Wear 292–293 (2012) 1–10

Contents lists available at SciVerse ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Mechanisms of channel formation on glasses by abrasive waterjet milling

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ARTICLE INFO

Article history:
Received 8 February 2012
Received in revised form
31 May 2012
Accepted 21 June 2012
Available online 28 June 2012

Keywords:
Abrasive waterjet
Milling
Machining
Viscous flow
Turbulent flow
Milling performance

ABSTRACT

An investigation of the formation mechanisms of channels milled by abrasive waterjet (AWJ) on an amorphous glass is presented, based on the jet flow characteristics and erosion theories. It is found that the channels are formed through four different zones, i.e., an opening zone, a steady-cutting zone, an unsteady-cutting zone, and a finishing zone. These zones are respectively associated with a secondary viscous flow generated upon the jet impact on the top surface of material, a turbulent flow developed during the penetration of the jet into the material, a transition or laminar flow at the downstream of the jet, and a vortex and damping flow caused by the accumulation of the low-energy solid particles at the bottom of the channel. Bulges are found at the channel bottom and close to the channel wall machined at high nozzle speed as a result of a force induced by the acceleration/deceleration of the moving nozzle when changing direction during the operation. It is found that large high nozzle traverse speed and/or small standoff distance result in lay marks featuring with parallel grooves at constant distance. Sawtooth waves are observed on the machined surface when the cross feed is small. The effect of process parameters on the channel formation process as well as the milling depth, material removal rate (MRR), and wall inclination angle are then discussed. It is found that the milling depth and machined surface quality can be reasonably controlled through the selection of process parameters.

1. Introduction

The AWJ technology has received considerable attention from industry owing to its beneficial characteristics in machining of various materials, particularly difficult-to-machine and thermal sensitive materials [1,2]. However, unlike conventional machining technologies in which solid forms of cutting tools are used to machine components to a defined geometry at high accuracy, the performance of AWJ cutting depends strongly on the dynamic behaviour of the jet. When striking on a target material, an AWJ uses the energy carried by the liquid and the abrasive particles contained to cause material removal through erosion. The jet energy will reduce as the jet penetrates into the material. When the jet moves during machining, below a certain penetrating depth, the jet is significantly deflected which results in a sudden change of the cutting-front curvature. This causes striation marks which can be observed on the machined sidewall; and the zones associated with the change in jet deflection are generally described as the "smooth cutting zone" and the "rough or striation cutting zone", respectively [3,4]. In a non-through cut process, the diversion of the deflectable jet caused by the accumulation of abrasive particles may form large pockets in a very lower region [1]. In addition, the reduction of kinetic energy at the downstream of a deflectable jet has been recognized as a main cause for the formation of the taper of cuts and flange angle that are among some special kerf geometrical characteristics in AWJ machining [1,2]. At a micro scale, the material removal mechanisms are different when cutting different types of materials. Whereas chip formation and ploughing are important material removal mechanisms when cutting ductile material [2], lateral cracking that forms a continuously growing micro-crack network is a possible material removal mechanism when cutting brittle materials such as glass or ceramic [5]. For other materials such as fiber reinforced composites, dictation by broken fibers and fiber pullout becomes an important part of the material removal process [6–8]. A simulation study [9] has shown the effect of the rebounding angles of particles after impacting and the hardness of workpiece materials on the surface topography machined by an AWJ. In spite of the fact that AWJ is being increasingly used in the manufacturing industry, it has been primarily limited to slit cutting through considerable research and development efforts in the last decades, e.g., [8–12]. The complex, deflectable characteristics of AWJ makes its use for other machining operations more challenging. For instance, in milling, the milled cavity often has the dimension larger than the diameter of a jet, and to perform a defined geometry, the jet has to move in multiple directions and follows a cyclic overlapping operation. In addition, AWJ milling is a non-through cut process

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0043-1648/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wear.2012.06.008

where the depth of cut and surface quality at the bottom of milled cavity needed to be properly controlled. The change of jet moving direction at its turning points will cause a deflection on the moving jet, and thus induce an unstable cutting action. The cyclic operation, on the other hand, will generate an area at the bottom of the milled cavity through jet overlapping motion which affects the surface roughness. It is apparent that the design of the machining system and the control of the operating conditions will affect the quality of the milled components, such as surface finish and dimensional accuracy. There have been some research attempts to use AWJ for milling operations, such as [13,14] where masking plates made of hard materials were used to control the machined features. Other studies, such as that by Kong et al. [15], on the 2D jet footprint profile (kerf) caused by an arbitrary moving jet in maskless controlled-depth milling applications have pointed out the importance of moving straight jet path and jet orientation relative to the target surface. There are also studies to assess the possibility of using AWJ to process materials that are difficult-to-cut by the conventional milling method, including ceramics [16], titanium alloy [17] and fiber-reinforced plastics [18], by examining the machined surface roughness, depth of cut and MRR with respect to process parameters. In order to promote the AWJ technology for reliable milling applications that can be widely accessed by industry, it is essential to understand the material removal process and the milled feature formation mechanism involved in the AWJ milling.

This paper presents an experimental investigation of the formation process and mechanisms for channels machined by AWJ milling. The experiment was conducted on a brittle, amorphous glass. A visualization study was employed to examine the channel formation process in relation to the jet flow characteristics and process parameters. The relations between the milling performance measures in terms of the milling depth, MRR and wall inclination angle with respect to major process parameters were analysed to give an insight into the control of the AWJ milling process.

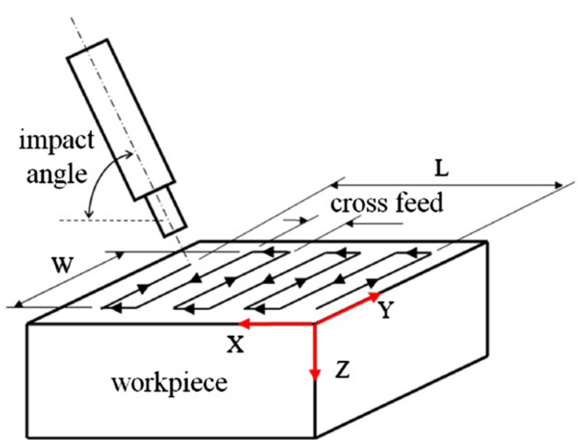

Fig. 1. Milling experimental setup.

2. Experiment

Fig. 1 shows the milling setup and how the nozzle moves to perform the milling tests. The experiment was conducted on a Flow International waterjet cutter equipped with a "Model 5X" single intensifier pump with the operating pressure of up to 415 MPa. The movement of the cutting head which followed two directions along the *X*- and *Y*-axes, namely feed and traverse directions, respectively, was controlled numerically by a 6-axis ABB IRB2400 robot using a C5 controller. To study the effect of the jet impact angle on the machining performance, the nozzle axis was set at an impact angle (α) with respect to the *X*-axis. Specimens with the dimension of $60 \times 50 \times 19$ mm and made of brittle soda-lime glass were used to facilitate the visualization study of material removal process. The mechanical properties of the glass are given in Table 1.

In AWJ machining, a large number of process variables are applicable and affect the machining process. For AWJ milling, additional parameters are involved, such as the nozzle cross feed (or feed) or jet overlap and the way in which the nozzle traverses motion is made in relation to the plane in which the jet impact angle is defined. However in this study, only five major and easy-to-control process parameters were considered, which were water pressure (P), nozzle traverse speed (u), jet impact angle (α), nozzle standoff distance (S_d), and cross feed (f_c), each of which was selected at multiple levels, as given in Table 2. The cross feeds of 0.38, 0.57 and 0.76 mm in fact correspond to 0.5, 0.75 and 1.0 times nozzle diameter, respectively. The other parameters which were kept constant, included orifice diameter (0.254 mm), nozzle diameter (0.762 mm), nozzle length (76.2 mm), garnet abrasive particles (80 mesh with average diameter of 0.18 mm), and particle mass flow rate (4.54 g/s). The Taguchi experimental design array was used to construct the milling tests. Two sets of tests were considered. The first set included an orthogonal array for nozzle traverse speed, standoff distance and cross feed, combined with a full-factorial array for the three jet impact angles at the pressure of 150 MPa, which resulted in 27 test runs. In the second set, the four levels of water pressure were tested at two levels of the nozzle traverse speed (55 and 145 mm/s), two levels of nozzle standoff distance (2 and 20 mm), and one level of jet impact angle and cross feed (at 0.57 mm and 45°, respectively), which formed 16 combinations in a full-factorial experimental deign. Two of the 16 test runs repeated the test conditions in the first set, so that in fact a total of 41 test conditions were considered. Nevertheless, to increase the reliability of the test data, all the 16 runs in the second test set were conducted and for the repeated ones, the average data were acquired for analysis.

Table 2
Experimental parameters.

Nozzle traverse speed (mm/s)	10, 55, 100 and 145
Water pressure [MPa]	100, 150, 200 and 250
Jet impact angle [°]	45, 60 and 75
Standoff distance [mm]	2, 11 and 20
Cross feed [mm]	0.38, 0.57 and 0.76

Table 1
Properties of the specimen material (soda-lime glass).

Modulus of elasticity [GPa]	73	Knoop hardness [kg/mm^2]	575 ± 20
Tensile strength [MPa]	19.3	Fracture toughness [MPa mm$^{1/2}$]	0.75
Compressive strength [MPa]	248	Thermal conductivity [W/mK]	1.05
Poisson's ratio	0.22	Density at 21 °C [g/cm^3]	2.5