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Three-dimensional stochastic modeling of metallic surface roughness resulting from pure waterjet peening

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ABSTRACT

We propose a new approach named FEM-Stochastic approach for predicting the surface roughness resulting from waterjet peening of a metallic surface. This approach consists three aspects. One is Coupled Eulerian Lagrangian (CEL) simulation for studying the deformation behavior of single droplet; the second is the stochastic analysis for synthesizing a deformed surface; the third is to calculate the surface roughness parameters. CEL simulation results agree well with the liquid impact theory. Four situations with a different number of droplets (1000, 5000, 10,000 and 20,000) are analyzed, for which the deformed target surfaces and corresponding roughness profiles are shown and compared. Calculated values of roughness parameters indicate that there are three stages of evolution for the arithmetic average height R_a and quadrature average R_q. Those are: roughness increase stage, roughness decrease and roughness steady-state stage, respectively. The total roughness R_t and kurtosis parameter R_{ku} decline gradually when more and more droplets are modeled because the sharp ridges formed by fewer droplets are obliterated by the impingement of subsequent droplets. Skewness parameter R_{sk} values are all negative, no matter how many droplets, moreover, its absolute value becomes increasingly smaller as the number of droplet changes from 1000 to 20,000. The present spatial model of droplets, although still incomplete, is capable of synthesizing a deformed surface and calculating the relevant roughness parameters.

1. Introduction

We showed in a previous paper that a two dimensional analysis cannot determine the surface roughness profile of a waterjet peened metallic surface (Xie & Rittel, 2017). The problem will therefore be tackled from another perspective. For this, one needs to reconsider the peening process, particularly the contact between waterjet and target material surface, with the involvement of a very large number of single droplet impacts. In region II of the jet, the water column has transformed into a myriad of droplets with different diameters due to the atomization effect. The impact pressure is an accumulative consequence of every droplet impact. It is neither continuous along the axial direction nor is it smooth along the radial direction.

In this paper, we propose a new approach, as illustrated in Fig. 1, which consists of modeling the single droplet impact at first, then devising a method to add/average all the individual contributions in order to reproduce the deformed surface, and finally calculating the resulting roughness parameters based on that synthetic surface profile.

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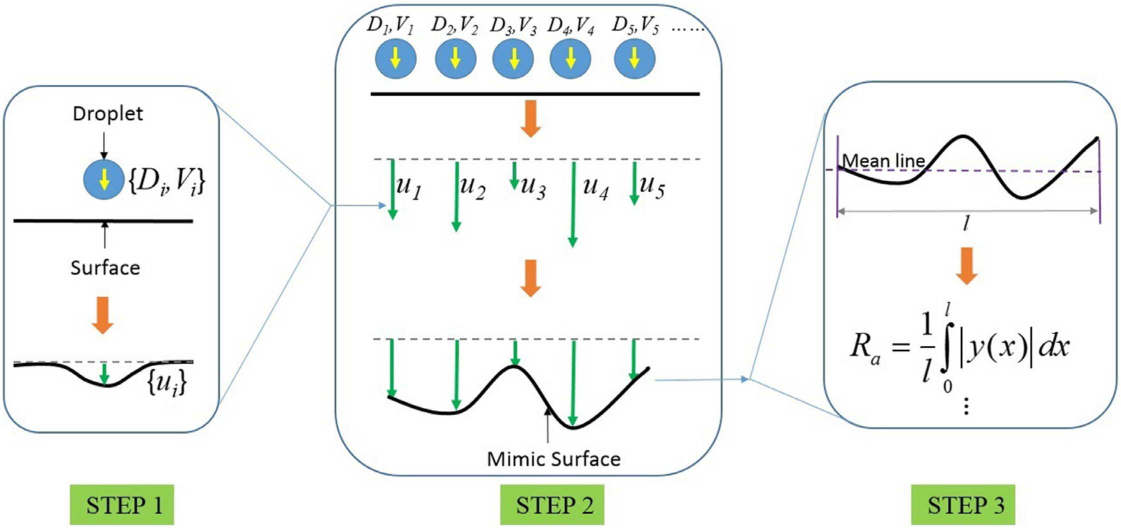

Fig. 1. Schematic representation of the FEM—Stochastic analysis procedures. STEP 1: model the single droplet impact and obtain the maximum vertical displacement of target surface; STEP 2: place a large number of droplets into the contact area and assume each droplet produces a vertical deformation according to the results of STEP 1 and connect all the endpoints of deformation vectors to synthesize a surface; STEP 3: calculate the various surface roughness parameters.

Many papers regarding droplet dynamics have been published since the 19th century. The English physicist A.M. Worthington gave a fascinating introduction to this field in 1876 (Worthington, 1876), and his book "*A Study of Splashes*" concludes all his main research achievements on the physics of splashes. Yarin published a review article (Yarin, 2006) which surveys the drop impact dynamics from experimental, theoretical and computational aspects. Likewise, experimental work due to Rioboo, Tropea, and Marengo (2001) revealed six possible morphology of drop impact on a dry surface.

As of today, finite element packages, such as Abaqus/Explicit (Abaqus, 2014), provide three available strategies for modeling the fluid-solid interaction problem: Arbitrary Lagrangian Eulerian (ALE), Smoothed Particle Hydrodynamics (SPH) and Coupled Eulerian Lagrangian (CEL). Each of them has been adopted by researchers to study the waterjet machining problem. Mabrouki, Raissi, and Cornier (2000), Maniadaki, Kestis, Bilalis, and Antoniadis (2007) and Gong, Wang, and Gao (2011) used ALE implemented in LS-DYNA 3D code to handle the waterjet and target interaction problem. Ma, Bao, and Guo (2008) compared three computational models and stated the SPH-FEM hybrid model they developed was more efficient than ALE when dealing with the fluid-solid interaction, especially the waterjet penetration problem. Hsu, Liang, Teng, and Nguyen (2013) used CEL technique to simulate a waterjet at a speed of 570 m/s impacts on a flat PMMA plate, and provided an accurate quantitative details of stress, strain and deformation fields that would be difficult to reproduce experimentally. At the time of droplet collapse, the droplet undergoes a large amount of volumetric deformation at a high strain rate. Based on our previous experience (Xie, Nélias, Walter-Le Berre, Ogawa, & Ichikawa, 2015), the CEL is a good choice for eliminating the element distortion problem which frequently occurs during the simulation process of high strain rate and high strain gradient problem.

Specification of droplet size in the downstream of waterjet is not only of utmost importance for the design, operation, and optimization of waterjet systems, but also for our prediction. Experimental results showed that the droplet ranges from infinitesimal to a maximum of 200 µm (Boyaval & Dumouchel, 2001; Sellens, 1989). A finite maximum diameter exists because aerodynamic forces and a non-zero minimum diameter exists because of the cohesive surface tension forces. Since small droplets do not have enough momentum to travel a long distance, a gradation of droplet sizes in the waterjet axial direction occurs, and thus only large droplets exist in the downstream locations (Yoon et al., 2004). The same phenomenon appears along the radial direction (Li et al., 1991). Large droplets are less affected by the air entrainment and subsequent interact with turbulent eddies in the entrained air, while smaller droplets are generally swept toward the waterjet centerline. Eventually all the droplets will have more uniform size at farther downstream.

Babinsky and Sojka (2002) reviewed three available methods for modeling drop size distributions: the empirical method, the discrete probability function method, and the maximum entropy principle method.

The classical empirical method consists of collecting data for a wide range of nozzles and operating conditions then fitting the data to a curve. A few popular empirical distributions used are log-normal, root-normal, Rosin–Ramble, Nukiyama–Tanasawa, and log-hyperbolic distributions (Asadollahzadeh, Torkaman, Torab-Mostaedi, & Safdari, 2017a, 2017b). One can see two problems with the empirical method: first, none of the above distribution is universal and can accurately fit a large fraction of the available data; second, extrapolating the data to operating regimes beyond the experimental range is difficult.

The discrete probability function (DPF) method assumes that the initial fluid structure separates into ligaments, and these ligaments break up into ligament fragments, and finally collapse into droplets. It involves a detailed instability analysis for