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A NEW SENSING SYSTEM TO MONITOR ABRASIVE WATERJET NOZZLE WEAR

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Abstract

A wear sensor system for direct and almost on-line tracking the wear of an abrasive waterjet (AWJ) nozzle is proposed. The wear sensor is based on the conductive loops which will be placed on the ceramic's substrate and embedded on the tip of the nozzle. At the heart of this wear sensor system is a wear sensor probe which includes conductive loops divided into four sections. In this arrangement, each conductive loop includes a wearable conductive portion embedded at a particular location within the tip of the AWJ nozzle. The integrity or wear condition of the AWJ nozzle is indicated by the electrical closed or open circuit condition of each conductive loop. The continuity status of each wear sensor probe is converted to logic one or logic zero digital data information which are sampled periodically by a central processing unit (CPU) for providing a visual or audible indication in response to a predetermined erosion or wear condition. Additionally, the CPU is programmed to analyze collected wear data in order to determine the direction of the wear propagation and to provide the information to the controller to compensate for the increase in the AWJ nozzle inside diameter.

1. INTRODUCTION

The abrasive waterjet (AWJ) cutting technique is one of the most recently introduced machining methods. In this cutting technique, a thin, high velocity waterjet accelerates abrasive particles that are directed through an abrasive waterjet nozzle at the material to be cut. Advantages of abrasive waterjet cutting include the ability to machine hard materials, minimal heat build-up and few deformation stresses within the machined part, exceptional surface quality and metal removal rate, and omnidirectional machining that is ideal for automation.

One of the most critical parts that influences the technical and economical performance of an abrasive waterjet cutting system is the AWJ nozzle. The detection of the AWJ nozzle wear is currently performed visually, either through direct inspection of the tip of the nozzle or indirectly when a deterioration of the quality of surface cut and the workpiece dimensions is observed.

Computer control makes AWJ cutting a prime candidate for application in flexible manufacturing systems. Automated equipment needs the ability to detect nozzle wear early before kerf width exceeds acceptable limits. The methods used to detect AWJ nozzle wear could be categorized into two groups: direct and indirect. Direct methods make an assessment of nozzle wear by either measuring the inside diameter of the nozzle at its tip, or measuring the material loss of the nozzle by radiometric techniques. During direct measurement of the ID of the nozzle, the cutting process has to be interrupted and the jet turned off. Obviously, this method is not suitable for on-line nozzle wear measurement. The requirements for special preparation of the nozzle as well as potential hazards due to radioactivity makes the radiometric technique unsuitable for use on shop floor. Indirect methods are based on the measurement of some parameters that are correlated to the AWJ nozzle wear such as the change of the stream diameter at the nozzle exit, or the change of the workpiece normal force, level of noise, vibration, etc. A critical review of possible sensors for monitoring the AWJ nozzle wear was given by Kovacevic and Evizi [1].

A number of methodologies based on measurements of the parameters that are correlated to the nozzle wear were investigated [1-3]. Based on the preliminary analysis [1], it was proven that the change in the level of noise could be used as an appropriate parameter for indirect monitoring of the nozzle wear. To predict nozzle wear (the change of the ID on the nozzle outlet) under varying cutting conditions the model-based approach was proposed by Kovacevic [3]. The presence of nozzle wear is identified by estimating a parameter which is proportional to the nozzle wear. The average workpiece normal force generated by the impacting abrasive waterjet is used as a measured variable. A proposed nozzle wear sensing methodology estimates the nozzle wear in the presence of varying traverse speed as a cutting parameter.

Besides the change of the workpiece normal force level, its signal characteristics will also change with an increase in nozzle wear. It was shown [2.3] that nozzle wear could be detected and monitored by analyzing the dynamic portion of the workpiece normal force signal generated by the impacting abrasive waterjet. A time-series analysis technique was used to characterize the workpiece normal force signal with an autoregressive model. It was found that there is a strong correlation between the nozzle wear and the values of the autoregressive model parameters. The autoregressive model parameters could be constantly updated according to the workpiece normal force signal dynamics which are strongly dependent on the change of the exit diameter of the nozzle. This type of sensing technique can be applied in adaptive control where the model for a workpiece normal force will be continually estimated in order to be able to on-line track the nozzle wear.

However, because of the complexity of the AWJ cutting process, and the size of the workpiece it is very difficult to provide the conditions to monitor the workpiece normal force generated by the impacting abrasive waterjet. Thus, the practical use of such an AWJ nozzle wear sensing methodology is rather limited.

The objective of this paper is to present a wear sensor system that is able to track the wear on an AWJ nozzle directly and almost on-line. The proposed wear sensor system is based on a wear sensor probe which includes conductive loops divided into four sections. The integrity or wear condition of the AWJ nozzle is indicated by the electrical closed or open circuit condition of each conductive loop. Before the explanation of the proposed sensing system is given let us analyze the effect of the AWJ nozzle wear on the cutting performances.

2. A BRIEF REVIEW OF SOME SENSING TECHNIQUES TO MONITOR AWJ NOZZLE WEAR

Nozzle wear in a cutting operation by AWJ is undesirable because it severely degrades the quality of cut surfaces and causes undesirable changes in work geometry. Therefore, it is necessary, from a process automation point of view, that a sensing system be devised to detect the extent of AWJ nozzle wear during cutting operations so that the worn nozzle can be identified and replaced in time.

The AWJ nozzle acts mainly to focus the spreading jet and accelerate the abrasive particles which do not penetrate the jet stream. The increased wear of the AWJ nozzle makes the clearance between waterjet and AWJ nozzle larger. Obviously, the greater the diameter of the AWJ nozzle's outlet, the smaller the probability is of the abrasive particles getting into the water due to the lower transverse particle velocity.

Currently, there is no AWJ nozzle wear sensing system available. However, some of the already existing measuring techniques could be used to measure off-line or on-line nozzle wear. The measuring set-up can be optical, electrical, mechanical, or acoustic. Some of these methods are discussed in this section.

2.1 Optical Sensing Techniques

Because both the kerf width and the jet diameter of nozzle discharge are related to the actual value of the ID at the exit of the nozzle, these two variables could be used for monitoring AWJ nozzle wear. An optical method to track nozzle wear could be based on image processing and vision system technology.

2.2 Sensing AWJ Nozzle Wear by Monitoring the Level of Noise

An acoustic sensing method could be used to detect a worn AWJ nozzle. Depending on the discharging geometry of the nozzle, flow excitation may be tonal (generated by periodic vortex shedding) or random (generated by turbulent flow). Specifically, a change of nozzle ID could be related to a change in the sound generated by the jet flow.

2.3 AWJ Nozzle Wear Sensing System Based on Wear Probe

An AWJ nozzle wear sensor based on a probe that senses wear by a conductive loop was invented and tested at the Syracuse University Abrasive Waterjet Cutting Laboratory [4]. This wear sensor system consists of a wear probe in the form of a conductive loop embedded in the tip of the nozzle, which is exposed to the effects of erosion and abrasion wear. The predetermined threshold representing the nozzle life criterion will be detected by this sensor. In the instant when the ID of the nozzle reaches a predetermined threshold diameter, the conductive loop will be cut, opening the electronic circuit. That will cause immediate closing of the pneumatic valve, and the entire system will be shut off. Through an appropriate alarm device, the machine operator can be signaled that the AWJ nozzle has worn to its limit and take corresponding action. However, the proposed AWJ nozzle wear sensing system cannot on-line monitor the increase in the nozzle ID, detect the direction of the wear propagation, or provide the controller with necessary information in order to compensate for the increase in the AWJ nozzle ID.

To achieve all these features a new AWJ nozzle wear sensing system based on wearable probes is proposed. A detailed description of the proposed sensing system is given in the following section.

3. DESCRIPTION OF THE PROPOSED AWJ NOZZLE WEAR SENSING SYSTEM

As was already stated, the rate of change of the inside-diameter at the nozzle outlet will be used to quantify the nozzle wear. It is evident that the outlet of the AWJ nozzle will determine the final shape of the abrasive waterjet and its cutting performances. In order to produce high-quality parts on a fully automated AWJ system it will be necessary to on-line monitor the nozzle wear on its outlet. Such a requirement could be satisfied with the proposed nozzle ID change monitoring system.

The new wear sensor system for monitoring the rate of change of the AWJ nozzle ID on its outlet consists of the wear sensor probe and logic unit connected to the PC. A simplified circuit diagram of a wear sensor probe is shown in Fig. 1. It consists of a ceramic substrate and the wear probe divided into four quadrants with a hole in the center of diameter equal to the inside diameter of the new AWJ nozzle (for example ID = 1.2mm). Within each quadrant lies a number of conductive loops, spaced 0.05mm apart. The sensor is attached to the tip of an AWJ nozzle where it will be subjected to the same abrasive and erosive modes of wear as the nozzle itself. Each conductive loop will be cut when the nozzle has worn to its position and since the location of each loop on the probe is known in advance the AWJ nozzle wear status could be determined. The last conductive loop in the wear probe

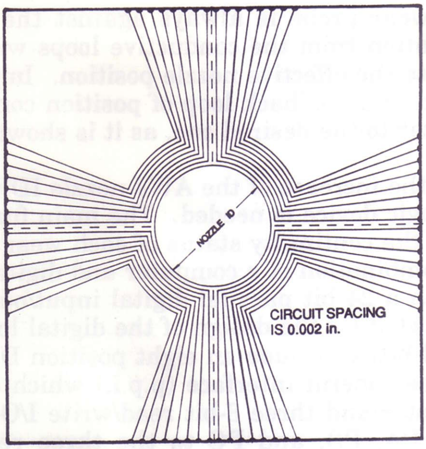

Fig. 1. Abrasive waterjet nozzle wear probe.

will determine the maximum allowed increase in the nozzle ID. In the proposed arrangement of the conductive loops, total of eight loops, the maximum allowed nozzle ID is 2mm, which represents a 66% increase with respect to the original one. It is evident that the number of conductive loops in the wear probe can vary depending on the maximum allowed increase of the nozzle ID.

If the orientation of an AWJ nozzle is known throughout the cutting of a particular workpiece then the wear probe may be used to obtain more precise cuts along that workpiece. Consider the desired straight line cut shown in Fig. 2. If the nozzle and wear probe assembly were aligned such that one of

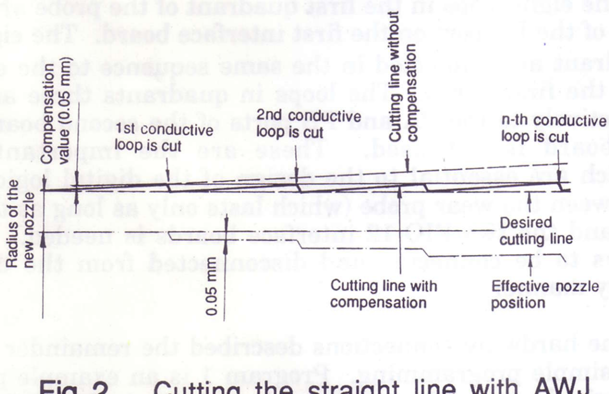

Fig. 2. Cutting the straight line with AWJ when the increase in the AWJ nozzle inside-diameter is compensated.

the quadrants of the wear probe is always against the cut surface of the workpiece then information from the conductive loops within that quadrant could be used to compute the effective nozzle position. Implementation of the effective nozzle position in a feedback loop of position controller will provide an actual cut much closer to the desired one, as it is shown in Fig. 2.

In order to monitor the increase of the AWJ nozzle ID with the conductive wear probes a digital logic device is needed. The main function of the digital logic unit is to monitor the continuity status of each wear sensor probe. This can be done with the combination of a computer and digital input board. The Metra-Byte PIO-12 with a 24 bit parallel digital input/output (I/O) interface for an IBM PC was selected for the design of the digital logic unit. The main features of the selected board include an eight position D.I.P. address switch and a programmable peripheral interface (p.p.i.) which consists of an 8-bit write only control register and three 8-bit read/write I/O ports. Metra-Byte has given the names PA, PB, and PC to the three respective I/O ports. Programming of the p.p.i. is accomplished by writing the appropriate 8-bit word to the control register in order to configure each of the three I/O ports (PA, PB, and PC) as either input or output. We can then read from or write to these ports as desired. Note that since the PIO-12 is a parallel device all 8-bits of a given port must be read from or written to in one step.

Consider an AWJ nozzle wear probe with eight conductive loops in each quadrant. A digital logic device for the wear probe can be constructed from two Metra-Byte interface boards and an IBM PC. Two boards are needed since the probe has a total of 32 loops and a single board can monitor only 24 of those loops. A block diagram of the device is shown in Fig. 3. The wear probe conductive loops may be powered by an external source or by the IBM PC's built in power supply as shown in the figure. The conductive loops are then connected to the individual bits of the I/O ports. When a conductive loop is closed and powered a logical value of one will be stored in the bit connected to that loop. When the loop is cut the logical value in that bit will change to zero. In Fig. 3 the eight loops in the first quadrant of the probe are connected to the eight bits of the PA port on the first interface board. The eight loops in the second quadrant are connected in the same sequence to the eight bits of the PB port on the first board. The loops in quadrants three and four are connected respectively to the PA and PB ports of the second board. The PC port on each board is not used. These are the important electrical connections which are essential to the design of the digital logic device. A junction box between the wear probe (which lasts only as long as the nozzle it is attached to) and the two PIO-12 interface boards is needed. This would allow the probes to be connected and disconnected from the digital logic device in an easy manner.

With all of the hardware connections described the remainder of the logic device involves simple programming. Program 1 is an example program for the designed logic device. The program is written in MICROSOFT GW-BASIC. The program reads the PA and PB ports of each Metra-Byte PIO-12 interface board and displays the extent of wear within each quadrant to a

```
10    OUT & H203, &H92
      (configures PA and PB ports of 1st board for input)
20    OUT  &H303, &H92
      (configures PA and PB ports of 2nd board for input)
30    RO=O.047/2.0
      (set initial nozzle radius in inches)
40    CLS
      (clear the screen)
50    LOCATE 10,5:PRINT "QUAD 1"
      (set up screen display)
60    LOCATE 11,5:PRINT "Quad 2"
70    LOCATE 12,5:PRINT "QUAD 3"
80    LOCATE 13,6:PRINT "QUAD 4"
90    I1%-INP (H200)
      (examine PA port of 1st board)
100   I2%=INP (&H201)
      (examine PB port of 1st board)
110   I3%=INP (&H300)
      (examine PA port of 2nd board)
120   I4%=INP (&H301)
      (examine PB port of 2nd board
130   N%=0
      (counter for look-up table)
140   N%=N%+1
150   IF  (N%=1)  THEN I%=I1%
160   IF  (N%=2)  THEN I%=I2%
170   IF  (N%=3)  THEN I%=I3%
180   IF  (N%=4)  THEN I%=I4%
190   DELR=0.0
      (initialize change in radius due to nozzle wear)
200   IF (I%=0)    THEN 900
      (if all loops are worn then branch to AWJ system shut-down
      routine)
210   IF (I%=254)  THEN DELR=0.002
      (look-up table)
220   IF (I%=252)  THEN DELR=0.004
230   IF (I%=248)  THEN DELR=0.006
240   IF (I%=240)  THEN DELR=0.008
250   IF (I%=224)  THEN DELR=0.010
260   IF (I%=192)  THEN DELR=0.012
270   IF (I%=128)  THEN DELR=0.014
280   CP%=9+N%
290   LOCATE CP%, 13:PRINT USING "#.###";RO+DELR
300   IF (N%<4)    THEN 140
310   GOTO 90
900   AWJ system shut-down routine begins here
```

Program 1. GW-BASIC code for logic device

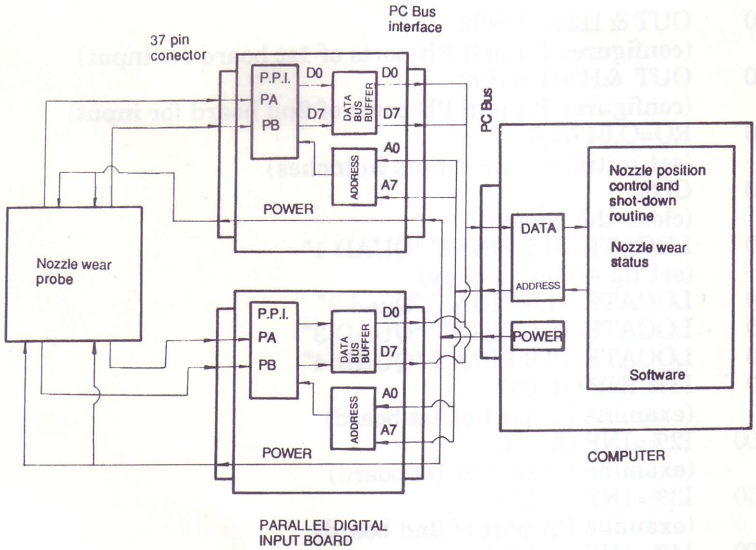

Fig. 3. Block diagram of logic device

video monitor. When the outermost conductive loop in any quadrant is cut the program branches to an AWJ system shut-down routine.

With an appropriate alarm device, the machine operator can be signaled when the AWJ nozzle ID reaches the maximum allowed value in order to take corresponding action.

The proposed AWJ nozzle wear sensing system is characterized with the following advantages:

- the monitoring of the nozzle ID is direct and almost on-line;
- the sensing system is able to detect the direction of the wear propagation;
- the sensing system will provide the positioning control with necessary information in order to compensate for the increase in the AWJ nozzle ID (in increments of 0.05mm).

4. CONCLUSIONS

Based on the results presented in this paper, the following conclusions can be drawn:

- One of the most critical parts that influences the technical and economical performance of an abrasive waterjet cutting system is the AWJ nozzle.

- An automated AWJ cutting system needs the ability to detect nozzle wear before kerf width exceeds acceptable limits.
- The rate of change of the inside-diameter at the AWJ nozzle outlet could be used to quantify the nozzle wear.The final shape of an abrasive waterjet and its cutting performances will be determined by the outlet of the AWJ nozzle.
- The wear sensor system for tracking the rate of change of the AWJ nozzle inside-diameter at its outlet is proposed.
- The proposed AWJ nozzle wear sensing system provides:
    - the direct and on-line tracking of the nozzle inside-diameter,
    - the direction of the wear propagation, and
    - the positioning controller with necessary information in order to compensate for the increase in the AWJ nozzle inside-diameter.

5. ACKNOWLEDGEMENT

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