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MONITORING THE DEPTH OF ABRASIVE WATERJET PENETRATION

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Abstract—In order to control the uniformity of the abrasive waterjet penetration into the workpiece, it is necessary to devise a monitoring methodology that can indirectly monitor the depth of abrasive waterjet penetration. It was shown that the workpiece normal force generated by an abrasive waterjet could be used as the indicator of the depth of jet penetration, and that a force-feedback control holds promise as an effective way to regulate the depth of jet penetration. The effects of different abrasive waterjet process variables on both the depth of cut and the workpiece normal force are discussed.

INTRODUCTION

THE INTRODUCTION of the abrasvie waterjet (AWJ) as a machining method has opened a new way of machining difficult-to-machine materials. This cutting technique is one of the most recently introduced machining methods in which an abrasive, such as garnet, aluminum oxide, or silicon carbide, is accelerated by a thin, high velocity waterjet, and directed through an abrasive waterjet nozzle at the material to be cut.

Originally, the AWJ machining technique was used only for linear cutting and shape cutting of difficult-to-machine materials, such as titanium, superalloys, glass, composites, metal matrix composites and advanced ceramics. However, today this technology is used in such machining applications as turning, drilling of small diameter holes and milling.

To produce a cavity with controlled depth is a basic problem of the AWJ milling operation. The depth of penetration of the abrasive waterjet is determined by the mechanics of the jet-material interaction process [1]. In the AWJ milling operation, the depth of AWJ penetration is a function of a number of factors, including: waterjet pressure; abrasive flow rate; abrasive grain size; stand-off distance; traverse speed; angle of impact; AWJ nozzle wear; etc.

A model for predicting the depth of cut with abrasive waterjets in different materials was proposed by Hashish [2]. The erosion model was used with a kinematic jet-solid penetration model to yield expressions for depths of cut according to different modes of erosion along the cutting kerf. However, in order to create a comprehensive model to predict the depth of penetration in AWJ milling, a number of problems need to be solved: identification of the basic microcutting mechanisms; identification of the role of hydrodynamic loading on the microcutting process; determination of the distribution of particle size and its impact parameters; solution of the kinematic equations that relate local material volume removal rates to traverse parameters; analysis of the three-dimensional process of jet penetration; development of the basic model of particle–solid interactions in repeated impact situations; etc.

Due to the inherent complexity of the milling process with AWJ and our incomplete understanding of it, this approach, which relies on the mathematical modeling of the physics of the process, is limited in applicability. However, from a process automation point of view, it is necessary that a monitoring methodology be proposed that can assess the depth of abrasive waterjet penetration and control its uniformity. Such a

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monitoring methodology could be further implemented into an adaptive control system which optimizes the milling operation by AWJ in terms of the major process parameters.

The objective of this paper is to develop the methodology to monitor the depth of AWJ penetration into the workpiece. A detailed description of the experimental results and proposed methodology to monitor the uniformity of the jet penetration into the workpiece is given in the following sections.

EXPERIMENTAL SET-UP

The abrasive waterjet cutting system used in this investigation is shown in Fig. 1. The system consists of an intensifier pump connected to an abrasive waterjet cutting head. The abrasive waterjet cutting head consists of a sapphire orifice, an abrasive waterjet nozzle, and a mixing chamber. The cutting head is manipulated by an x–y positioning table with a CNC controller.

In order to investigate the influence of abrasive waterjet cutting paramters on the depth of AWJ penetration, five factors were selected: waterjet pressure; abrasive flow rate; stand-off distance; traverse speed; and AWJ nozzle-inside-diameter. Waterjet pressure was varied from 200 to 300 MPa. The jet traverse speed, which was controlled by a CNC x–y positioning table, was varied from 0.423 to 0.953 mm/s. Abrasive flow rate was varied from 7.58 to 22.7 g/s, and stand-off distance was varied from 3.17 to 12.7 mm. The AWJ nozzle-inside-diameter was varied from 1.2 to 2.2 mm. In order to establish the relationship between the basic cutting parameters and the depth of AWJ penetration, a factorial exeriment was designed. A two-level five-factor factorial design scheme, which requires 32 experimental runs, was adapted for this study. Table 1 identifies the factors used and their levels. Cylinders of 76 mm in diameter and 50 mm in length, made of a mild steel AISI 1020, were used as specimens. The cuts made were at least 50 mm in length.

For this particular study, the depth of AWJ penetration and the workpiece normal force were measured for each set of variables. The depth of AWJ penetration was measured at three locations along the cuts. A special depth micrometer stem with a

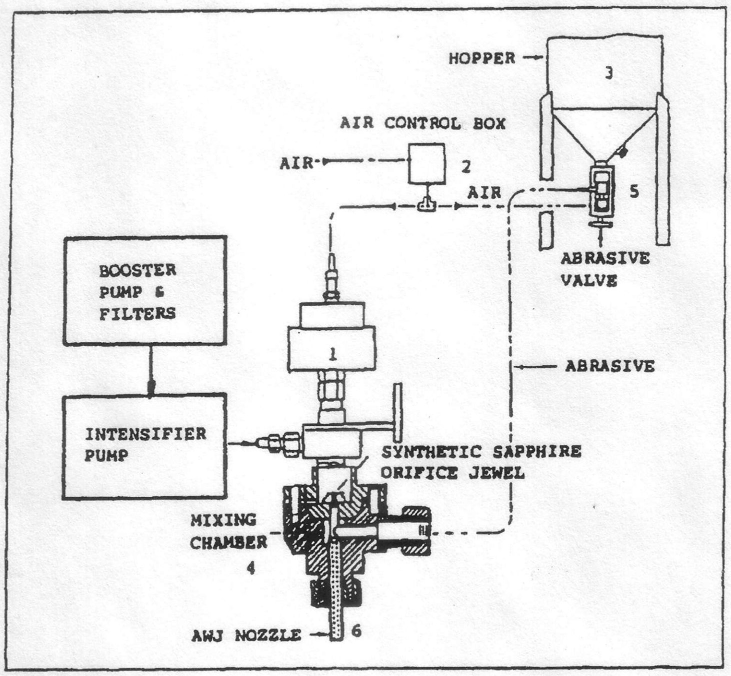

Fig. 1. General concept of abrasive waterjet cutting system.

TABLE 1. LEVELS OF THE CUTTING PARAMETERS IN MONITORING THE DEPTH OF AWJ PENETRATION

AWJ nozzle-inside-diameter (mm)	1.2	1.6	2.2
Abrasive flow rate (g/s)	7.5	13.1	22.7
Stand-off distance (mm)	3.1	6.3	12.7
Traverse speed (mm/s)	0.42	0.63	0.95
Waterjet pressure (MPa)	200	245	300

fine tip was used for depth measurement, and depths were verified with measurements of sample cross-sections. The workpiece normal force was measured by a piezoelectric crystal force sensor mounted on the worktable over the catcher.

The proportional electric charges for the workpiece normal force were amplified and converted into proportional voltages. These signals were passed through a low pass filter in order to remove frequencies above 20 Hz and then were fed into an A/D board in an IBM PC. The force signal was sampled at a frequency of 50 Hz. Figure 2 shows an instrumentation and data acquisition system. The average values for depth of penetration and workpiece normal force were used in further analysis.

In order to keep the study within reasonable length, the other factors were kept constant. These factors were assigned as follows: diameter of waterjet orifice = 0.33 mm; length of abrasive waterjet nozzle = 63.5 mm; angle of impact = 90 degrees; and type of abrasive and its grain size = garnet, Mesh no. 120.

After a collection of all data, SYSNLIN procedure in SAS package (SAS Institute Inc.) was used to estimate the parameters in the relationship between the depth of AWJ penetration and workpiece normal force as the functions of the selected cutting parameters.

EFFECTS OF THE SELECTED PROCESS PARAMETERS ON THE DEPTH OF AWJ PENETRATION

Waterjet pressure

In abrasive waterjet cutting, increasing the waterjet pressure is the most effective method of increasing the cutting ability. The main reason for this is that the jet's rate

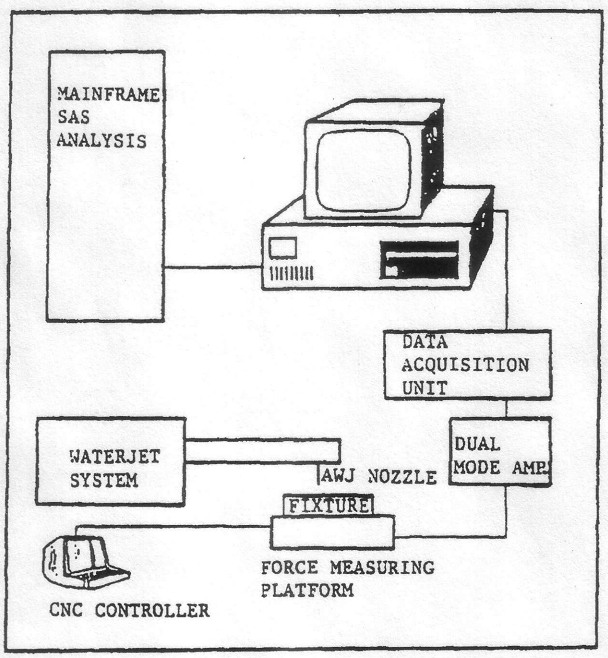

FIG. 2. Instrumentation and data acquisition system.

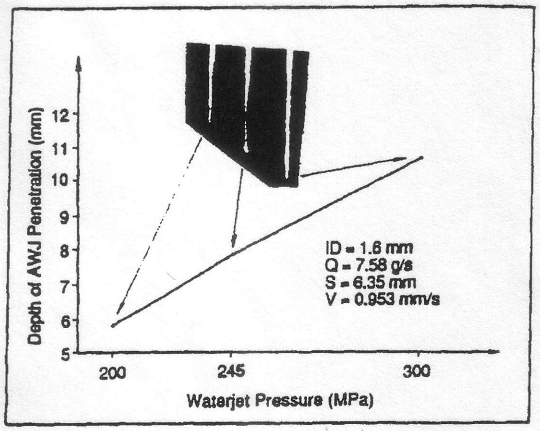

FIG. 3. Effect of waterjet pressure on depth of AWJ penetration.

of change of momentum and the velocity of the particles at the nozzle exit are increased in accordance with the waterjet pressure, resulting in increased impact energy. Figure 3 shows a typical trend of the effect of pressure on the depth of AWJ penetration. It is apparent that the depth of penetration will increase with increasing pressure. The rate of change of depth of AWJ penetration with waterjet pressure declines as waterjet pressure increases.

Abrasive flow rate

For the selected conditions, the depth of AWJ penetration slightly increased with the increase of the abrasive flow rate (Fig. 4). Increasing the abrasive flow rate beyond a critical value will cause the depth of AWJ penetration to be reduced [3].

The velocity of the particles will depend on the abrasive flow rate. Preliminary measurements ofi the average particle velocity under different waterjet pressures (from 170 to 275 MPa) and abrasive flow rates (from 3.02 to 18.87 g/s) were performed using a Laser Doppler Velocimeter. The range of the measured velocity was from 230 to 370 m/s. Similar results were obtained by Swanson [4]. Figure 5 shows a decrease in the particle velocity with an increase of the abrasive flow rate from 11.3 to 15 g/s. The decrease in abrasive particle velocity is larger at higher waterjet pressures. The particle velocity has the strongest influence on the cutting effect.

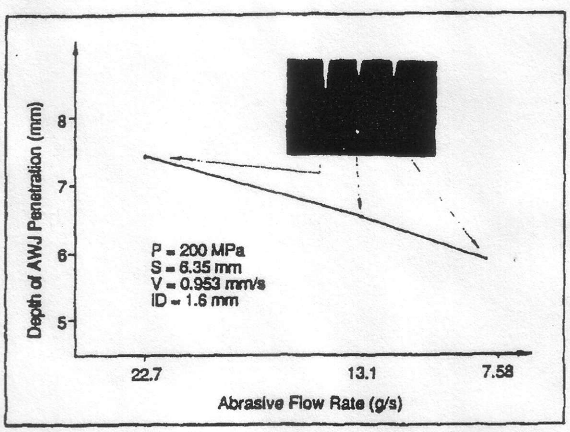

FIG. 4. Effect of abrasive flow rate on depth of AWJ penetration.

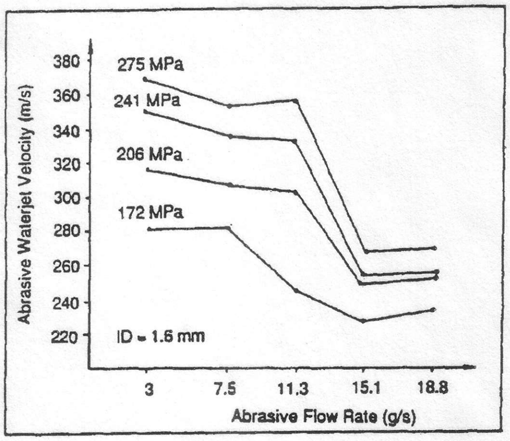

FIG. 5. The abrasive waterjet velocity with respect to abrasive flow rate at different waterjet pressures.

Traverse speed

The effect of the traverse speed on the depth of AWJ penetration is illustrated in Fig. 6. With an increase in the traverse speed, the depth of AWJ penetration will decrease, but the rate of the kerf area generation may increase.

Wear of the AWJ nozzle

One of the most critical parts that influences the technical and economical performance of an AWJ cutting system is the AWJ nozzle. The rate of change of the nozzle-inside-diameter that will be used to quantify the nozzle wear is influenced by various AWJ cutting parameters, such as waterjet pressure, water flow rate, abrasive material, flow rate, and grain size, and geometry and material of the nozzle.

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 of the abrasive particles getting into the water, due to the lower transverse particle velocity.

Figure 7 shows the structure of the abrasive waterjets expelled from the new nozzle and from the worn-out nozzle under the same conditions. From Fig. 7, it is evident that the new nozzle will form a coherent jet with focused abrasive particles. In contrast, the worn-out nozzle will produce a spreading jet. Increased clearance between the AWJ nozzle and the waterjet will cause incomplete mixing of the abrasive particles with the waterjet. The result of this is reduced cutting ability.

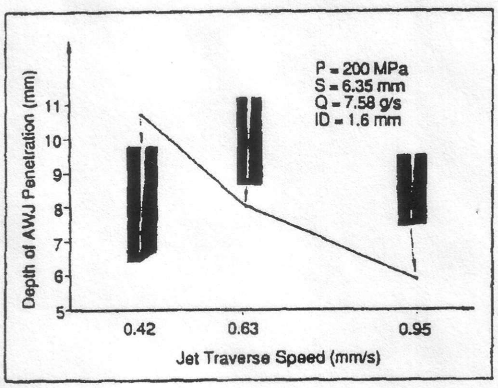

FIG. 6. Effect of jet traverse speed on depth of AWJ penetration.

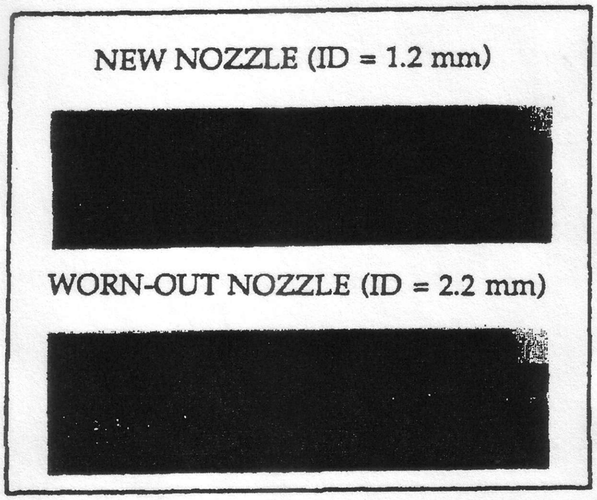

Fig. 7. Abrasive waterjet issuing from new and worn-out nozzles (waterjet pressure P = 207 MPa, abrasive flow rate Q = 3.7 g/s, exposure time t = 10 μs).

Figure 8 shows the effect of the increase of the nozzle-inside-diameter on the depth of AWJ penetration. From Fig. 8, it is apparent that for the selected working conditions, the depth of AWJ penetration will increase gradually as the inside diameter of the nozzle increases. Further increase of the nozzle-inside-diameter will cause a sharp decrease in the depth of AWJ penetration, and the surface quality of the kerf will deteriorate. The larger jet diameter will generate the larger width of cut. However, the effective jet diameter becomes smaller, due to wall friction and a reduction in abrasive impacts caused by rebounding and jet deflection [3]. From Fig. 8, it is evident that there is an optimal nozzle-inside-diameter at which the depth of AWJ penetration will be maximized. For the selected conditions, the optimal nozzle-inside-diameter is around 2.2 mm, which is about 83% larger than the original diameter (1.2 mm).

Stand-off distance

Figure 9 shows the effect of stand-off distance on the depth of AWJ penetration. From Fig. 9, it is evident that the increase of stand-off distance will reduce the depth of cut. The larger stand-off distance depresses the jet's energy, which is not suitable for deep cutting.

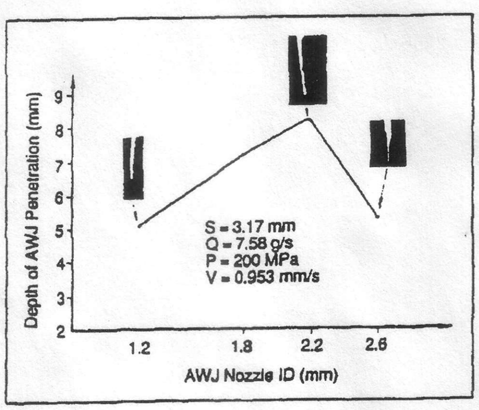

Fig. 8. Effect of nozzle-inside-diameter on depth of AWJ penetration.

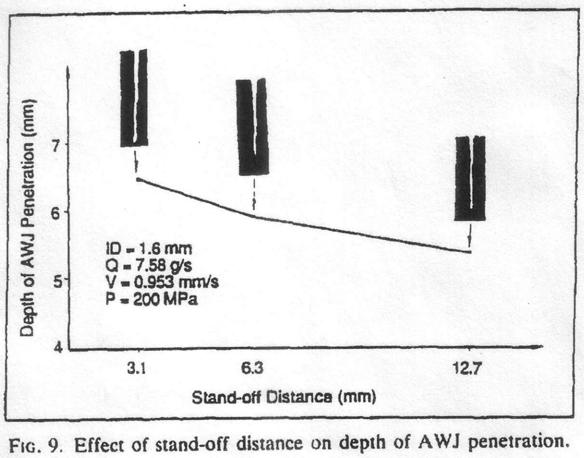

FIG. 9. Effect of stand-off distance on depth of AWJ penetration.

THE RELATIONSHIP BETWEEN THE DEPTH OF AWJ PENETRATION AND THE WORKPIECE NORMAL FORCE

In order for the AWJ milling operation to be economically viable in manufacturing, high metal removal rates, good surface quality, uniform depth of jet penetration, and a high degree of repeatability must be achieved. The main problem in the AWJ milling operation is to achieve uniform depth of jet penetration as a function of the number of process input variables. The effect of the most influential process input variables on the depth of AWJ penetration was analyzed in the previous section.

However, in order to relate the depth of AWJ penetration to the several independent variables, a factorial approach to the experimental design was adopted. The process input variables of greatest interest for this investigation are:

waterjet pressure (P);
abrasive flow rate (Q);
traverse speed (v);
stand-off distance (D); and
nozzle-inside-diameter (ID).

The responses measured during the experiments were:

depth of AWJ penetration (d); and
workpiece normal force.

Traverse speed is the velocity of the jet with respect to the workpiece. The workpiece normal force is defined as the vertical force acting on the workpiece caused by the impacting jet.

The relationship between the depth of AWJ penetration and workpiece normal force with respect to the process input variables is quantified by the empirical equations. The influence of waterjet pressure, abrasive flow rate, stand-off distance, jet traverse speed, and nozzle-inside-diameter on the depth of AWJ penetration and the workpiece normal force is determined through a 2^5 central composite factorial design. After conducting the experiments, the data for the depth of AWJ penetration and the workpiece normal force were fitted with the stepfunctions using the SYSNLIN procedure from the SAS package. The models correlating depth of AWJ penetration and workpiece normal force with selected process input variables can be expressed as:

$$d = 0.00139\, ID^{0.756} Q^{0.211} S^{-0.139} v^{-0.74} P^{1.47} \tag{1}$$

$$F = 0.076\, ID^{0.877} Q^{0.136} S^{-0.072} v^{0.06} P^{0.782} \tag{2}$$

where d = depth of AWJ penetration (mm)
F = workpiece normal force (N)
ID = AWJ nozzle-inside-diameter (mm)
Q = abrasive flow rate (g/s)
S = stand-off distance (mm)
v = traverse speed (mm/s)
P = waterjet pressure (MPa).

An excellent fit to the data was achieved yielding a multiple correlation coefficient or R^2 value of 0.944 and 0.975, respectively.

These models estimate the depth of AWJ penetration and the corresponding workpiece normal force for each feasible set of process input variables. Figure 10(a–c) shows the effects of AWJ nozzle-inside-diameter, abrasive flow rate, stand-off distance, jet traverse speed, and waterjet pressure on the depth of AWJ penetration. As was already concluded in the previous section, the depth of AWJ penetration will increase with increasing waterjet pressure, abrasive flow rate, and nozzle-inside-diameter. However, the depth of AWJ penetration will decrease with increasing jet traverse speed and stand-off distance.

The effect of AWJ nozzle-inside-diameter, abrasive flow rate, waterjet pressure, stand-off distance, and jet traverse speed is shown in Fig. 11(a–c). In general, from Fig. 11(a–c), it could be concluded that the workpiece normal force will increase with increasing waterjet pressure, abrasive flow rate, and nozzle-inside-diameter. It will decrease with increasing stand-off distance and will be only slightly affected by jet traverse speed.

The methods used to detect the depth of AWJ penetration could be categorized into two groups: direct and indirect. Direct methods provide a measurement of the depth of cut by interrupting the cutting process. Obviously, this method is not suitable for on-line controlling the uniformity of the depth of cut. Indirect methods could be based on the measurement of some paramters that are correlated to the depth of AWJ penetration, such as the average workpiece normal force or acoustic emission.

Present AWJ systems use an "open-loop" approach, where off-line calibration experiments are performed in order to find an optimal combination of the process input variables that will generate the required depth of cut in a particular material. However, in order to be able to control the uniformity of the depth of AWJ penetration, especially when a disturbance is present in the process, it is necessary to be able to on-line monitor the depth of cut as well as to on-line adjust the selected process input variable. It is shown through this analysis that there is a strong correlation between the depth of AWJ penetration and the generated workpiece normal force. By analyzing the exponents in equations (1) and (2) it is evident that all process input variables, except the jet traverse speed, have the same effect on the depth of AWJ penetration and workpiece normal force. The jet traverse speed will only slightly influence the magnitude of the workpiece normal force but will drastically affect the depth of AWJ penetration. It means that this process input variable, despite its ease of control, cannot be used to control the depth of cut by monitoring the magnitude of the workpiece normal force. The change of the AWJ nozzle-inside-diameter due to nozzle wear could be considered as a disturbance in the process, which will cause a change in workpiece normal force as well as in depth of cut. As it is shown in Fig. 12, the depth of AWJ penetration could be monitored and controlled by using a force-feedback system and adjusting, for example, waterjet pressure in order to compensate for the negative effect of the nozzle wear on the depth of cut.

Consider now the need to achieve a depth of AWJ penetration of 12 mm in the mild steel AISI 1020. One of the possible combinations of the process input variables will

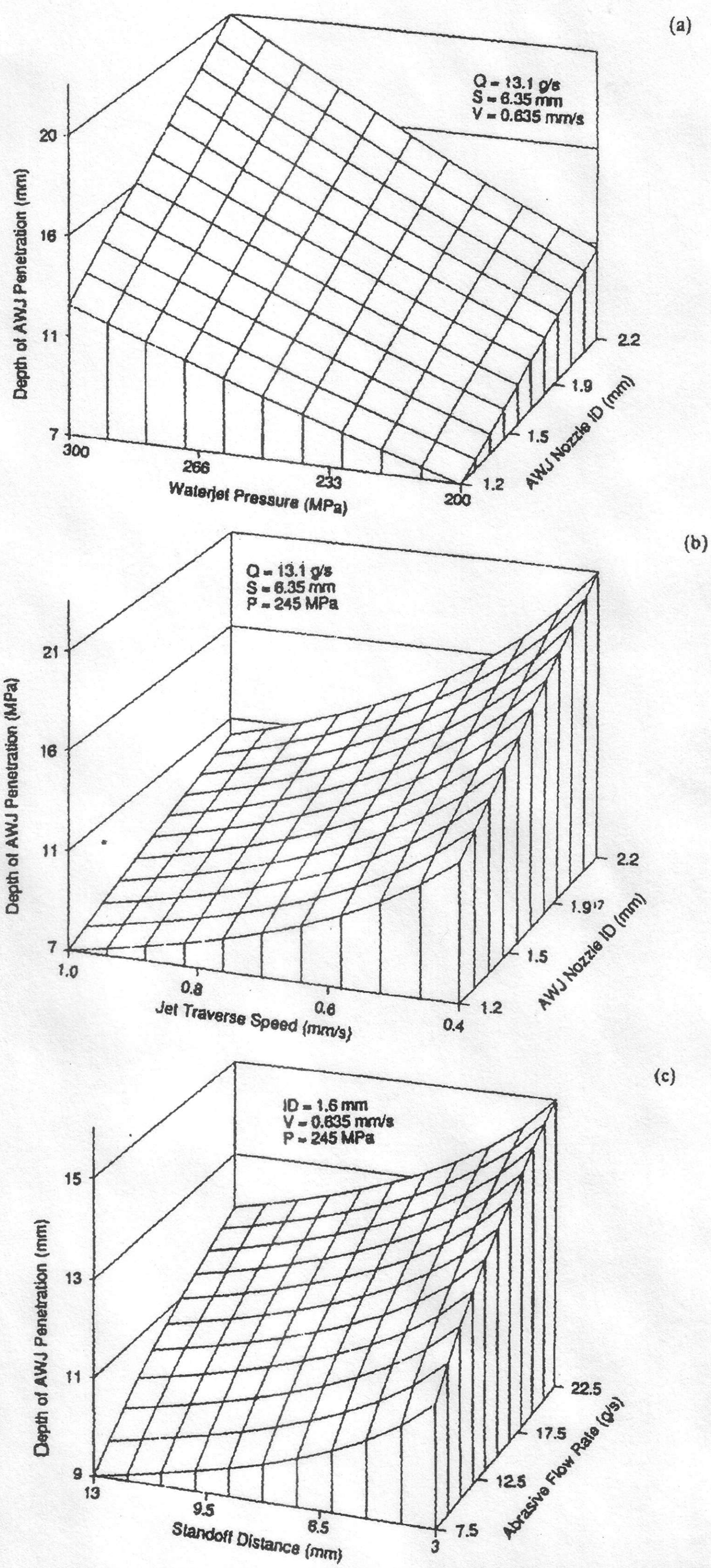

FIG. 10. Effects of nozzle-inside-diameter, abrasive flow rate, stand-off distance, jet traverse speed, and waterjet pressure on depth of AWJ penetration generated by using equation (1).

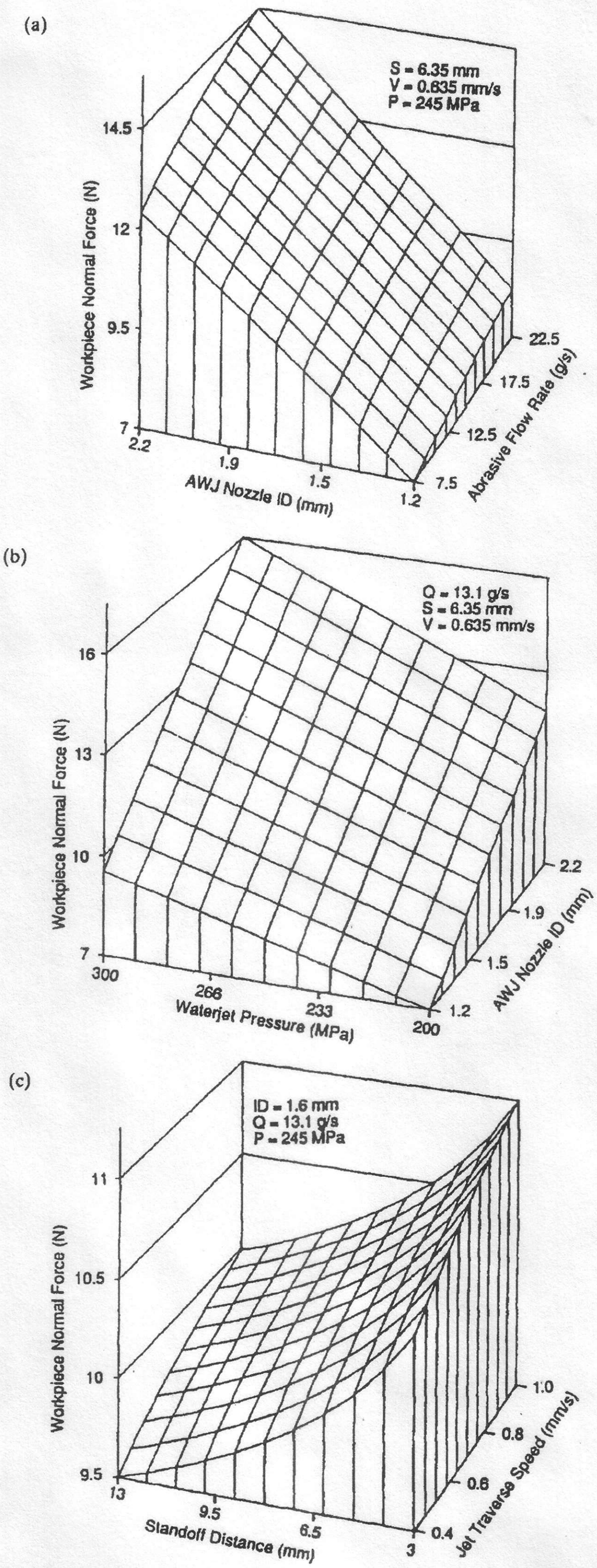

FIG. 11. Effects of nozzle-inside-diameter, abrasive flow rate, stand-off distance, jet traverse speed, and waterjet pressure on workpiece normal force generated by using equation (2).

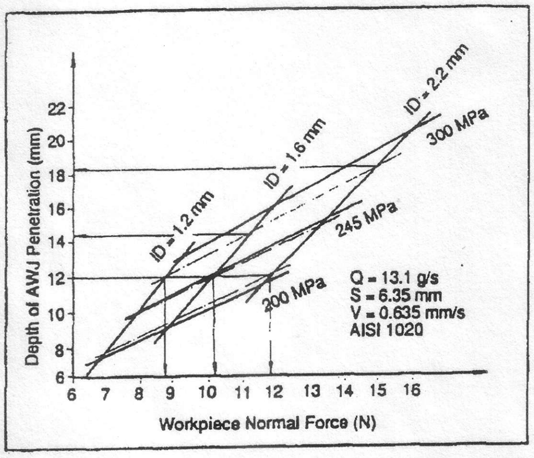

FIG. 12. Relationship between workpiece normal force and depth of AWJ penetration for the different waterjet pressures and AWJ nozzle-inside-diameters.

be: abrasive flow rate of 13.1 g/s; stand-off distance of 6.35 mm; jet traverse speed of 0.635 mm/s; nozzle-inside-diameter of 1.2 mm (new nozzle); and corresponding waterjet pressure of about 280 MPa. The workpiece normal force generated under these conditions will be about 8.7 N. However, if the AWJ nozzle-inside-diameter is increasing as the result of the wear, then the depth of AWJ penetration will increase without changing other process input variables. For example, for the semi-worn nozzle with an inside diameter of 1.6 mm, the expected depth of cut will be about 14.2 mm, and for the worn out nozzle of 2.2 mm, the depth of cut will be 18.2 mm. In order to keep the depth of cut on the desired level of 12 mm, in both cases, it is necessary to change the waterjet pressure. Namely, in the case of the semi-worn nozzle waterjet, the pressure should be set at 240 MPa, and in the case of the worn nozzle, the waterjet pressure should be 205 MPa. These findings have important practical implications because they allow the desired depth of cut to be achieved in the presence of the disturbances by monitoring the level of the workpiece normal force. In general, it will not be possible to constantly adjust the waterjet pressure to ensure that the required value of the depth of cut is always achieved. However, based on the fact that the AWJ milling operation lasts only for a short period and that the nozzle wear rate is low, there is no need for frequent adjustment of the waterjet pressure in order to keep the desired depth of AWJ penetration. A large increase in the magnitude of the workpiece normal force will indicate the presence of nozzle wear and show that the depth of cut is exceeding the acceptable limit. For example, in the analyzed case, the 15% increase in the workpiece normal force corresponds to the increase in the nozzle-inside-diameter from 1.2 mm to 1.6 mm, as well as from 1.6 mm to 2.2 mm. Choosing to monitor smaller changes in the workpiece normal force will obviously require more frequent adjustments of the waterjet pressure, but as a result a more uniform depth of cut will be achieved. It should be mentioned here, however, that the change in the waterjet pressure will influence the overall hydraulic efficiency of the jet and nozzle wear rate and, thus, the cutting performances as well.

CONCLUSIONS

To directly monitor the depth of AWJ penetration is impractical. In order to estimate the achieved depth of cut, it is necessary to use some parameters that are correlated to it. Through extensive experimentation it was shown that the workpiece normal force generated by the impacting jet could be used as a valuable indicator of the achieved depth of AWJ penetration.

The complexity and somewhat unpredictable nature of the abrasive waterjet milling operation limits the possibility of developing a mathematical model that could be used to estimate the achieved depth of cut into the given material for the selected process input variables. Because of that, in this study, the correlation between the depth of cut and a number of process input variables, such as waterjet pressure, abrasive flow rate, stand-off distance, jet traverse speed, and AWJ nozzle-inside-diameter, based on the experimental data, was developed. Multiple regression analysis was used to form the proposed correlation. This correlation provides the combination of the process input variables in order to achieve the desired depth of cut.

In practice, the proposed procedure for monitoring the achieved depth of cut will function in the following way. For a given material and a known AWJ nozzle-inside-diameter, an adequate set of process input variables such as waterjet pressure, abrasive flow rate, stand-off distance, and jet traverse speed will be selected based on the proposed model. The magnitude of the corresponding workpiece normal force will be calculated. During the AWJ milling operation, the magnitude of the workpiece normal force will be monitored and used as the indicator of the achieved depth of cut. Any fluctuations in the magnitude of the workpiece normal force will indicate changes in the depth of cut. In the analyzed example, it was shown how the effect of an increase in nozzle-inside-diameter could be compensated for by adjusting the waterjet pressure.

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