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On ultrahigh velocity micro-particle impact on steels—A single impact study

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ABSTRACT

A computational model for the impacts of ultrahigh velocity micro-particles on steels, at the conditions relevant to abrasive waterjet (AWJ) machining, is developed using the AUTODYN software. By introducing the work hardening effect at the strain rate above 10^4 s^{-1} and Bao–Wierzbicki fracture locus into Johnson–Cook material models, the developed model can more realistically reflect the material behaviour subject to ultrahigh velocity micro-particle impacts. An experiment with high velocity (350–700 m/s) particle impacts on a high tensile steel was conducted, and the resulting crater volumes were measured and used to assess the computational model. It is found that the average error of the simulated crater volumes from the corresponding experimental data is within 10%. Based on the developed model, the transfer from impact energy to plastic work, and finally to crater volume is studied, along with the relation between plastic deformation, crater volume and material removal as well as the effect of impact variables and the target material yield strength on the impact behaviours. Three material failure modes (failures induced by inertia, elongation and adiabatic shear banding) are identified for spherical particle impacts. It is shown that while the crater formation is caused by plastic deformation near the impact site, the material removal process is associated with ductile failure mechanisms which are not only dependent on the magnitude of the plastic strain, but also the stress and thermal conditions.

1. Introduction

Fundamental research of material response to the impacts of particles at high velocities and small dimensions has mainly been derived from a perspective of solid erosion theories, which were developed in a quasi-static manner for impact velocities below 200–300 m/s [1–7]. A comprehensive review can be found in [8,9]. The reason why the impact velocity in the research of solid erosions (mainly for particle size from several μm to 1 mm) has been limited to about 200–300 m/s is primarily due to the challenge of accelerating the particles. In previous studies [1–7], the micro-particle was accelerated either by its gravity, kinetic energy through a rotor or compressed air. The recent emergence of AWJ machining technology, which uses highly pressurized water, enables the easy acceleration of micro-particles to several hundred meters per second [10–12]. Noticeably, just because of the very high impact velocity of the abrasive particles, AWJ is able to offer the capability to machine difficult-to-machine materials [8,13–15].

However, there is little experimental work in regard to impacts by high velocity particles relevant to the AWJ technology, although hypervelocity particle impacts up to 20 km/s were considered in the past [16]. An experiment of single abrasive particle impact using AWJ by Junker et al. [17] limits the maximum particle velocity to 220 m/s and the measurement was made to the 2-dimensional "sphericity" of the generated craters, not the actual crater geometry. Further, the particle velocity is assumed to be the same over the jet, which in fact is in a significant variation [10]. Similarly, the work by Ahmadi-Brooghani et al. [18] also limited the particle velocity to 220 m/s. More recently, a single impact computational model involving a single impact experiment in AWJ at the impact velocity of 581 m/s has been reported [19]. Unlike in the AWJ machining where the abrasive particles are harder than the workpiece, in this study steel balls were used as the abrasive particles that were softer than the target material, the Ti–6Al–4V alloy, so that steel ball failure was the main phenomenon, not the removal of target material. Further, the steel ball velocity used may be over-estimated according to [20]. Therefore, the acquisition of the experimental data for high-velocity impact by AWJ would be beneficial to both experimental and theoretical study of high-velocity impacts.

The modelling work on high velocity micro-sized particle impact is far from satisfaction. Although a significant steep

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Nomenclature

A	Johnson–Cook yield stress constant
B	Johnson–Cook strain hardening constant
C	Johnson–Cook strain rate 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_j	jet diameter (μm)
d_p	particle diameter (mm)
$E_{0,1}$	kinetic energy before and after impact, respectively (J)
$E^i_{pl\times wk}$	plastic work of element i (J)
E_{net}	net consumed energy (J)
$E_{pl\times wk}$	plastic work (J)
G	shear modulus (MPa)
K	bulk modulus (MPa)
$K_{1,2}$	Bao and Wierzbicki fracture parameters
m	thermal softening coefficient
m_a	mass flow rate of abrasives (g/s)
m_w	mass flow rate of water (g/s)
n	Johnson–Cook strain hardening exponent
P	waterjet pressure (MPa)
pg	picogram
T^*	homologous temperature
r_x	x-coordinate of crater center in the jet (μm)
r_y	y-coordinate of crater center in the jet (μm)
u_p, u_0	initial particle velocity (m/s)
u_1	rebound particle velocity (m/s)
V_{crater}	crater volume (μm^3)
$\overline{Y}$	averaged flow stress over plastic zone and deformation history (GPa)
$\overline{Y}_i$	averaged flow stress over the deformation history of element i (GPa)
Y_i	yield stress of element i (MPa)
Y_i^t	yield stress of element i at cycle t (MPa)
α	particle impact angle (degrees)
$\dot{\varepsilon}^*$	dimensionless ratio of plastic strain rate when $\dot{\varepsilon}_0=1.0\ s^{-1}$
ε_f	plastic strain to fracture
$\dot{\varepsilon}$	plastic strain rate (s^{-1})
ε	equivalent plastic strain
$\dot{\varepsilon}_0$	reference plastic strain rate (s^{-1})
$d\varepsilon$	infinitesimal plastic strain
$\Delta\varepsilon$	incremental plastic strain
ρ_w	water density (g/cm^3)
σ^*	stress triaxility (ratio of hydro-pressure to von Mises stress)
ω	the coefficient of net consumed energy in particle kinetic energy before impact
ϕ	the plastic work coefficient

material hardening behaviour starting from the strain rates of 10^2–$10^4\ s^{-1}$ has already been found for a variety of ductile materials, e.g. copper [21] and steel alloys [22,23], the reported computational models [17,24–29] did not consider this strong work hardening effect at high strain rates involved in the particle impact process. A numerical study [30] taking this into account successfully predicted crater volume formed at the high strain rate conditions. Recent work on angular particle impact below 120 m/s considered this effect and were verified by particle impact experiments [31–33].

In order to characterize the material failure behaviour, a large number of studies [19,24,25,29,31–33] employed the Johnson–Cook (JC) material failure criterion [34]. However, the JC failure model has its limitations, and a more realistic Bao and Wierzbicki (BW) model has been proposed [35] which has resulted in a significant improvement in representing the material fracture modes and patterns [36,37]. In addition, there are concerns about the smooth particle hydrodynamic (SPH) meshing method used for modelling chip separations in previous investigations [32,33], since the SPH mesh has an inherent problem of what is called tensile instability [38,39] which can result in non-physical fracture [40,41]. Because the material separation is a dominant phenomenon in the material removal process under particle impacts, an extra caution should be taken when using the SPH mesh to reveal the material removal process.

From the above analysis, there is an apparent need to study the micro-sized particle impacts at high velocity relevant to AWJ machining to understand the material behaviour under the impact and the material removal process. In this investigation, a numerical model for the material response to the ultrahigh velocity micro-particle impacts is developed. The developed model includes a modification to the JC strength model to take into account the significant work hardening effect at very high strain rates, as well as a replacement of the original JC fracture locus with a more realistic BW fracture locus [35]. As a start and for providing a fundamental understanding, this study will look into the single impact only using the ANSYS AUTODYN software as the platform for modelling. The target material is a high-tensile steel AISI 4340. The model is then verified using the data from a single micro-particle impact experiment at the impact velocities from 350 to 700 m/s. A computational investigation is finally carried out to understand of the material response to the high velocity micro-particle impacts and the underlying material removal mechanisms.

2. Computational model for single particle impact

Due to its advantages in modelling the material behaviour such as plasticity, failure, strain-hardening and thermal softening, the commercial ANSYS AUTODYN software is used in this study. The development of the model is given below.

2.1. Material behaviour models

In this study, a constant elastic modulus K is used, and a linear equation of state is employed for its simplicity along with a constant shear modulus G. The JC strength model [42] expresses the von Mises flow stress as

$$Y=(A+B\varepsilon^n)(1+C\ln\dot{\varepsilon}^*)(1-T^{*m}) \quad (1)$$

The symbols in the equation are as given in the Nomenclature. It has been found that the linear function of the logarithmic strain rate over the full range of strain rate expressed in Eq. (1) is not suitable for high strain rate response from 10^6 to $10^8\ s^{-1}$ [22,43,44] involved in the particle impact process in this study according to the work in [16]. Therefore, similar to [33], the second bracket in Eq. (1) was substituted with the Cowper–Symonds equation [45] according to the high strain rate yield strength data from [22].