Numerical Simulation of Abrasive Water jet Cutting Process using the SPH and ALE Methods

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Abstract: On account of some complexities such as fluid-structure interaction and extra-large deformation problems, complete simulation of abrasive water jet cutting process is very hard. The main goal of this paper is to overcome these difficulties through comprehensive simulation in LS-DYNA commercial software. For this purpose the Smoothed Particle Hydrodynamics (SPH) and Arbitrary Lagrangian Eulerian (ALE) methods are employed. Utilizing these methods, the depth of water jet penetration and mechanism of erosion are simulated for a certain test case. In addition, the effect of water pressure and traverse speed on depth of penetration are examined. Comparison between the obtained results using both methods showed that the numerical results are in good agreement with available experimental data.

Keywords: Cutting, Water jet, Erosion, SPH, ALE.

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1 INTRODUCTION

Abrasive Water Jet (AWJ) cutting technology has individual benefits such as eliminating thermal effect from the work piece, low machining forces, good surface quality and high flexibility. These specifications extend the utilization of this method in recent years. Pressurized water flows through an orifice with a diameter between 0.08 and 1 mm accompanied by hard abrasive particles generating a high speed jet. When a work piece is subjected to the impact of a water jet, it will be cut by the material removal process due to the kinetic energy of each abrasive particle. Accordingly, this method can be employed to cut metal sheets, glass, stone, ceramic and composite materials. The components of an AWJ machine is chematically illustrated in Fig. 1.

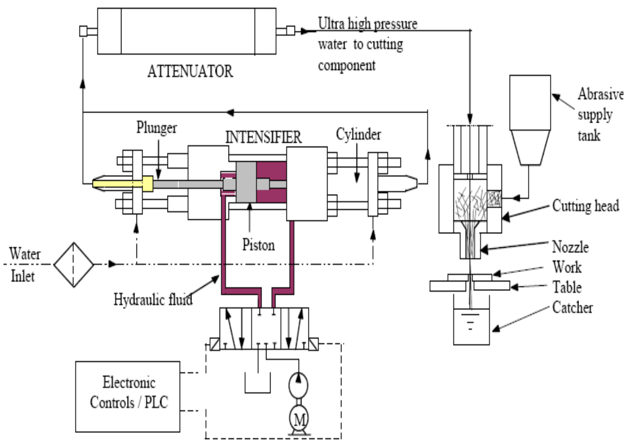

Fig. 1 A setup of an AWJ cutting machine [1]

The development of the AWJ technology in order to optimize and determine its performance needs to consider economic and careful investigations. Various experimental and theoretical researches have been conducted in this regard [1, 2]. Due to high cost and limited performance, the numerical simulation of this process is essential. However, simultaneous presence of fluid and solid is one of the important aspects of a numerical simulation. Additionally, because of extra deformation and large distortion in the computational grids, fluid model discretization can't be constructed by means of the Lagrangian element.
The investigation of the literature shows that in all simulations of this process via FEM, either a single abrasive particle impact is simulated [3, 4], or the pressure loading due to the AWJ flow on the target is considered for simulation [5].
One of the existing methods for solving the simultaneous presence of fluid and solid, in a coupled fashion, is using Eulerian grids to model fluid and Lagrangian grids to model work piece. Many softwares are incapable of such a simulation. In this regard, one of the early efforts has been made by Takafoli [6]. However, he considered just a solid abrasive particle in his research model.
Another problem in the AWJ simulation is the presence of the abrasive particles within the water jet. As a computational point of view, CPU time will be increased due to increasing number of these particles.
Two methods are presented in this paper to overcome these simulation difficulties. In the first method, the SPH method, requiring only nodes and no mesh of elements, is employed to model the water jet eliminating the grids distortion of the related mesh models. One of the specifications of this method is using a random algorithm to distribute the abrasive particles within the jet flow. The second method, named as the ALE method, is also presented to simulate the fluid-solid interaction and to solve the problems arising due to the presence of abrasive particles.

2 A BRIEF REVIEW OF SPH AND ALE BASICS

2.1. The SPH method

The SPH method does not require a finite element mesh and it is classified as a mesh free or mesh less method. Mesh free methods have been recently considered in many research areas. The important feature of this method is that the computational mesh generation is not necessary and thus the approximate solution is obtained based on the nodal data that are distributed within the computational domain. The advantages of this method in comparison with the FEM are as follows [7]:

- Having high convergence rate
- Ability to consider a model discontinuity through enrichment of the standard shape functions
- Not sensitive to mesh distortion difficulties in large deformation problems
- Ability to provide solutions with the desired degree of continuity

SPH method is one of the old methods that have been used in the mesh free concept. It was developed and advanced by Monaghan et al. (1977) in astrophysical research.

In this method, the state of a system can be represented by a collection of distributed particles. These particles move freely in a computational domain, carry all the computational information, and can be regarded as interpolation points or field nodes. Since there is no connection between particles, the possibility of solution under large deformation is provided.

In this numerical method, a function *f* is approximated by multiplying *f* with a smoothing kernel function, and then integrating over the computational domain as follows [8].

$$\langle f(x) \rangle = \int_{\Omega} f(x')W(x-x',h)dx' \quad (1)$$

where *x* and *x'* denote the position vectors at different points and *W* is the kernel function.

Eq. (1) can be discretized into a form of summation over all the nearest neighboring particles inside the region controlled by the smoothing length for a given particle *j* at a certain instant of time.

$$\langle f_i \rangle \approx \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W(x-x'_j, h_i) \quad (2)$$

where *m* and *ρ* represent the mass and density of particle *j*. Also, *n* is the total number of particles within the smoothing length that affects particle *i*.

One of the well-known engineering commercial softwares that uses this method is called LS-DYNA. This software provides the using of the SPH method coupled with the finite element method (FEM) to simulate engineering problems. A flow chart diagram for a coupled SPH-FEM approach is illustrated in Fig. 2.

2.2. ALE method

One of the most important subjects in areas related to the computer simulation of computational fluid dynamics and/or nonlinear solid mechanics is determination of the relationship between the deformable medium and the related grid points.

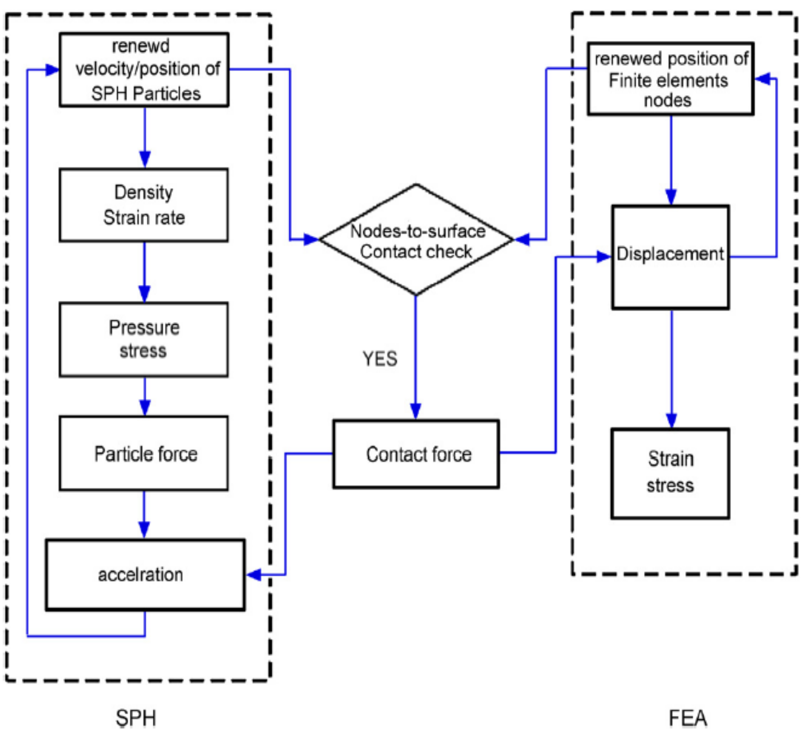

Fig. 2 SPH-FEM coupling technique [9]

Here is a brief summary of three simulation methods: Lagrangian, Eulerian, and ALE method.

- Lagrangian method: in this method each of the generated grid points follows the material particle trajectory. Thus, the Lagrangian viewpoint provides for the simple following of the interaction phenomenon with different materials. However, the weakness of this method is related to disability of the grids to follow the large deformation of materials.

- Eulerian method: In this method, the grid is stationary, but the continuum media moves with respect to the grid. So the large deformation phenomenon has not any effect on the structure of the grid. It must be noted that this method is not capable of simulating the interaction between materials.

- ALE method: due to the weakness of both the Lagrangian and Eulerian models, a technique has been developed called the ALE method which has the potential to combine the abilities of the two mentioned methods in a single model. In this model grid points are able to move independently from material particles.

The above mentioned methods are schematically illustrated in Fig. 3.

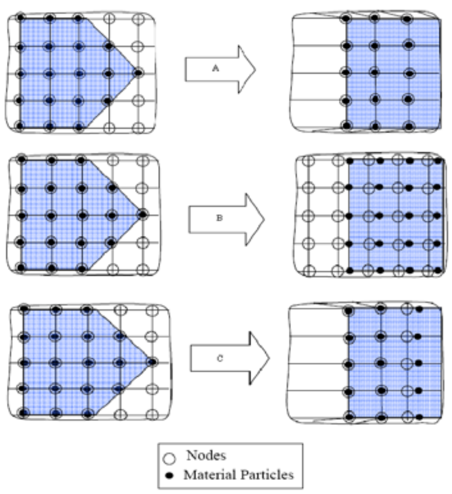

Fig. 3 A) Eulerian, B) Lagrangian, C) ALE [10]

These features exist in some softwares such as LS-DYNA. The possibility of connection and interaction between the Lagrangian structural grid and the Eulerian fluid grid is provided in this software.

3 RESULTS AND DISCUSSION

In this section, the simulation of the water jet machining is conducted using LS-DYNA. In this regard, the SPH and the ALE methods have been employed.

3.1. SPH Simulation

The coupled SPH/FEM methods are used to simulate AWJ machining simulation. The target material is modelled by FEM and the abrasive water jet is modelled by SPH particles. In order to apply the SPH method in the simulation process, the following assumptions are considered.

- The velocity of water jet is defined uniform and the output velocity profile is not taken into account. The jet velocity is determined by applying the Bernoulli equation at the inlet and outlet of the pipe considering the effect of fluid loss in the nozzle [11].

$$V_J = 40.24\, P^{1/2} \tag{3}$$

- After entering the air, the water jet remains in the jet core before reaching the target material and the water droplets have not yet been. The fluid properties, such as stagnation pressure, are constant along the jet stream axis in the jet core. The average core length is determinable from the following formula [11].

$$X_C / d_N = 100 \tag{4}$$

  where d_N denotes the water jet diameter.

- The normal velocity of the abrasive particles is equal to the water jet velocity. Because of the large nozzle length and low number of particles, a common velocity for the water is considered.

- In the present study, only a limited interaction between the abrasive particles and the water jet is simulated and the whole process of accelerated abrasive particles after injection into the mixing chamber is not considered.

In order to validate the obtained results, the required conditions for the water jet cutting simulation are considered in accordance with the experimental conditions defined in [12]. These data are shown in table 1.

Table 1 AWJ cutting conditions [12]

Parameter	Value
Water jet pressure, Mpa	100-350
Water jet nozzle, mm	0.33
Traverse rate, mm/min	23
Abrasive flow rate, g/s	2.56
Stand-off distance, mm	3
Abrasive mesh No.	80
Mixing tube diameter, mm	1.02

The Abrasive water jet has the height of 76 mm and the diameter of 1.02 mm and it is discretized by 2938 SPH particles. This amount of particles selected here is based on the diameter size of a single abrasive particle obtained from experiments (about 367 μm). The null-material models along with Gruneisen equation of state in LS-DYNA are employed for introducing the material model of the water. The considered essential parameters to be related to each model are indicated in tables 2 and 3.

Table 2 The null-material properties used for water [13]

Parameter	Value
Density, kg/m^3	1000
Cut-off pressure, Pa	-10^5
Dynamic viscosity, Pa.s	10^{-3}

Table 3 The coefficients value in Gruneisen equation used for water

Parameter	Value
Velocity of sound, m/s	1480
gamma	0.4934
a	1.397
S_1	2.56
S_2	-1.986
S_3	0.2286

The abrasive particles are made up of garnet whose properties are presented in table 4. These particles are also modeled by the SPH method.

The Null-material model is used for abrasive particles. The linear polynomial equation of state is considered for the material behavior of the abrasive. The proposed state equation is taken into account in accordance with [14] as follows:

$$P = C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4\mu + C_5\mu^2 + C_6\mu^3)\rho_0 e \qquad (5)$$

Table 4 The material properties of garnet abrasive [6]

Parameter	Value
Material density, kg/m^3	4325
Elasticity module, GPa	248
Poisson's coefficient	0.27

To distribute the abrasive particles among the water jet particles, the volume percentage of each material is firstly determined based on the water and abrasive particles mass flow rates, and the water jet volume. The number of SPH particles of the garnet and the water flow is obtained considering the volume of each abrasive particle and its real size. For example, there are 2340 water SPH particles and 58 abrasive SPH particles in the model at 100 MPa pressure. Finally, the abrasive SPH particles are distributed randomly among the water SPH particles in the model as shown in Fig. 4.

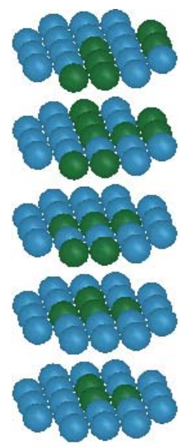

Fig. 4 Distribution of the abrasive and water SPH particles

To simulate the target piece which is made of low carbon steel alloy (Table 5.), eight-node brick element with kinematic hardening material model capability is used. This model has dimensions of 30×10×55 mm and is meshed by the fully integrated eight-node element to overcome the hour-glass modes problem.

Table 5 The values of mechanical properties of the used low carbon steel alloy [12]

Parameter	Value
Material density, kg/m^3	7860
Elasticity module, Gpa	210
Poisson's coefficient	0.284
Yield stress, MPa	260
Tensile strength, MPa	350
Failure strain	0.33

The initial velocity of particles including vertical and horizontal components is defined via Bernoulli's equation and transverse speed of the machine in accordance with [12]. These velocity values are assigned to the particles through INITIAL-VELOCITY command in LS-DYNA. Also, the boundary conditions (BC) of target piece are defined using NON-REFLECTING property which eliminates the reflected stress waves. To avoid rigid body motion, all degrees of freedom of the bottom side of the target piece are constrained.

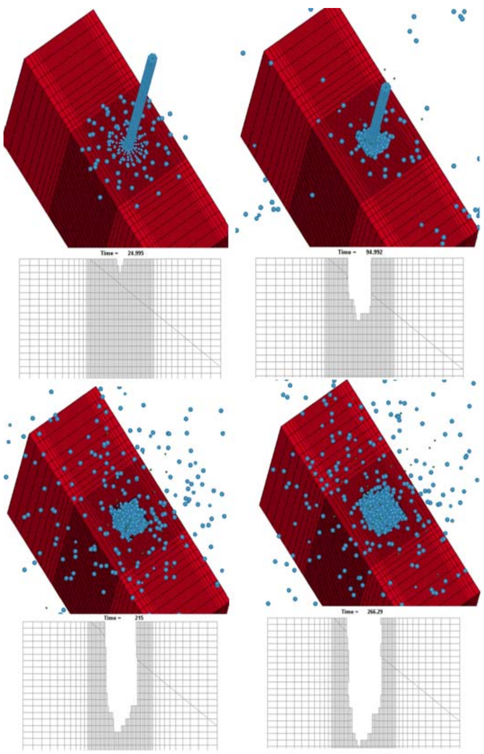

Fig. 5 The cross section of the work piece at different time intervals

The contact between the water jet and the target is defined using CONTACT-ERODING-NODES–TO-SURFACE command. It must be noted that all SPH particles pose as slaves and the target piece poses as master. Here, the depth of cut can be determined by applying the velocities due to different pressures.

Fig. 5 shows the cross section of the target piece during water jet cutting simulation.

3.2. ALE simulation

In this section, all assumptions, parameters and experimental conditions are selected as presented in the previous section. In addition to the target piece and the water jet, the surrounding air must also be modeled in the ALE simulation (Fig. 6). All of the mentioned components must be modeled by ALE elements. The required properties for the air simulation are presented in tables 6 and 7.

Table 6 The Null model properties of air [6]

Parameter	Value
Density, kg/m^3	1000
Cut-off pressure, Pa	-10
Dynamic viscosity, Pa.s	1.67×10^{-5}

Table 7 the constants of linear state equation of air

Parameter	Value
Initial internal energy	106×0.25
C_0	0
C_1	0
C_2	0
C_3	0
C_4	0.4
C_5	0.4
C_6	0

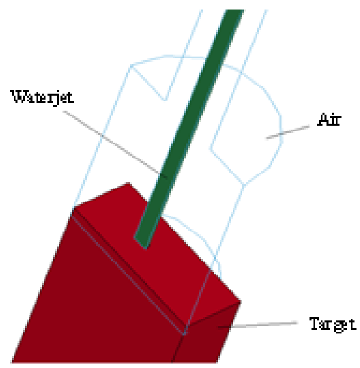

Fig. 6 Half of the ALE model

To reduce CPU time, the target piece has dimensions of of 15×10×55 mm. However, because of applying infinite boundary conditions, the considered dimensions do not have any effect on the results.

Here, some necessary commands for performing the ALE simulation in LS-DYNA are explained.
INITIAL-VOLUME-FRACTION tool is used to define volume percentage of each material in this simulation. In fact, this command removes the restriction that each element should be composed of one substance.

ALE-REFERENCE-SYSTEM-GROUP is an ability that forces the water jet and the air elements to follow the water jet trajectory. This command is the distinction of ALE with Eulerian and coupled Euler-Lagrange approach.

CONSTRAINED-LAGRANGE-IN-SOLID command provides the connection between Lagrangian (slave) and Eulerian or ALE mesh (master).

Finally, the depth of cut can be determined under different initial velocities. Fig. 7 shows the cross section of the target piece during water jet cutting simulation under 100 MPa pressure.

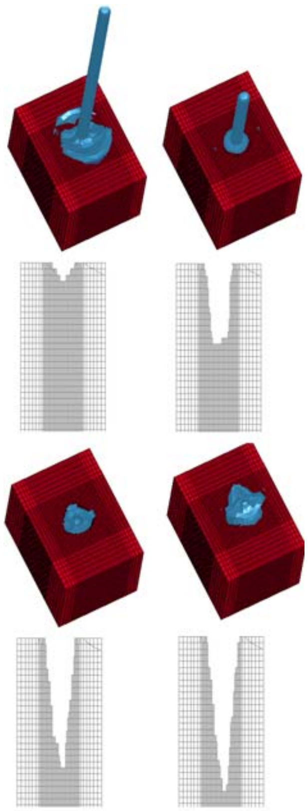

Fig. 7 The cross section of the work piece at different times

3.3. Results

The obtained cutting depth using the SPH and the ALE simulation at several pressure values are compared with available experimental results in Fig. 8. As it is illustrated in this figure, the cutting depth increases as the applied pressure is increased (due to the increasing energy of the water jet). It is important to note here that the results of the ALE method have lower values than those obtained from the SPH method and the experimental investigation. The main reason for this difference is that each abrasive particle in the SPH method is considered as a single concentrated mass, while in the ALE method, all abrasive particles are dissolved in water.

To investigate the effect of jet transverse rate on the cutting depth, another model based on the information presented in [2] is constructed. All working conditions except the abrasive mass flow rate and jet transverse rate in this reference is the same as [12].

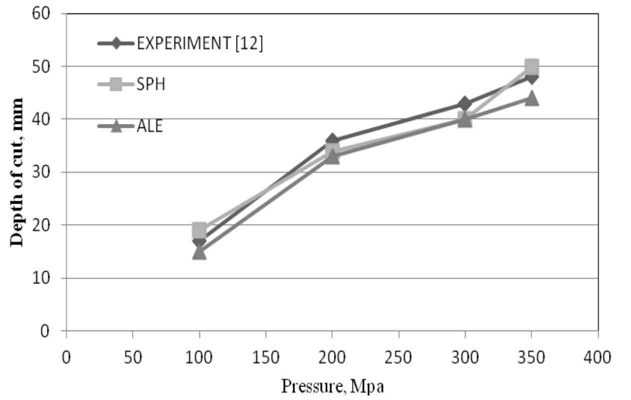

Fig. 8 Change of cutting depth under various pressures.

Fig. 9 illustrates the effect of jet transverse rate on the cutting depth at 250 MPa pressure and 7.5 g/s mass flow rate. As it shown in this figure, the obtained results are in a good agreement with the experimental results.

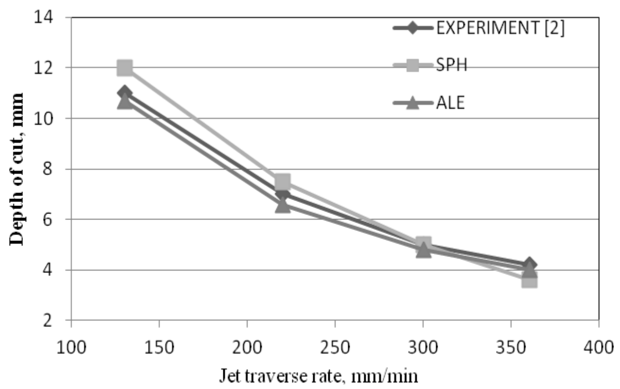

Fig. 9 Effect of jet transverse rate on the cutting depth

Here, the main reason for reduction of the cutting depth along with increasing jet transverse rate is to reduce the number of abrasive particle collisions. It can be seen that the results of the ALE method have lower values than the experimental results.

4 CONCLUSION

The water jet cutting simulation using the SPH and the ALE method was conducted in this study. There are three important subjects including fluid-solid interaction, impact dynamics and abrasion in this phenomena. Based on the specific features of

LS-DYNA for simulating this type of cutting problems and the ability to analyze the above subjects simultaneously, this software was used as an analysis tool. The obtained results match very well with the experimental data and indicate the reliability of this software to simulate such machining process. Of course, this software has weakness for contact modeling, because some SPH particles may penetrate into the target piece without facing any resistant.

The investigations show that the obtained results from the ALE method have smooth behavior in contrast with sinusoidal behavior in the SPH method. However, the ALE simulation spends much CPU time to determine the parameters affecting coupling.

Finally, the present water jet cutting simulation by these current methods compared to the older methods is considerably superior. But the overall judgment between the ALE and SPH methods is needed for further investigations.

REFERENCES

[1] Akkurt, A., Kulekci, M. K., Seker, U., and Ercan, F., "Effect of Feed Rate on Surface Roughness in Abrasive Waterjet Cutting Applications," Journal of Materials Processing Technology, Vol. 147, 2004, pp. 389-396.

[2] Paul, S., Hoogstrate, A. M, Van, L., and Kals, H. j. j., "Analytical and Experimental Modeling of the Abrasive Water Jet Cutting of Ductile Materials," Journal of Materials Processing Technology, Vol. 73, 1998, pp. 189-199.

[3] Hassan, A.I., and Kosmol, J., "Dynamic Elastic-Plastic Analysis of 3D Deformation in Abrasive Waterjet Machining," Journal of Materials Processing Technology, Vol. 113, 2001, pp. 337-341.

[4] Junkar, M., Jurisevic B., Fajdiga M., and Grah M., "Finite Element Analysis of Single-Particle Impact in Abrasive Water Jet Machining," International Journal of Impact Engineering, Vol. 32, 2006, pp.1095-1112.

[5] Guo, Z., and Ramulu, M., "Investigation of Displacement Fields in an Abrasive Waterjet Drilling Process: Part 2. Numerical Analysis," Experimental Mechanics, Vol. 41, 2001, pp. 388-402.

[6] Takafoli, M., "Finite Element Simulation of Cutting Steel by Water Jet Along with Abrasive Particles," MSc. Dissertation, Mechanical Dept, Tehran Univ., 2007.

[7] Liu, G. R., "Mesh Free Methods-Moving Beyond the Finite Element Method", CRC Press, 2003.

[8] Liu, G. R. and Liu, M. B., "Smoothed Particle Hydrodynamics-A Meshfree Particle Method", World Scientific Publishing, 2003.

[9] Attaway, S. W., Heinstein, M. W., and Swegle, J. W., "Coupling of Smooth Particle Hydrodynamics with the Finite Element Method," Nuclear Eng Des 150, 1994, pp. 199–205.

[10] Carlos Alberto H. O., "Robust Bird-Strike Modeling Using LS-DYNA," MSc. Dissertation, Mayaguez Campus, Puerto Rico Univ., 2006.

[11] Momber, A.W., Hydroblasting and Coating of Steel Structures, Elsevier, 2003, Chap. 2

[12] Hassan, A.I., Chen, C., and Kovacevic, R., "On-line Monitoring of Depth of Cut in AWJ Cutting," Int J Mach Tools Manu, Vol. 44, No. 6, 2004, pp. 595–605.

[13] Steinberg, D.J., "Spherical Explosions and the Equation of State of Water," Lawrence Livermore National Laboratory, Livermore, CA, 198.

[14] Grujicic, M., Pandurangan, B., Qiao, R., Chee Seman, B.A., Roy, WN., Skaggs, RR., and Gupta, R., "Parameterization of the Porous Material Model for Sand with Different Levels of Water Saturation," Soil Dyn Earthqu Eng, Vol. 28, No.1, 2008, pp. 20–35.