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Computational fluid analysis of abrasive waterjet cutting head †

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Abstract

Waterjet cutting is an appealing technology for cutting thick materials with zones that must not be affected by heat. This paper presents computational fluid dynamics (CFD) and theoretical analyses to optimize the mixing of components by the multi-phase approach. Water, air, and abrasives are mixed in a mixing chamber. This modeling is used to predict the influence of air and abrasives on the mixing at different distances within the mixing tube. At the same time, particle tracking was conducted to monitor the erosion rate density at the nozzle wall. Results show that nozzle length has an effect on the mixing of water, air, and the abrasives, and that the velocity of the waterjet influences the erosion rate at the nozzle wall. The k-ε turbulence model was used for simulation of the abrasive coupled with air. This investigation reveals that the erosion in the nozzle body is higher at the initial zone and that as the length of the nozzle length increases, the volume fraction of air increases accordingly. The entrance of the orifice is affected by a highly pressurized water stream (with minimal particulate matter), which causes chipping at the leading edge. To reduce the turbulence inside the mixing chamber, the use of a vacuum assist could be helpful, but precautions should be taken in order that the abrasives do not escape from the mixing chamber.

Keywords: AWJ; CFD; Erosion; Multiphase mixing

1. Introduction

Abrasive waterjet (AWJ) machining is a versatile process capable of cutting almost any material, with a reasonable finish on the machined surface. Its characteristics include extremely low cutting force and negligible thermal effects. The focus tube in a waterjet cutting system accelerates the abrasive particles used for cutting. The faster the abrasive jets, the better the performance. Abrasive jets are made up of two continuous phases and a solid particle phase, which makes them much more complex than plain waterjets. The velocity distribution is a crucial parameter in abrasive waterjet precision cutting. The most replaceable part in a waterjet cutting head is the focusing tube, which helps the abrasive particles to mix with water and air. Due to high velocity and shear stress developed on the focusing tube wall, erosion occurs. As a result, jet coherence decreases and the diameter of the focusing tube increases, which are undesirable in precision cutting [1]. Unlike problems encountered in the other fluid dynamics, water is compressible in AWJ under high pressure. Abrasive waterjet velocity was calculated [2] from the momentum balance of Bernoulli's equation and the compressibility factor. To measure the erosion of the focusing tube, a destructive [3] experiment was previously conducted. The wear of a wall due to the erosive effect of particle impact is a complex function of particle impact, particles, and wall properties.

A simulation was conducted to determine the characteristics of erosion in cutting materials for different particle angles. The erosion model of Finnie [4] provided [5] a way to determine the material removal or erosion rate density. Ansys CFX 11.0 was used for the computational fluid dynamics (CFD) simulation, where investigation was done on the waterjet air and abrasive velocity, as well as the erosion in the focusing tube by varying the mass flow rate of the abrasive and shape factor of the abrasive particles.

2. Theory

2.1 Theoretical waterjet velocity

$$V_{th} = \sqrt{\frac{2p}{\rho}} \tag{1}$$

Compressibility of water

$$\frac{\rho}{\rho_\circ} = \left(1 + \frac{P}{L}\right)^n \tag{2}$$

The resulting equation of the waterjet is

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$$V_j = \sqrt{\frac{2L}{(1-n)\rho_0}\left[\left(1+\frac{P}{L}\right)^{1-n} - 1\right]} \tag{3}$$

where L= 300 MPa and n= 0.1368 at 25° C

Compressibility factor

$$\psi = \frac{V_j}{V_{th}} = \sqrt{\frac{L}{P(1-n)}\left[\left(1+\frac{P}{L}\right)^{1-n} - 1\right]} \tag{4}$$

This compressibility factor and the coefficient of discharge can be used to express waterjet velocity

$$V_j = C_d \psi V_{th} \tag{5}$$

2.2 Erosion model

For nearly all metals, erosion is found to vary with impact angle and velocity according to the relationship

$$E = kV_p{}^n f(\gamma) \tag{6}$$

where E= dimensionless mass

V_p= particle impact velocity, n=2

$f(\gamma)$ = dimensionless function of impact.

Implementation in Ansys CFX

$$E = \left(\frac{V_p}{V_o}\right)^n f(x) \tag{7}$$

where $V_0 = \left(\frac{1}{\sqrt[n]{k}}\right)$

$$\text{Erosion rate} = E * \acute{N} * m_p \text{ (kg/s)} \tag{8}$$

where Ń=number rate, m_p=mass of particle.

The overall erosion of the wall is therefore the sum over all particles. Erosion rate density (kg/s/m^2) will provide the erosion zone of the focusing tube wall. For coupling air and abrasive, two types of coupling were used, namely, one-way coupled and fully coupled. One-way coupling simply predicts the particle paths based on the flow field, and, therefore, does not influence the continuous phase flow. Fully coupled particles exchange momentum with the continuous phase, allowing the continuous flow to affect the particles, and the particles to affect the continuous flow.

Shape factor is an important parameter for abrasive particles. A circular particle has a maximum shape factor of 1.0; the more irregular the particle is, the lower its shape factor. Erosion was investigated by changing the shape factor of abrasive particles.

3. Geometry and parameters

For the CFD simulation, a 3-D model of the cutting head was designed and ICEM CFD software was used for meshing. All the necessary boundary conditions were applied in Ansys CFX 11.0.

Table 1 shows the geometrical and boundary conditions for the CFD analysis. In the symmetrical model, the computation was made in less time as the total number of mesh decreased compared to the full model. Whenever possible, Ansys CFX suggests applying symmetry.

Table 1. Geometrical and boundary parameters.

Geometry/ boundary conditions	Parameters
Geometry	Orifice diameter=0.96 mm Coefficient of discharge, C_d=0.8 Mixing chamber diameter=4.2 mm Mixing chamber length=3 mm Focus tube diameter=1.5 mm Focus tube length=70 mm Abrasive inlet diameter=1.56 mm
Boundary conditions	Abrasive mass flow rate= 8, 20, 30 g/s Abrasive density=7854 kg/m^3 Abrasive shape factor=1, 0.9, 0.7 Air velocity=5 m/s Water pressure=470 MPa Density of water=1134 kg/m^3 V_0=1.0 m/s Fluid solid coupling= One-way coupled and fully coupled

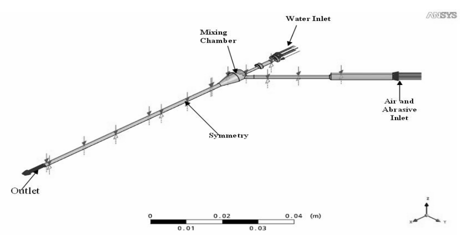

Fig. 1. Boundary conditions applied to the cutting head.

4. Experiment

Major simulation results were compared with theorem and the previous experiments performed by different scholars. The performed to ensure that the simulation [6] was an accurate investigation to measure the jet velocity [7]. For this measurement, a high-speed camera was used to observe the jet travel time and distance. In addition to the KODAK SR-Series motion analyzer, waterjet machine form TOPS CO., LTD was used for this experiment. The set frame rate of the camera will record the time and the standoff will determine the distance. If the velocity of the jet remains constant, considering the high-speed jet and very small standoff distance of 60 mm, then it is possible to measure the velocity up to 600 m/s jet for frame rate 10000 fps. It is possible to calculate the jet velocity by dividing the standoff distance by the time calculated from the required frames that are needed to travel the distance. Experimental parameters were considered according to the boundary conditions applied during the simulations.

5. Results and discussion

From Eqs. (1), (3), and (4), V_{th}= 970 m/s; V_j=934 m/s; Ψ=0.96 Considering the coefficient of discharge and compressibility from Eq. (5), V_j = 0.8X0.96X 970= 745 m/s

The maximum velocity of water determined in the CFD analysis was 735 m/s at the orifice exit, as shown in Fig. 2. After mixing with air and abrasive, the waterjet velocity found

Table 2. Variation velocity and maximum erosion for different mass flow rate of abrasive.

Mass Flow rate (g/s)	Max Erosion (Kg/s/m^2)X10^8	Velocity of abrasive (m/s)
8	0.96	295
20	2.414	290
30	3.62	287

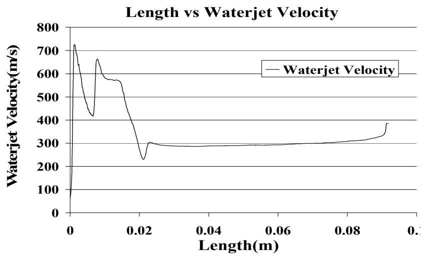

Fig. 2. Waterjet velocity variations along the cutting head.

at the focusing tube exit was 384 m/s, whereas the steel velocity was found to be 300 m/s for one-way coupling with air. Due to the change in the mass flow rate of the abrasive particles, the velocity of the abrasives remained unchanged. However, for fully coupled with air, the maximum velocity of the waterjet at the nozzle exit varied, and with the increase in mass flow rate the velocity decreased as the water had to accelerate more particles. Table 2 shows the variation of the abrasive (180 microns) and erosion on the wall for fully coupled abrasive.

Abrasive particles are accelerated inside the focusing tube, therefore, the velocity increases with the length of the focusing tube. Thus, the length of the focusing tube is crucial in the optimization of the waterjet. Fig. 3 shows the velocity increment of the abrasive inside the focusing tube.

The turbulence of water, air, and abrasives inside the mixing chamber create a very complex state. An attempt [8] was made to visualize the mixing by recreating the water channel and air-abrasive channel with Plexiglas material. Results of that attempt showed that the vortex-type flow dominates the flow pattern in the suction zone. The present CFD simulation shows the vortex created inside the mixing chamber. From the animation of the air stream line, the vortex phenomenon provides the initial mechanism of abrasive entrainment. Figure 4 illustrates the vortex created inside the mixing chamber by water (yellow), Air (rainbow), and abrasives (red).

M. Powell [9] explained that the kinetic energy and momentum are transferred from the high-pressure water beam to the abrasive particles. The kinetic energy is applied along the sharp edges of the particles. Therefore, the shape factor has an effect on abrasive velocity.

After applying the shape factor in the abrasive particle analysis, the abrasive velocity increased in the waterjet. For a shape factor of 0.9 and particle size of 100 micron, abrasive velocity were 309.5 m/s and 305 m/s for the one-way and fully-coupled models, respectively. Despite the reduction in the mean diameter, the particle velocity was higher when the

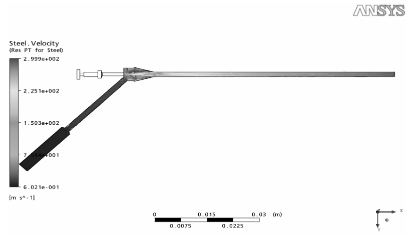

Fig. 3. Acceleration of abrasive along focusing tube.

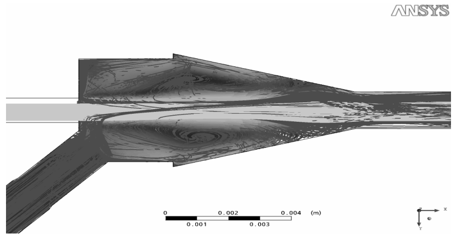

Fig. 4. Mixing of water, air and abrasive.

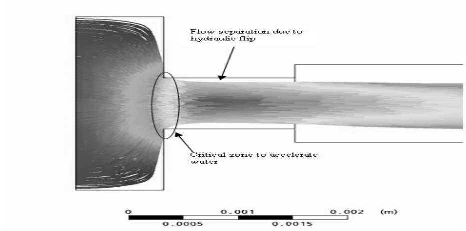

Fig. 5. Flow around orifice.

shape factor was applied, which indicates that using irregular shape particles will produce a better surface in the cutting specimen.

Hydraulic flips, flow separation, or cavitations [10] occur with a sharp edge orifice at high pressure. Figure 5 shows the hydraulic flip and critical zone of the orifice responsible for accelerating water. According to M. Powell, chipping could occur at the entrance of the orifice if water contains suspended particles.

M. Nanduri investigated nozzle wear by applying three types of investigations and divergent wear types. At a short distance from the focusing tube, entrance wear was at maximum. Our CFD simulation shows the same manner of erosion. In Fig. 6, similar to the experimental results, the erosion rate density decreases along the length of the focusing tube.
To determine the effect of shape factor on erosion of the focusing tube, 0.7 and 0.9 shape factor were applied while keeping the mass flow rate constant at 8 g/s for 100 micron particle size. Results yielded a higher erosion rate density for shape factor 0.7 than for shape 0.9. This means that if circular abrasive particles are used, then the cutting efficiency will decrease; however, the life of the focusing tube will increase. The opposite will be true for the case of irregularly shaped abrasive particles. Table 3 shows the variation in velocity and erosion for one-way coupling case for variation of shape factor with a constant mass flow rate of 8 g/s.

To visualize the effect of mass flow rate on erosion for both

Table 3. Effect of shape factor on the velocity of abrasive and maximum erosion on the focusing tube wall.

Shape factor	Max Erosion (Kg/s/m^2)X10^8	Velocity of Abrasive (m/s)
1	.96	299.9
0.9	1.45	305
0.7	2.48	309.5

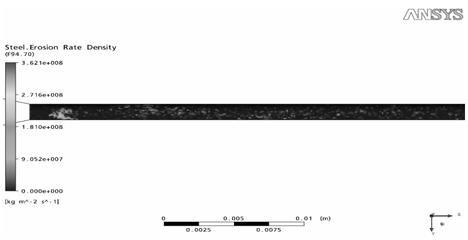

Fig. 6. Erosion on the focusing tube wall.

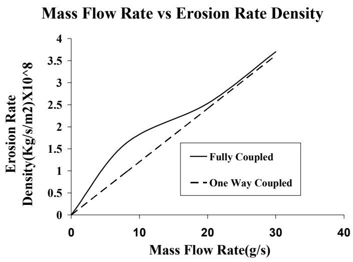

Fig. 7. Effect of mass flow on the erosion of focusing tube wall.

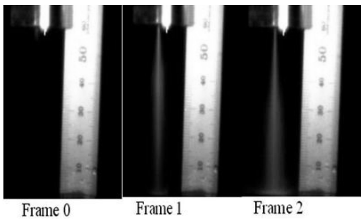

Fig. 8. Measurement of the waterjet velocity.

one-way and fully coupled models, coupling was done between air and abrasive. As one-way components coupling do not share each other's momentum, the erosion became linear, whereas, for fully coupled particles, erosion is nonlinear and has higher value. Fig. 7 shows the effect of mass flow on the erosion of the focusing tube wall.

The first three frames shown in Fig. 7 are the propagation of a high-speed waterjet. For 10000 fps, the time gap between two frames was 1/10000 s. For 470 MPa pressure, the required time was less than 2/10000 s, which indicates that the velocity was less than 400 m/s. Simulated velocity of the waterjet cutting was 384 m/s, therefore, the simulation and experimental results were very close.

6. Conclusion

The simulation results show that the length of the focusing tube is responsible for accelerating the abrasive particles, and that the erosion rate increases on the focusing tube wall with the change in the particle shape factor. If the mass flow rate of the abrasive is very high, then the efficiency of a jet could decrease as the thin waterjet stream has to accelerate more particles. The high-speed turbulent waterjet comes in contact with a relatively low-speed air stream, thus, a vortex will be created inside the mixing chamber, which has an effect on the mixing of different phases. The stream line vector for abrasive particles depends on the shape of the mixing chamber. Currently, the mixing cylinder is generally cylindrical in shape. Further investigation is needed to visualize the mixing for circular-, elliptical-, and hyperbolic-shaped mixing chambers, as they are able to guide the stream line to the jet in a more controlled way compared to the cylindrical chamber.

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