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A new model for predicting the depth of cut in abrasive waterjet contouring of alumina ceramics

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ABSTRACT

A new predictive model for the depth of cut in abrasive waterjet (AWJ) contouring of alumina ceramics is developed using a dimensional analysis technique. The model is then experimentally verified when cutting an 87% alumina ceramic within the practical range of process variables. It is found that the model can give adequate predictions of this cutting performance measure with about 1% average error.

1. Introduction

Machining performance, including depth of cut (or depth of jet penetration) and cut quality, is a major technological challenge to the abrasive waterjet (AWJ) machining technology. This challenge becomes more intensified as the technology is more widely used in industry. A continual research and development effort has been made to explore its underlying science with an aim to increase its machining performance and application domain, as documented by Kovacevic et al. (1997), Momber and Kovacevic (1998) and Wang (2003a). Liu et al. (2004) carried out a computational fluid dynamics (CFD) study to understand the jet and particle dynamic characteristics so as to optimize the jetting and process parameters for enhancing the cutting performance. Wang and Liu (2008) later developed a jet characteristic model that enabled to evaluate the particle velocity distribution along and across an AWJ. Harashima et al. (2000) have also developed a model for particle velocity, or acceleration instead, that provided a good understanding of the dynamic characteristics of particles inside an AWJ. Investigations have been carried out on the material removal mechanisms in AWJ cutting of various materials. In his comprehensive study of the material removal mechanisms under the impacts of an ultrahigh pressure AWJ, Hashish (1984) reported that cutting wear and deformation wear were the primary material removal modes in the AWJ cutting process. He also reported on the conditions under which each wear mode might occur. Wang (1999) revealed the material removal mechanisms for polymer matrix composites under ultrahigh velocity particle impacts, which complemented the cutting wear and deformation wear modes reported by Hashish (1984). To further understand the kerf formation process and enhance the cut quality, Chen et al. (2003) studied the striation formation mechanisms on the

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Nomenclature

a, b, c, C's, K, q, s, x, y, z	constants
d_j	nozzle diameter (mm)
d_p	average particle diameter (mm)
E	modulus of elasticity (MPa)
h	depth of cut in straight cutting (mm)
h_c	depth of cut in contouring (mm)
H_d	material dynamic hardness (MPa)
k_d	discharge coefficient for jet velocity
k_e	particle impingement efficiency
k_m	momentum transfer efficiency
m_a	abrasive mass flow rate (g/s)
m_p	average mass of a particle (g)
m_w	water mass flow rate (g/s)
MRR	material removal rate (mm^3/s)
n	number of particles supplied in a time unit (s^{-1})
P	water pressure (MPa)
R	profile curvature radius (mm)
S_d	standoff distance (mm)
u	nozzle traverse speed (mm/s)
v	particle velocity (m/s)
v_j	waterjet velocity (m/s)
V_s	volume of material removal by a particle (m^3)
w	average kerf width (mm)

Greek letters

α	particle attack angle (°)
ρ_p	particle density (kg/m^3)
ρ_w	water density (kg/m^3)
σ_f	material flow stress (MPa)

surfaces formed by AWJ cutting. This study provided a basic understanding of this surface characteristic and formed the basis to improve the AWJ cutting process for an improved surface quality.

Studies have been undertaken on developing new cutting techniques to enhance the cutting performance of the AWJ cutting process. Hashish and Du Plessis (1979) and Wang et al. (2003) investigated the multipass cutting process and found that this cutting mode was not only able to increase the application domain of the AWJ cutting technology, but also increased the major cutting performance measures, such as the depth of cut, as compared to the single pass cutting mode within the same cutting time. Wang (2003b) further studied the AWJ cutting process where the nozzle was tilted forward in the direction of nozzle traverse motion. He found that when cutting an alumina ceramic material in the single pass cutting mode, titling the nozzle in a small angle of about 10° (or 80° jet impact angle) could result in more than 20% increase in the depth of cut as compared to the orthogonal cutting situation with the 90° jet impact angle. In the study of one of the most interesting cutting techniques, Lemma et al. (2002) and Wang (2007) found that by superimposing a pendulum-like oscillation movement to the nozzle traverse motion, the nozzle oscillation cutting technique could significantly increase some cutting performance measures. They showed that this cutting technique could increase the depth of cut in the single pass cutting mode by up to 82%. Moreover, Wang (2003b) and Zhong (2008) have respectively studied the combined use of multipass cutting with jet impact angle and multipass cutting with nozzle oscillation cutting techniques to further increase the AWJ cutting performance.

In order to effectively control and ultimately optimize the AWJ cutting process, predictive models for the various cutting performance measures, such as the depth of cut, are required. Yang et al. (2007) used a neural network approach in modelling the surface roughness, while Saxena and Paul (2007) developed numerical models for the various kerf characteristics. A number of mathematical models for the material removal rate and depth of cut have been reported, including those using solid particle erosive theories (Hashish, 1984, 1989; Wilkins and Graham, 1993), an energy conservation approach (Chen et al., 1996; Wang, 1999; Wang and Guo, 2002), fracture mechanics (El-Domiaty and Abdel-Rahman, 1997; Paul et al., 1998), dimensional analysis (Wang, 2007) and accumulating the micro-cutting processes of individual abrasive particles (Zeng and Kim, 1992), although those are essentially semi-empirical models with the constants in the models determined by cutting tests.

It is important to note that a vast majority of the investigations has been directed towards AWJ straight-slit cutting with very limited effort to study AWJ contouring, although the latter is a more common process. By its very nature, AWJ lags, or tails, behind the jet entrance point as it cuts into a workpiece. In AWJ contouring, this jet tail-back nature coupled with the varying jet traverse direction causes the jet to remove more material from the concave kerf wall (the outer kerf wall with larger radius) than from the convex kerf wall (with smaller radius), and generates different kerf tapers on the two kerf walls, as reported by Wang (2003a) and Wang and Liu (2006a). It also reduces the jet energy in the direction of jet penetration, which in turn reduces the depth of cut. Wang and Liu (2006a, 2006b) have presented an analysis of the cutting performance and the associated models for AWJ contouring of alumina ceramics. This paper presents a more comprehensive model for the depth of cut in AWJ contouring of alumina ceramics. The model is verified by an experimental investigation when cutting an 87% alumina ceramic.

2. Predictive depth of cut model

AWJ cutting process involves a large number of variables that affect the cutting performance. To consider all these variables is either impossible or will result in many unknown parameters in the final equation, making the model too complicated or unrealistic for practical use. In addition, there is not sufficient knowledge of some phenomena associated with the AWJ cutting process, such as particle interference and fragmentation (Wang, 2003a). As a result, to theoretically model the depth of jet penetration has been proven to be extremely difficult (El-Domiaty and Abdel-Rahman, 1997; Wang, 2003a); even with the assistance of cutting tests to obtain the required coefficients, the final equations are still very complicated for practical use, in addition to their very low prediction accuracy. By contrast, dimensional analysis (Svobodny, 1998) is a powerful analytical technique in describing the relation-