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A GENERAL OVERVIEW OF WATERJET SURFACE TREATMENT MODELING

Alex Chillman* and M. Ramulu
Department of Mechanical Engineering, Box 352600
University of Washington, Seattle, WA 98105

M. Hashish
Flow International Corporation
Kent, WA 98032

ABSTRACT

Since its introduction, the waterjet has gained immense popularity as a non-conventional machine tool for the processing of materials. Specifically, the waterjet has established itself as a tool for applications in the surface preparation industry. The waterjet has shown an inherent ability to (i) texture surfaces, (ii) remove bulk material in stripping applications, and (iii) induce a beneficial compressive residual stress in the subsurface layers to increase the fatigue performance of components. These three processes have been shown to be highly intertwined. The severity of waterjet surface preparation is governed by the system parameters; namely the supply pressure, nozzle traverse rate, standoff distance, orifice diameter, cleaning head geometry, jet angle, and exposure time. Numerous experimental studies have been performed surrounding the use of waterjets for the surface preparation processes listed above; while few models have been published to describe the material removal and peening capabilities of the waterjet. This paper provides a general summary of key modeling investigations, and discusses the applications, advantages, and limitations.

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* Research Engineer; Flow International Corporation

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1. INTRODUCTION

The ultra-high pressure waterjet (WJ) has gained increasing interest as a tool for surface preparation. Surface preparation refers to any process that is used to modify, enhance, or remove the exposed surfaces of a component or structure. Applications that require surface preparation range from low precision processes like rust removal from ship hulls to controlled processes such as texturing automotive cylinder bores to promote the adhesion of thermal spray coatings. The wide range of surface preparation processes that exist today can be broken down into three major categories:

i. Cutting, stripping and removal of unwanted coating / material (erosion)
ii. Generation of controlled surface textures, often to optimize coating or paint adherence
iii. Surface and subsurface modification to increase component fatigue life (peening)

Waterjets have been experimentally evaluated for stripping, texturing, and peening applications – with continually increasing research beginning in the 1960's. Early studies focused on the effectiveness of cutting materials including wood, polymers, and rock. Over the last 50 years, numerous experimental studies have been performed from sub-surface modification (peening) and material removal (erosion) standpoints, but a limited number of predicative models have been developed to characterize the waterjet–material interaction.

The goal of this paper is to summarize the basics fundamentals of waterjet-material impingement, and provide a historical perspective of past modeling investigations surrounding (i) waterjet structure, (ii) waterjet impact, and (iii) jet-material interaction.

2. WATERJET STRUCTURE AND DROPLET IMPACT

A key study characterizing the jet structure of a round jet was performed by Yanaida in the 1970's [1– 2]. Generally speaking, three regions exist in a waterjet: the initial, transition, and final region. In the initial region, the waterjet can be considered a solid continuous beam with a high axial dynamic pressure and very little air content. There exists a wedge-like cone that is assumed to exhibit jet velocities equal to the nozzle exit, as seen in Figure 1. Also, there is a mist zone which begins to form on the edges of the jet; this is a zone where the water begins mixing with air, and vortices are often observed. The mist zone exhibits both low velocity and low energy. At the end of the initial region, the interaction of the waterjet with the surrounding air results in the breakup of the waterjet stream into droplets – this is deemed the transition zone. Continuous interactions between the waterjet and air media result in a further disintegration of the droplets as the jet travels in the transition zone. This leads to a reduction in waterjet (now droplet) velocity, and a widening of the effective flow field. The transition zone is the region typically used for waterjet surface preparation processes. After exiting the transition region, the waterjet enters the final zone, where it has dissipated too much energy to effectively modify the surface or sub-surface of the workpiece – this is an unusable zone.

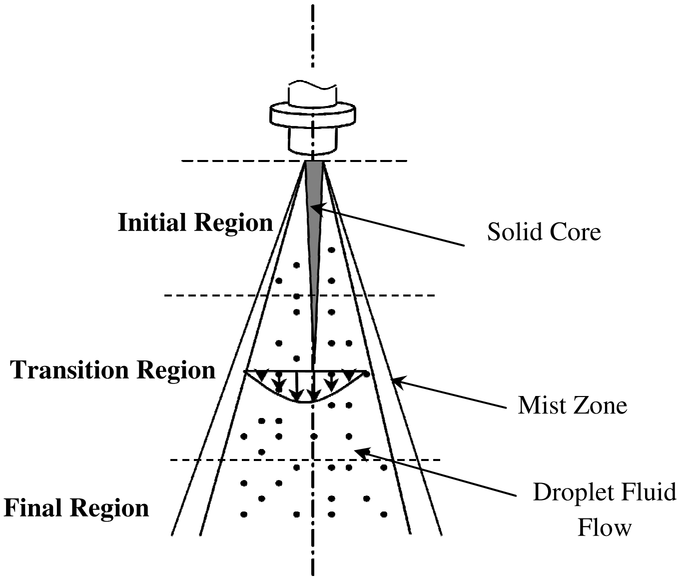

Figure 1. Change in jet structure with distance from nozzle.

Studies performed by Adler et al in the 1970's [3, 4] focused on the material removal processes during droplet impact, which is known to occur in the transition region of the waterjet. The main failure mechanisms that were highlighted are:

i. direct deformation
ii. stress wave propagation
iii. lateral outflow jetting
iv. hydraulic penetration

The impact sequence can be broken into two major phases: (a) the pressure build-up phase prior to fully-developed lateral outflow jetting and (b) the pressure release phase as the drop collapses onto the surface (see Figure 2). During phase (a), the contact zone will begin to expand, with the non-uniform pressure distribution reaching a maximum value [5]. These will lead to the generation of dilatational, distortional, and Rayleigh surface waves in the material. Fracture will typically occur in the regions of high tensile stresses, which occur at the boundary of the depressed zone (Mode i, ii). Failure can also occur due to the interaction between lateral jetting and small surface cracks located an extended distance away from the impact zone (Mode iii, iv).

The theory of droplet impact has served as a means for predicting the reaction loads in the transition region of the waterjet. The fundamental concept of an increased contact pressure when liquid impacts a surface was initially realized in 1928 by Cooke – and was later deemed the water-hammer pressure [6]. The water-hammer pressure was first considered to define the sudden closure of valves in piping, thus a cylindrical head of water comes to a sudden stop – but it has been shown to also describe the phenomenon of waterjet impingement. The water hammer pressure is defined by:

$$P_{im} = \rho_w C_o V_{im} = \dot{m} C_o \qquad (1)$$

where ρ_w is the density of water, C_0 is the speed of sound in water, V_{im} is the impact velocity, and $\dot{m}$ is the mass flow rate of water.

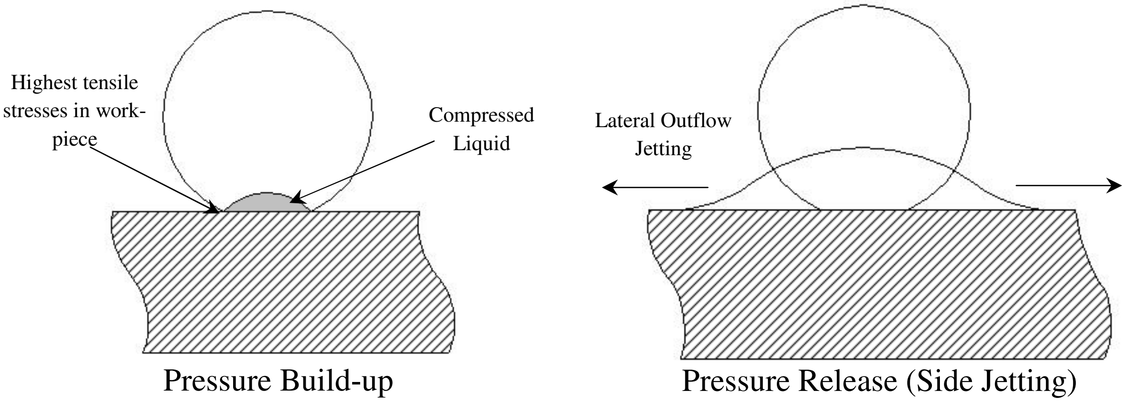

Figure 2. Mechanics of droplet impact.

The water hammer pressure is proportional to the impact velocity of the waterjet. It has been found that the impact velocity of the waterjet reduces as the radial distance (r) from the centerline increases within the transition zone. Experimentation performed by Erastov [7] in the 1960's determined a mass flow rate distribution predicted by:

$$\frac{\dot{m}}{\dot{m}_m} = \left(1 - \xi^{1.5}\right)^3 \qquad (2)$$

$$\text{where } \xi = \frac{r}{R}$$

where R is the radius at the jet at a given standoff distance. In 1974, Yanaida [8] published an alternate explanation of the pressure distribution within the transition zone of the waterjet, defined by:

$$\frac{P_{im}}{P_m} = \left(1 - \xi^{1.5}\right)^2 \qquad (3)$$

It can be seen that these two empirically determined distributions will provide differing results if the water-hammer pressure relationship (Eq. 1) is substituted into Eq. 2.

3. REVIEW OF WATERJET SURFACE PREPARATION MODELS

3.1. Early Modeling Efforts

Numerous studies were performed in the 1960's – 1980's looking at the mechanisms of material removal using waterjets. Key materials of interest were rock, concrete, polymeric materials, and wood products. The following is a summary highlighting the approaces considered during select studies – however it is important to state that this discussion provides only a brief glance at the studies performed during this timeframe.

Due to the complex nature of the waterjet removal process, many of the studies performed were semi-empirical in nature. They were developed from analytical principles, but due to the quantity and nature of the parameters and interactions, they relied on some empirical constants determined through experimental efforts.

Mohaupt [9] performed a semi-empirical study based on the energy balance equations between the waterjet and various polymeric materials – with good correlations to experimentally obtained data (Delrin, Plexiglas, and Polycarbonate materials). The energy of the waterjet was defined by the nozzle diameter, supply pressure, and traverse rate.

Two alternate studies into the cutting of rock were performed by Crow [10] and Rehbinder [11]. Crow's model was based on the assumption that the impacting waterjet created a pressure in the pores that exist within the material. The rock, in turn, is in a continuous state of fracture one grain diameter beneath the cutting surface. Rehbinder's approach varied, suggesting instead the rock exhibits a characteristic erosion resistance and threshold pressure to initiate erosion.

Hashish [12] performed a study defining equations that describe the governing jet–material interactions during pure waterjet cutting of various wood materials. Hashish's model related the cutting depth and specific energy to the jet parameters, cutting speeds, and material properties. This model was one of the first that accounted for the material properties of the workpiece, rather than characterizing the material removal based solely on jet parameters and empirically determined coefficients.

3.2. Continued Efforts in Erosion Modeling

In addition to the early waterjet cutting models, studies focused on the phenomenon of rain erosion were performed by Springer in the 1970's [13]. These studies highlighted the importance of the cumulative damage in droplet impact, and empirical relationships were developed to predict the threshold number of droplets that would be expected to initiate erosion in the work-piece. One expression developed by Springer stated that for a droplet impinging on a surface of a coating, the impact stress is equal to the water hammer pressure multiplied by a coefficient which is a function of droplet size, coating thickness, densities of the liquid, coating, and substrate, as well as the speed of sound in all three media. This water hammer pressure will generate a dynamic stress – and it is assumed that coating material is removed when the equivalent dynamic stress is higher than or equal to the endurance limit of the coating. Mathematically, this can be depicted as:

$$\lambda \, \dot{m} \, C_0 \geq S \qquad (4)$$

where S is the endurance limit of the coating material, $\dot{m}$ is the mass flow rate, C_0 is the acoustic velocity in water, and λ is a stress coefficient depending on the droplet size, coating thickness, and properties of the liquid, coating, and substrate material. It should be noted for a homogenous material, $\lambda = 1$. This model only considers the failure of the coating material – it does not account for bond failure at the coating-substrate interface.

The above relationship described by Springer has been considered as a basis for more recent waterjet modeling efforts. Leu et al [14, 15] modeled the stationary waterjet cleaning process based on the fundamental droplet–material relationship defined by Springer, and the jet structure relationships of Yanaida. Leu's model allowed for a predicative means of determining both the critical cleaning standoff distance (the maximum height at which coating removal will no longer occur) and the expected cleaning width. Experimental verification stripping an oil-based paint at pressures up to 320 MPa showed strong agreement to the predicted trends. While the model provided a means of predicting the material response during impingement by a stationary waterjet, most applications require surface coverage and involve relative motion between the tool and workpiece.

Citing this limitation, Meng, Geskin, Leu, Li, and Tismenseskiy presented an additional model to predict the critical cleaning standoff distance and the cleaning width for a moving waterjet [16]. This model was based on the semi-empirical study performed by Springer that found the mass loss per droplet impact (γ) can be defined by:

$$\gamma = \beta \left(\frac{\lambda \ P_{im}}{S_u}\right)^n \left(\frac{\pi \ d_d{}^3}{6}\right) \rho_c \tag{5}$$

where β is an empirical constant, n is an empirical constant, d_d is the droplet diameter, S_u is the ultimate tensile strength of the coating, and ρ_c is the density of the coating. The jet structure considerations of this model did not differ from that of Leu [15], and the result of this study was a semi-empirical model that showed strong capabilities at accurately predicting the cleaning width of low-strength coating materials. The model does not account for the incubation time that is required for erosion to initiate, which limits its use with high-strength substrate and coating materials. The final expressions Meng arrived at to define the critical standoff distance (SOD_c) and the cleaning width (w) are functions of:

$$SOD_c = f\ (\eta_0,\ \underbrace{\beta,\ \lambda,\ n,}_{\substack{\uparrow \\ \text{Empirical} \\ \text{Constants}}}\ \underbrace{C_0,\ \rho_w,\ \xi,\ r_n,\ C,\ P_S,\ k,}_{\substack{\uparrow \\ \text{Process Parameters and} \\ \text{Fluid Properties}}}\ \underbrace{u,\ S_u,}_{\substack{\uparrow \\ \text{Material} \\ \text{Properties}}}\ \rho_C) \tag{6}$$

$$w = f\ (\xi\ , C\ , SOD\ , SOD_c\ , n) \tag{7}$$

where η_0 is coating mass loss per unit area, C is the spreading coefficient, P_s is the supply pressure, k is a constant to define hydraulic losses, and u is the traverse rate. It is important to note that the cleaning width expression is not symbolically integrable, thus the relationship between cleaning width and standoff distance cannot be defined in a close-form equation. Because of this, numerical integration must be performed. The trends of the model depict the cleaning width increasing with standoff distance until a maximum is reached at approximately 0.6 times the critical standoff. A graphical representation of the cleaning width–standoff relationship for a moving waterjet defined by Meng can be seen in Figure 3. Experimental validation displayed the effectiveness of this model at predicting the cleaning width of painted surfaces [16].

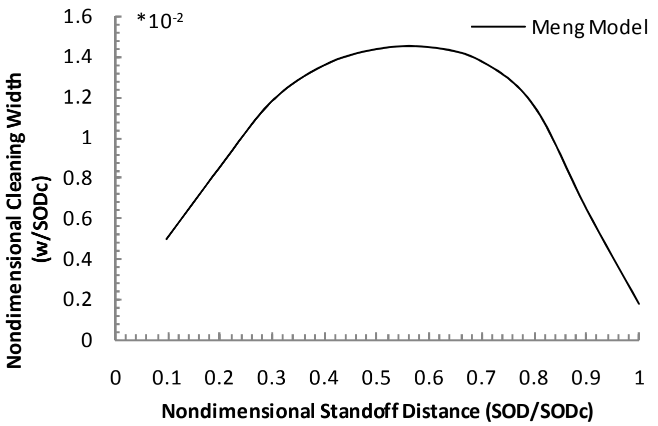

Figure 3. Cleaning width versus standoff distance, both non-dimensionalized with respect to critical standoff distance.

Additionally, it should be mentioned that the models developed by Meng and Leu (and previous modeling efforts) do not take into account the effect jet structure (droplet diameter, etc) has on the material removal trends. Experimental studies with metallic materials have shown that the removal of material is highly dependent on standoff distance – thus the initial/transition structure of the waterjet (see Figure 4) [17]. The erosion (cleaning) width follows the trend highlighted by Meng, however at small standoff distances no erosion is evident. It is not until the jet begins to breakdown into droplets that erosion is initiated for the given set of conditions.

Louis, Milchers, and Pude [18, 19] performed an analytical study to describe the de-coating (stripping) process by incorporating the linear accumulation of the damages from single droplets. The model takes into account three processes:

i. The accumulation of damage before the erosion begins.
ii. The erosion of the coating without the influence of the material interface.
iii. The erosion of the coating near the material interface.

The accumulative damage was used to describe the fatigue of the material, and the assumption was made that it could be defined by the Palmgren-Miner-formulation of linear damage accumulation. A series of empirical constants were considered, determined based on regression fitting against experimentally obtained data. The final relationships defined by Louis et al. formulated the erosion depth based on the location relative to the centerline of the waterjet – thus allowing for a semi-empirical representation of the kerf geometry.

Key simulation models have also been performed to characterize the material removal process using finite element approaches [20]. Mabrouki performed a finite element study using LS-Dyna3D to model the waterjet-target interaction for a coated-substrate target. The model highlighted a high stagnation zone at the impact center with a surrounding ring of damage. This correlates well with experimental results obtained removing an epoxy-resin paint from a steel substrate [21].

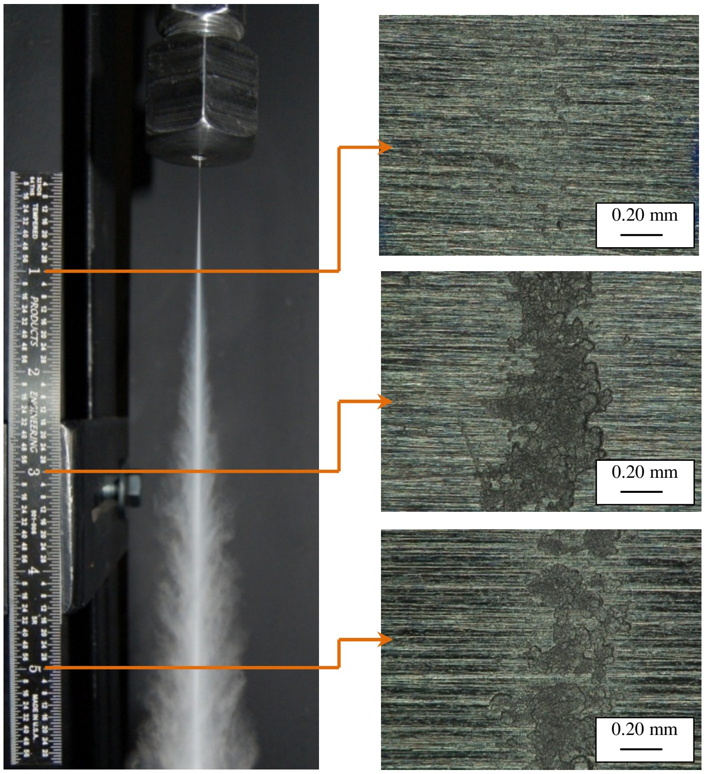

Figure 4. Waterjet processed titanium surfaces showing degree of erosion relative to the highlighted standoff distances. Jet conditions: $P = 414$ MPa; $u = 30$ mm/s; $d_n = 0.254$ mm. *(Scale in inches).*

3.3 Waterjet Peening Models

Waterjet peening is a cold working process that can impart compressive residual stresses in the surface and subsurface layers of the target material – which is known to improve component's fatigue performance. Conventional peening methods utilize solid particulate, whereas waterjet peening relies on the droplet breakdown of the jet in the transition zone. Waterjet peening has proven to be a beneficial process due to the potential of inducing compressive residual stresses without drastically altering the surface topography of the target material. Extensive experimental work has been performed to characterize the effectiveness of waterjet peening on metallic materials, yet few modeling studies have been performed to date.

Kunaporn, Ramulu, and Hashish developed a model to determine the effective standoff distances for the waterjet peening process [22]. Waterjet peening typically takes place in the transition zone, at a standoff distance that does not initiate erosion while still impacting with high enough pressure to initiate yielding in the sub-surface layers. Kunaporn proposed that the momentum of a liquid jet exiting a round nozzle remained constant between the nozzle and the point of impact on the target. Kunaporn defined the minimum impact pressure required to initiate yielding of a material as P_y, which is then defined as $C_1 * S_y$ where C_1 is a numerical constant. The final standoff distance where a waterjet can be expected to initiated yielding can then be determined from:

$$\mathrm{SOD_f} = \frac{d_n}{2\tan\frac{\alpha}{2}}\left[\left(\frac{2\,C_0}{P_y}\,\frac{P_s}{u}\right)^{\frac{1}{3}} - 1\right] = \frac{d_n}{2\tan\frac{\alpha}{2}}\left[\left(\frac{2\,C_0}{C_1\,S_y}\,\frac{P_s}{u}\right)^{\frac{1}{3}} - 1\right] \qquad (8)$$

where α is the jet angle, d_n is the orifice diameter, and S_y is the yield strength of the material. The constant C_1 is a value depending on the geometry of the interfacial pressure based on the elastic theory, which Kunaporn shows can be determined by finite element analysis (FEA) [22, 23]. Previous results have yielded a C_1 value of 1.59 for Al-7075-T6 given surface loading of the theoretical Hertzian pressure, which can be used as an initial prediction to determine the effective peening range.

Additional numerical studies into the effect waterjet peening has on residual stress distributions have also been performed [24, 25].

4. CONCLUSIONS

While this review provided a high-level look at the historical approaches for waterjet modeling, it is important to realize that the basic fundamental concepts have remained rather constant throughout the years. The basics of the droplet impact theory, energy balance, and momentum balance have continued to serve as the foundation of waterjet modeling. The modeling efforts highlighted in Section 3 can be summarized as shown in Table 1.

Table 1. Summary of key modeling efforts highlighted in Discussion.

		Models		
Affected Surface	**Examples**	**Physical**	**Semi-empirical**	**Simulation**
Droplet Impact	-	Heymann; 1969 [26] Adler; 1972 [3,4]		
Coating	*Coating Removal*	Springer; 1976 [13]	Meng; 1998 [16] Leu; 1998 [14, 15] Louis; 1999 [18]	Mabrouki,2002 [20]
Substrate Surface	*Texturing*			
	WJ Milling	Brunton; 1979 [5] Springer; 1976 [13]	Crow; 1973 [10] Mohaupt; 1974 [9] Hashish; 1978[12] Rehbinder; 1980 [11]	
Subsurface	*Peening*	Kunaporn; 2005 [22]		Kunaporn; 2004 [23] Rajesh; 2004 [24, 25]

One common theme that becomes evident when reviewing the existing waterjet material erosion models is the complexity of the physics involved with the process. To further capture the detailed physics of the process, additional considerations could be made towards the areas waterjet structure (droplet formation) and material resistance to the onset of erosion (influence of initial surface roughness and material properties).

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6. NOMENCLATURE

C	Spreading Coefficient
C_0	Acoustic velocity in water
d_d	diameter of a water droplet
d_n	Orifice Diameter
k	Coefficient accounting for flow resistance in waterjet plumbing
$\dot{m}$	Mass flow rate of water droplets per unit area
$\dot{m}_m$	Mass flow rate of water droplets per unit area at center of cross section
P_{im}	Impact Pressure
P_m	Impact pressure at center of cross section
P_s	Pump supply pressure
P_y	Minimum impact pressure that will initiate yielding of material
r	Variable radius from jet centerline
r_n	Orifice Radius
R	radius of waterjet in droplet zone
S	Endurance limit
S_u	Ultimate tensile strength
S_y	Yield Strength of material
SOD	Standoff distance
SOD_c	Critical cleaning standoff distance
u	Nozzle Traverse Rate
V_{im}	Impact Velocity
α	Jet spreading angle
β	Numerical Constant (Meng)
ρ_c	Coating Density
ρ_w	Density of water
λ	Stress ratio
ξ	dimensionless parameter
η_0	Coating loss per unit area
γ	mass loss per droplet impact