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Finite element modelling of overlapping abrasive waterjet milled footprints

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ABSTRACT

Successful automatic simulation of the resulting surface obtained by abrasive waterjet (AWJ) milling is dependent on the ability to model the overlapped jet footprints. In this article an attempt has been made to develop a finite element (FE) model to simulate the overlapping AWJ milled footprints over a range of step-over distances, water pressures and traverse speeds at 90° jet impingement angle. A methodology has been proposed by which multiple overlapped AWJ milling passes can be simulated without being computationally extremely expensive. The FE results are validated by comparing the simulated footprints and erosion rates with the corresponding experimental data. The workpiece material is modeled as Ti6Al4V, an extensively used material in the aerospace industry, and the abrasive particles are modeled as garnet which is a commonly used abrasive during AWJ machining. The model provides the opportunity to study and improve the mass distribution of the abrasive particles around the jet central axis. The simulated footprints and erosion rates obtained when overlapping the jet footprints are shown to be in good agreement (with maximum errors under 15%) with the experimental data. The results of this research are quite encouraging while taking into account the possible sources of errors within the experimental data (e.g. non-constant pressure, particles sizes and fragmentation).

1. Introduction

With the continuing development of new difficult to cut materials, there is a need to identify and develop the capabilities of niche non-conventional processing techniques capable of manufacturing high value-added products (e.g. jet engine components, medical implants, optical components and smart actuators) made of advanced engineered materials (e.g. Ti-superalloys, composites). This is of critical importance in today's scenario with increasing emphasis being placed on the use of green and environmentally-friendly technologies for the generation of these components. The conventional machining operations (e.g. milling, grinding, drilling) are difficult to employ for the processing of these advanced difficult-to-cut materials as they lead to extensive tool wear and generation of surface malfunctions (e.g. deformed layers and cracks) [1–3]. On the other hand, the existing non-conventional machining processes, known by their low material rates, either leave undesired surface damages (e.g. recast layer—laser/EDM) or require special materials properties (e.g. electrical conductivity—EDM) [4].

Abrasive water jet (AWJ) machining is one of the most promising non-conventional machining processes that has the capability to machine difficult-to-cut materials with good geometrical accuracies and no thermal damage. The distinct advantages that AWJ machining offer include very low specific cutting forces, no thermal distortion, high flexibility and no eco-intoxications.

In the AWJ machining process, high pressure water is converted into a high velocity waterjet after passing through an orifice inside the cutting head. The abrasive particles are entrained and accelerated to high velocities by the waterjet. The mixture of water and abrasive is directed through the focusing nozzle towards the workpiece, and as a result the material removal is mainly caused by multiple impacts of high velocities abrasive particles. Since the material is removed by the attrition in AWJ machining, the process is capable of machining any material regardless of its properties. When the jet plume (mixture of abrasives and water droplets) impacts and erodes the target surface, it results in the generation of a unique footprint (kerf).

Since AWJ milling is influenced by several process parameters, such as water pressure, abrasive size, target properties, and cutting parameters (e.g. traverse speed), etc., by developing appropriate models for AWJ milling the footprint generation process can be analyzed more closely. Furthermore, the development of models to reliably predict the jet footprints is of principal importance in AWJ milling for the generation of desirable geometries, because

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Nomenclature

AWJ	Abrasive waterjet
d	Nozzle exit diameter (mm)
ER	Erosion rate (mg/mg)
$\dot{m}_a$	Abrasive mass flow rate (kg/min)
m_{FE}	Mass of one jet pass in the FE model (mg)
m_L	Mass of particles impinged per unit length (kg/mm)
n	Number of jet passes
P	Water pump pressure (Pa)
PWJ	Plain waterjet
SO	Step-over distance (mm)
SOD	Standoff distance (mm)
V_f	Traverse speed of the jet across the workpiece (m/s)
V_{imp}	Impacting velocity of the abrasive particles (m/s)

several single footprints overlap to produce the end shape. The aim of the current work is to build and validate an FE model that will simulate the overlapping AWJ milled footprints after multiple passes of the jet.

FE models focusing on single/multiple particles impact for AWJ machining [5–8] and for erosion in general for other processes [9–11] have been reported. Some of the common discrepancies in these FE models are; (i) the impacting particles are considered as rigid [5,7,8,11], which is not a good approximation in problems involving high velocity impact (350–600 m/s) such as in AWJ milling [12,13]. It has been demonstrated by Salman et al., [14] that impacting particles show fracturing even at lower impact velocities. (ii) The shape of the impacting particles is considered as spherical e.g. in Ref. [7,8] whereas in the experimental data used for model validation garnet particles are used as the abrasive material which possess sharp cutting edges. Therefore, in the FE model the important tearing (cutting) phenomena during the real particles impact would be replaced by a ploughing action of spherical particles [15]. (iii) The sizes of the impacting spherical particles in the FE models were miscalculated by considering them equal to the average particle size of the fresh abrasive used during the experiments [5,7,16]. It is well known that the abrasive particles undergo fragmentation during their entrainment in the cutting head and their average size is reduced by 35% after passing through the nozzle [17]. This difference in size will have a huge influence (2 to 3 times) on the mass and hence the kinetic energy of the impacting particles, given that during high velocity impact, the deformation behavior of the projectile and the target is dominated by inertia [18]. (iv) The velocities of impact selected for the abrasive particles in AWJ FE models [7], [8] deviate from the reported experimental velocities [12,13]. All these factors magnify the differences between the experimental and simulated conditions of impact and adversely affect the accuracy of the FE models. Some single particle impact FE models that consider the elastic–plastic approach for both the target and the particles and use experimental impact velocities have also been reported [19,20]. However, these models still need to be extended further to more real multiple particles impact situation to be able to simulate the real AWJ footprints.

Wenjun et al. [21] presented an FE model for AWJ penetration in workpiece by modeling abrasive particles and water as a predefined mixture in an Eulerian FE mesh, i.e. each element in the mesh is assigned two materials (water and abrasives). However, this approach completely neglects the particles shape effect which is crucial in problems where erosion is a result of multiple particles impact [15]. In addition, by considering the abrasive particles as a portion of individual elements in the mesh, the authors have also ignored the size effect of the abrasive particles. Moreover, no information has been provided regarding the impact velocity of the water and abrasive particles.

Another AWJ machining FE model has been presented by Jianming et al., [22]. This model uses a smoothed particles hydrodynamics approach to model the abrasive particles as spherical balls equivalent to the average diameter of the fresh abrasive i.e. before fragmentation. Only one size is used for the abrasive particles, whereas in reality they have a size distribution which also influences the depth of the cut [17,23]. This approach also models the garnet abrasive particles as spherical balls which will suppress the cutting action of the garnet particles which they possess in reality and will change the resulting erosion rate [15].

Anwar et al., [24] presented a half AWJ milling FE model and correctly selected the size distribution, shapes and experimental velocities of the abrasive particles. However, being a half model based on symmetry of the process, this model can only predict jet footprints for single pass of the AWJ. On the other hand, in real life milled 3D surfaces are generated when several single footprints overlap. This implies that in order to simulate the overlapping footprints, still a full scale 3D FE model is required.

In this paper a new FE model for AWJ milling of overlapping jet footprints is presented. A new approach has been discussed which makes it possible to predict the footprints for different number of jet passes (n). The main aim of this research is to present an FE model that can accurately predict the overlapping AWJ milled footprints.

2. Finite element (FE) modeling

FE package ABAQUS (version 6.9-1) is used for modeling the current problem. The key modeling challenges for simulating the overlapping AWJ footprints lies in the facts that; (i) the size of the problem (total no. of elements), i.e. the multiple jet passes and the target, is too large to be able to run by including them in one model. A methodology is required to make the simulation runs possible which is discussed later in this section. (ii) Selecting the correct mass distribution of the abrasive particles within the jet plume. Fig. 1 represents typical views of the FE model for overlapping footprints. The positions for the three jet passes and the step-over distance between the adjacent passes is shown in Fig. 1 (a). In the current work only three jet passes are simulated firstly because three passes are enough to get a good picture of the overlapping behavior of the footprints and secondly to save the computational time. The modeling procedure for the overlapping footprints is detailed below.

2.1. Material modeling

2.1.1. Workpiece material model

Due to the high strain rates expected in the target (Ti6Al4V) material during the particles impact [25], the Johnson–Cook (JC) plasticity model [26] is employed for modeling the flow stress behavior of Ti6Al4V and the JC damage material model [27] is utilized for simulating the erosion in the target [24]. The values for the material constants required in these models are acquired from the work of Lesuer [28].

It is observed in the previous researches [29–31] that the as-is material constants adapted for damage model results in excessive erosion in the target. This is due to the difference between the