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On ultrahigh velocity micro-particle impact on steels – A multiple impact study

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ABSTRACT

A computational model is presented to investigate the ultrahigh-velocity multiple particle impact process on steels. It uses a Monte Carlo framework to model the stochastic nature of the particle flow and the finite element (FE) method to model the individual particle impact process, while considering the thermal diffusion process. The model predictions show a reasonably good agreement with the corresponding experimental data using a high-tensile steel specimen at various conditions. A simulation study using the model is then conducted and shows that it is essential to consider thermal diffusion which causes the temperature at the impact site to rapidly cool down in a multiple particle impact process. As a consequence, the impact result is impact-sequence and impact-time dependent. The study reveals that inertia-induced fracture is the primary material removal mechanism at the normal impacts, while the thermal instability-driven failure, or specifically the adiabatic shear banding (ASB) induced failure, as well as the elongation-induced fractures are the two major material removal mechanisms at oblique impact angles. These failures occur at the pile-up lips (at normal and oblique impact angles) and the crater bottom (at oblique impact angles). It is the thermal-instability-driven failure that contributes to the higher material removal rate at oblique impact angles.

1. Introduction

The multiple impact process by high velocity small particles on a target is a typical process of solid particle erosion, causing surface damage and material removal from the target [1]. This material removal process is in fact used in the emerging abrasive impact machining technology [2] that has enhanced the capability in processing all kinds of difficult-to-cut materials [3]. The early understanding of the ductile erosion may be credited to Finnie and Bitter's model [4,5] in which ductile erosion is considered to involve deformation wear and cutting wear modes occurring simultaneously. The work by Hutchings et al. [6] using relatively large impacting balls has also contributed to the understanding of the erosion process on steels.

Following the above-mentioned pioneering work, considerable experimental investigations have been carried out to study the material removal mechanisms during the particle impact process [7–12]. However, the small dimension of the particles and the resulting extremely short impact period make it very difficult to directly observe the associated micro-material removal mechanism. As a result, these studies primarily rely on the observation of the eroded surfaces to derive the erosion process.

In recent years, numerical simulation has been used to study the erosion process by single particle impact [13–20]. As the erosion in real life may involve many particle impacts, a more realistic multiple particle impact process needs to be considered. For this purpose, several important investigations using the FE method in the last decade have been reported on particle wear [13] and high velocity particle erosion in abrasive waterjet (AWJ) machining [21–23] and sand blasting [24]. The FE method is advantageous in that it does not require many simplifications and assumptions as in the analytical method and is able to reveal the detailed process that cannot be directly observed by the experiment. Thus, FE is a good method to study the complicated particle impact process. However, an adiabatic assumption, i.e. no thermal diffusion, was commonly used during the multiple impact process in the previously reported studies. This is clearly an issue requiring further investigations because the rising temperature due to the target heating by impacts may be diffused during the relatively long intervals between consecutive impacts. Without considering this effect, the local plastic heating of the target can only be accumulated and, hence, thermal softening is over-estimated, so is the erosion rate.

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Nomenclature

a_i, b_i	constants
A	Johnson-Cook yield stress constant
B	Johnson-Cook strain hardening constant
D_f	Johnson-Cook damage factor
D_{fmax}	maximum of Johnson-Cook damage factor D_f
D_i $_{(i=1\ldots5)}$	Johnson-Cook damage constants
D	Cowper–Symonds equation parameter
d_j	jet diameter (mm)
d_p	particle diameter (μm)
G	shear modulus (MPa)
K	bulk modulus (MPa)
$K_{1,2}$	Bao and Wierzbicki fracture parameters
L	considered cutting length on target in simulation (μm)
L_1	jet traveling length in simulation (μm)
m	thermal softening coefficient
m_a	mass flow rate of abrasives (g/s)
m_p	mass of abrasive particle (g)
n	Johnson-Cook strain hardening exponent
P	waterjet pressure (MPa)
q	Cowper–Symonds equation parameter
r	impact distance ratio
r_p	particle radius (μm)
T^*	homologous temperature
t_i	impact time for particle i (μs)
t_n	non-impact time or cooling time (μs)
T_i	initial temperature before cooling (K)
u_0	initial particle velocity (m/s)
u_i	initial velocity for particle i (m/s)
v_t	nozzle traverse speed (mm/s)
Y	yield stress (MPa)
α	particle impact angle (degrees)
$\dot{\varepsilon}^*$	dimensionless ratio of plastic strain rate when $\dot{\varepsilon}_0=1.0\ \mathrm{s}^{-1}$
ε_f	plastic strain to fracture
$\dot{\varepsilon}$	plastic strain rate (s^{-1})
ε	equivalent plastic strain
$\Delta\varepsilon$	incremental plastic strain
σ^*	stress triaxility (ratio of hydro-pressure to von Mises stress)
δt	inter-arrival time between successive impacts (μs)

In order to realistically model the target heating and cooling cycles during the multiple impact process, it is necessary to know the time intervals between successive impacts as well as other non-deterministic parameters, such as particle size and impact location. Monte Carlo method is a powerful tool to deal with these stochastic parameters, and has been used for modeling some erosion phenomena [25,26]. Each impact in the multiple impact process is called a “unit event” in the Monte Carlo simulation. Because of this repetitive character, the impact conditions of the discrete unit event, such as the impact location, particle size and the time of impacts, can be simulated by the Monte Carlo method, with the overall erosion behavior summarized over all the discrete damage events. The “unit event” which was primarily studied analytically in the past [25–27] can then be modeled using the FE method to achieve a more accurate solution with access to more detailed information in the whole erosion process. It should be noted that the practical particle impact process is naturally a sequential process; therefore, the final erosion results may be sequence-dependent and treating the moving particles in grouped layers as in previous studies [13,21–24,28] may not reflect the actual impact phenomenon.

There are a number of influencing parameters in a multiple particle impact process, one of which is the overlapping particle impact condition. An early study [29] has found an optimum distance between which two impacts result in a maximum damage to the target surface. Although the study is primarily for erosive wear and the impact velocity is low (25 m/s), it reveals that the overlapping condition between particle impacts can be an important factor in affecting the material removal rate (MRR) under the multiple particle impact process involved in AWJ machining.

In an earlier study by the present authors [20], an FE study on the crater formation and the material failure modes under a single particle impact condition was conducted. The FE model is extended in this paper to investigate the multiple particle impact process, where a Monte Carlo framework is proposed to model the stochastic flow of impacting particles and thermal diffusion is considered in the multiple impact process. The model is verified by a series of AWJ cutting experiments under different process parameters involving both normal and oblique impacts. Based on the developed model, a computational study is finally carried out to reveal the multiple particle impact process, the material removal mechanisms, and the effect of process parameters.

2. Model development

The computational study involves a Monte Carlo simulation framework to obtain the multiple particle flow parameters of non-deterministic nature, and an FE model to analyze the individual impacts, as shown in Fig. 1. The Monte Carlo generation of particle flow parameters is implemented in Turbo C, and the data are then imported into the FE package, AutoDYN.

2.1. Monte-Carlo simulation of particle impacts

Fig. 1(a) shows a flow diagram of the Monte Carlo simulation framework developed in this study and Fig. 1(b) shows a schematic of the corresponding multiple particle impact process to be simulated. The flow diagram in Fig. 1(a) consists of three stages. The first stage is the initialization of the simulation parameters relevant to an AWJ machining process; this is followed by the generation of the stochastic particle flow using the Monte Carlo method; and the last stage is to input the generated particle flow parameters into the FE model to execute an FE analysis. These stages are discussed below.

The definition of L and L_1 in Stage 1 is depicted in Fig. 1(b), where L_1 is the distance that the nozzle travels from A to B and L is the cutting length to be considered in the FE model. The jet coverage on L when it enters into and exits from L is considered, as shown in Fig. 1(b). Constrained by practical calculation time, the simulated cutting length L is set to be equal to the jet radius. Due to the small uniformity coefficient of 1.46 for the abrasives used in the experiment, in the Monte Carlo model, the particle shape is assumed to be spherical as in an earlier work [20], and the particle size is assumed to be constant and equal to 180 μm in diameter, that is the average garnet particle size used in the experimental work. Other parameters used are abrasive flow rate $m_a=3$ g/s, jet diameter $d_j=0.762$ mm, standoff distance 2 mm and jet traverse speed $v_t=500$, 750 and 1000 mm/s. The low abrasive flow rate and high traverse speeds used are to reduce the number of particles to be involved in the FE simulation considering the