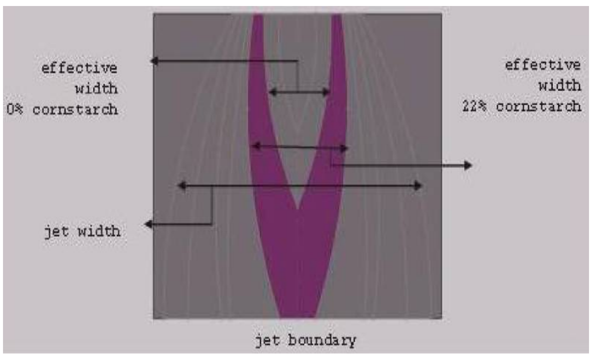
EFFECTIVE JET WIDTH

It is projected that the effective jet width is increased with the use of cornstarch shown in Figure 4. It can be shown that the jet kinetic energy increases when the additive flows with the jet. An obvious expression relates this energy to the mass flow and jet velocity:

$$\frac{dKE}{dt} = \frac{1}{2}(m_a + m_{ve})v^2 \quad ...(1)$$

where m_a and m_{ve} are the abrasive and cornstarch flow rates respectively and v is the particle (jet) velocity. This energy of the jet is an indicative of the jet effective width within which the particles have sufficient energy for material removal. It therefore determines the kerf geometry on the work material. Furthermore, the kerf width is dependent on the effective width (or diameter) of the jet, which in turn depends on the jet strength in that zone and the target material.

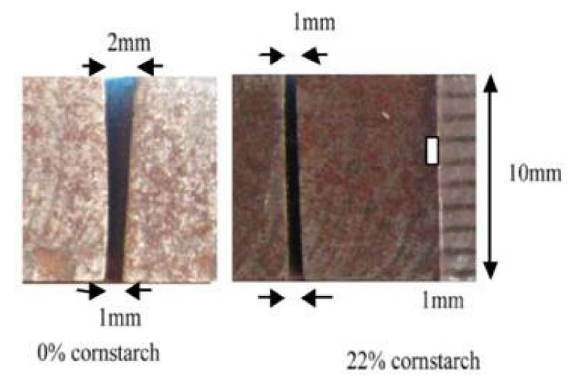
Figure 4: Increase of Effective Jet Width Upon Addition of Cornstarch



KERF TAPER ANGLE

The additive results in the reduction of the kerf taper angle as shown in the photographs in Figure 5.

Figure 5: Aluminum Sample Cut at Without (Left) and with (Right) Cornstarch



For the abrasive waterjet without additive, an expression to relate the kerf taper angle, θ, to the jet parameters may be mentioned as (Shanmugama and Masood, 2009):

$$\theta = f(p, V_t, S_d, \dot{m}_a, E) \quad ...(2)$$

where the operating parameters: p, V_t, S_d, $\dot{m}_a$ are the water pressure, traverse speed of the nozzle, standoff distance and abrasive mass flow rate, respectively, dj is the diameter of the jet, and E is the elastic modulus of the nozzle material. Although a full dimensional analysis must be carried out

Figure 6: Kerf Taper Angle vs. Cutting Speed Ratio for Marble

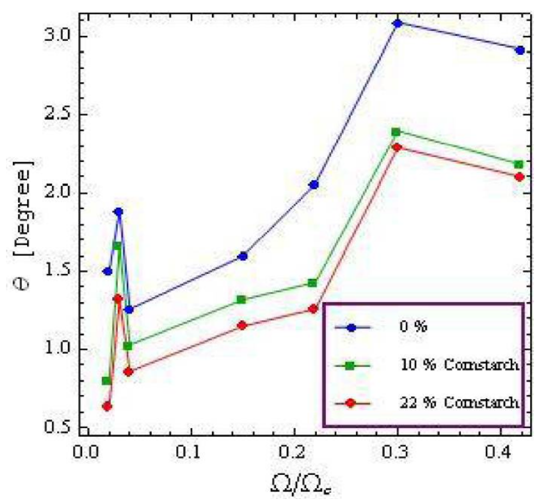


Figure 7: Kerf Taper Angle vs. Cutting Speed Ratio for Aluminum

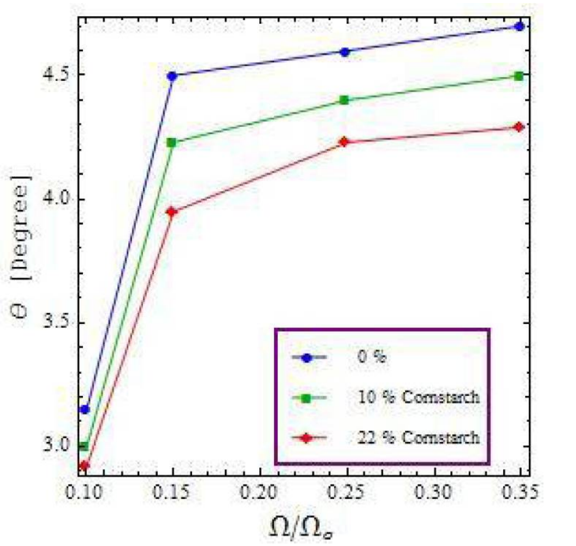
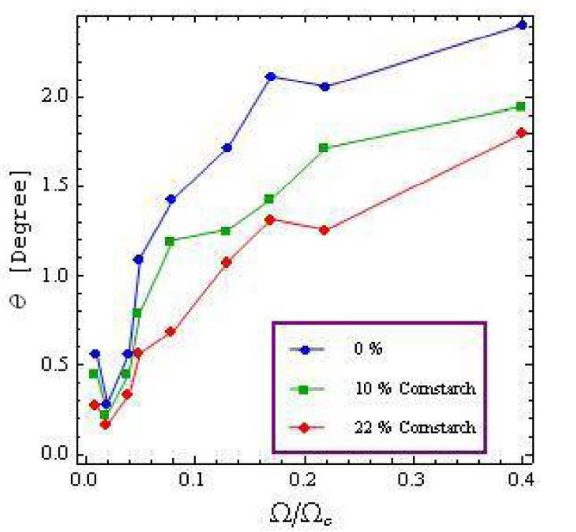


Figure 8: Kerf Taper Angle vs. Cutting Speed Ratio for Glass



to provide theoretical insight into the effect of additive on the kerf taper angle, it was evident through the experiment that the angle was sufficiently decreased. Figures 6 to 8 show the kerf taper angle reduction in the glass, marble and aluminum respectively. The burr is also reduced especially in the aluminum sample.

EFFECT OF FLUID VISCOELASTICITY

As mentioned, the addition of viscoelastic agent has resulted in an almost parallel cutting, burr reduction and increase of effective jet width. The first two effects are further reduced upon increase of cornstarch concentration. Moreover, the effective jet width widens in line with the increase of the additive concentration. The restriction of the equipment, especially the pump delivery however, governs the maximum possible concentration, which is chosen in this study.

A simplest dilatant model can be that of shear thickening obeying the power law as the constitutive equation:

$$\tau = k\dot{\gamma}^n \quad ...(3)$$

where $n > 1$, for shear-thickening.

where τ is the shear stress, γ is the shear rate, k is the consistency index and n is the power law index. Extension of the current study will include effect of the power law index on the cutting characteristics.

CONCLUSION

An experimental investigation has been carried out to study the viscoelastic properties of the additive on the abrasive jet stability. Prismatic jet cutting or else kerf taper angle reduction resulting from the developed normal stresses in the viscoelastic agent at high shear rates was achieved. The effective jet width, directly related to the jet energy is increased when cornstarch was added to the jet. The standoff distance can be minimized here resulting in further directing more coherent jet energy to the product and minimizing jet disintegration probability. The unwanted burr product was reduced especially in ferrous samples. Finally the viscoelastic agent appears to reduce the risk of breakage of fragile materials such as glass and brittle marble.

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