Investigation of AJM for deburring

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Abstract

Deburring is a major bottleneck in manufacturing organisations. In recent years abrasive jet machining has been gaining increasing acceptability for deburring applications. The influence of abrasive jet deburring process parameters is not known clearly. An experimental investigation has been conducted to identify the abrasive jet deburring process parameters and the edge quality of abrasive jet deburred components. For these experiments, an experimental design based on a Taguchi orthogonal array was used to systematically measure the influence of the major cutting parameters on abrasive jet deburred specimens made of stainless steel. An additional parameter viz. 'jet height' was identified, which latter significantly affects the deburring process. A profile projector was used to measure the edge quality and also visual inspection was conducted to ascertain the surface damage of the specimens. Results of the edge quality measurements supplemented with visual inspection were analyzed by the ANOVA method, as a result of which it was found that the burr removal was affected by the parameters jet height and angle of impingement. Also a statistical model was developed for the magnitude of the edge radius generated.

Keywords: Abrasive jet machining; Angle of impingement; Deburring; Jet height

1. Introduction

Most machined components involve deburring as a secondary operation, which increases the cycle time and cost of manufacturing. Deburring not only involves the removal of burrs from the component's edge but also involves maintaining edge quality. Controlled and consistent edge quality can improve product performance and life. Removing stress raisers at sharp corners by generating a controlled radius on the edge can substantially improve the thermal and mechanical fatigue strength of highly stressed components. Improved edge radius along with surface finish in passages through which gas or liquid will flow reduces boundary layer turbulence and improves flow rates. Improved edges and surfaces on gears increase their service life and power transmission efficiency. Manual deburring, in most cases, ensures the removal of burrs but not the

maintaining of the edge quality. It may, however, create a bottleneck in high volume manufacturing. Further, burrs in inaccessible areas cannot be handled this way. Inconsistency in the edge quality of manually deburred components results in inconsistency in the quality of the product. Other mechanical deburring methods such as vibratory deburring, brush deburring, etc., do not produce the desired edge quality. Also most of the mechanical deburring methods change the dimensions of the part slightly and mechanical forces cause thin sections to distort. Non-conventional methods such as abrasive jet machining (AJM), electrical discharge machining (EDM), and electrochemical machining (ECM) have several significant advantages over other deburring methods. These processes do not exert any mechanical forces; do not affect part dimensions except at edges; and provide a smooth radius at the edges. These characteristics make non-conventional processes more suitable for deburring. Of these processes, AJM is gaining increasing acceptability in recent years. However, the influence of the AJM parameters on deburring is not known clearly.

Fig. 1. Parameters associated with the AJM process.

Material removal in the AJM process is accomplished by the use of a continuous jet, which is produced by mixing abrasive particles with a high velocity air jet, which latter imparts momentum to the abrasive particles, accelerating them prior to their impingement on the workpiece. The abrasive particles serve primarily as the abrasive medium, providing a diverse group of micro-machining mechanisms assisting in material removal. Highly localised machining forces and a low magnitude of generated heat are two additional advantages of AJM. Fig. 1 shows the parameters associated with the AJM deburring process.

Sarkar and Pandey [1] and various other investigators have reported the effect of stand-off distance (SOD) on the material removal rate (MRR) and the penetration rate. Ingulli [2], Bhattacharya [3], and Verma and Lal [4] have researched the effects of abrasive flow rates on the MRR and the penetration rate. Wolak [5] has investigated the nozzle effect and Finnie [6] and Bitter [7] the effect of the angle of impingement. All of the above research work was done for primary machining processes such as cutting, hole machining, etc.,. Ramachandran and Ramakrishnan [8,9] in their review paper recommended AJM for

deburring. The effects of AJM parameters such as jet height and impingement angle were studied by Balasubramaniam [10].

The purpose of this paper is to distinguish the influence of each of the cutting parameters on the burr removal and the generation of the quality requirements of the edge. The influence of the input parameters on the other output parameters such as surface finish are not being considered here. Taguchi experimental design and analysis was used to systematically determine the influence of the cutting parameters on the quality of deburred stainless steel specimens. Burr removal and a specific type of edge generated were designated as the criteria for assessing the quality of the deburred specimens. The parameters investigated include the nozzle pressure (NPR), stand-off distance (SOD), the jet height (JH), the mixing ratio (MR), the abrasive grit size (ASIZE) and the angle of impingement (IANG). An optical profile projector was used to measure the edge quality and a visual inspection was carried out to ascertain the surface damage of the specimens. Result of the edge quality measurements supplemented with the visual inspection were analysed by the ANOVA method employing the software STATGRAPHICS.

Fig. 2. The concept of jet height.

2. Experimental set-up and procedure

2.1. Specimens

1.5 mm thick, 25 mm square, grade AISI304 stainless-steel sheets were used as the specimens. Burrs were generated at one corner of the specimens by a face milling operation. All of the specimens were stacked together and machined to generate the burrs. The burrs were measured with a profile projector, the average root thickness of the burrs being 0.68 mm.

2.2. Experimental set-up

All the experiments were performed with a direct pressure type dry abrasive jet machine mounted on an X/Y table, the specimens being held in a universal type vice. The nozzle was 2 mm × 2 mm in cross-section, 20 mm long and manufactured from OHNS hardened to 55–60 HRC. A height gauge was used to establish the necessary jet height.

2.3. Selection of the process parameters

Seven parameters, viz. SOD, mixing ratio, abrasive size, nozzle pressure, nozzle dimensions, traverse rate and angle of impingement, were identified as process

Table 1
Levels of variables in the first series of experiments

Variable	Experiment	
	Level 1	level 2
SOD (mm)	2	5
JH	0	$h/2$
NPR (kg cm^{-2}) ^a	3	6
IANG	0°	30°
AGS grit	46	60

^a 1 kg cm^{-2} = 98.1 kPa.

Table 2
Levels of variables in the confirmation experiment

Variable	Experiment		
	Level 1	Level 2	Level 3
JH	0	$h/2$	$3 h/2$
IANG	0°	15°	30°

parameters. Of these, the effect of the parameter traverse rate was eliminated by conducting the experiments on 1.5 mm thick specimens with a 2 mm wide nozzle. The effects due to the parameter nozzle dimensions were eliminated by using only one type of nozzle. In preliminary experiments it was found that an additional parameter viz. jet height was causing significant influence on the output parameter and hence further studies included this parameter also. Jet height is defined as the distance between the centre of the nozzle and the edge of the specimen and is expressed in terms of nozzle height (h). Fig. 2 illustrates the concept of the jet height.

2.4. Experimental design

Two series of deburring experiments, each constructed using a Taguchi experimental design array [11,12] and two sets of confirmation experiments were performed, the first series to identify the factors causing the burr removal and maintaining the edge quality and the second series of experiments to identify the factors influencing the magnitude of the edge radius generated. The results were verified by a confirmation experiment. Five independent parameters viz. SOD, abrasive size, mixing ratio, nozzle pressure and time were varied in the first experiment of the second series, only SOD being varied in the confirmation experiment.

The first series of experiments was performed using a 2-level, 16-run experimental design. Six independent variables, viz. SOD, JH, NPR, MR, IANG and ASIZE, were varied. The 16-run experimental design was chosen for its ability to investigate main effects and linear two variable interaction effects. The first series confirmation experiment was performed using a 3-level, 2-factor, 9-run experimental design. The values of three levels were selected based on the results obtained from the analysis of the previous experiment. In this 3-level experiment both of the independent variables JH and IANG were varied. To produce a fully crossed experimental design array for the 3-level design, four sets of nine runs totalling 36 runs were performed. Table 1 shows the level of each variable used in the first series and Table 2 shows the level of each variable used in the confirmation experiment.

Table 3
Response table

Deburred	Type of edge generated	Response
0	0	0
0	1	0
1	0	0
1	1	1

2.5. Experimental procedure

In the first series of experiments, the removal of burrs and a specific type of edge produced, in this case a convex radius, were kept as response parameters and, using a response table, Table 3, the output was assigned values of either '0' or '1'. The value '0' represents unacceptable quality and '1' represents acceptable quality. Measurements were reduced using the analysis of variance (ANOVA) technique of Taguchi to designate deburring quality. The software STATGRAPHICS was used to analyse the data. The percentage effect of each variable was calculated by the ratio of the individual parametric sum of squares to the total sum of squares of all parameters.

In the second series of experiments, the size of the convex radius generated at the edge was kept as the response parameter. Measurements were made using an optical profile projector and the data were analysed, the results of the analysis being utilized in developing a statistical model for the magnitude of the radius generated in terms of input parameters.

3. Statistical model

The functional relationship of dependent variables of the abrasive jet deburring process for the generation of an edge radius can be represented by the following first-order polynomial, ignoring quadratic and higher order effects:

$$Y(X) = C_0 + \sum_i^n C_i X_i \quad (1)$$

where C_0 is a constant and C_i is the first order coefficients. Based on the design of experiment approach, the radius generated can be represented in a form similar to that of Eq. (1):

$$R = C_0 + \sum_{i=1}^5 C_i X_i \quad (2)$$

where X_1 is the abrasive size in grits, X_2 is the mixing ratio, X_3 is the SOD in mm, X_4 is the nozzle pressure in kg cm^{-2} , X_5 is the time in s and R is the radius generated in mm. The data set obtained from the second series of experiments was used to determine the

coefficients of Eq. (2) by using the STATGRAPHICS software regression analysis at a correlation coefficient of 0.95.

4. Results

An optical evaluation of the deburred specimens indicated that during the removal of burrs from the specimens up to the top surface, one of three types of edges, viz. convex radius, concave radius and taper were generated automatically. Since the convex radius at the edge is generally accepted from a functional point of view, it was fixed as the desired output criteria and the other two types of edges were not considered. The size of the convex radius generated at the edge was found to vary with the various test conditions and also it was found to be limited to the root thickness of the burr. Inaccuracies in the setting of the parameter jet height resulted in either a small projection left out on the deburred surface or a step on the surface, depending upon the direction of the setting error. When the parameter SOD was changed beyond a particular length, 8 mm in this case, it was found that the burrs were not removed from the specimens. The surface-finish value at the top surface of the specimens was found to be changed up to a particular length after the deburring, the details of the change in the surface finish value not being presented here.

5. Deburring experiments

5.1. Deburring experiment series I

The first series of experiments was conducted with 6 independent variables in a fully-crossed 16-run experimental design. Visual inspection and measurements with an optical profile projector were undertaken to determine whether the burrs were removed and the convex radius was generated at the edge. The setting error on the jet height was taken in to consideration when deciding the edge quality. Using a response table, the output parameter was assigned either '0' or '1'. ANOVA of Taguchi analysis was performed with the output parameters to distinguish the relative influence of each independent variable on the output. Results of ANOVA suggest that JH and IANG were the only parameters influencing the output, other parameters, viz. SOD, NPR, MR and ASIZE having no influence on the output. Results of Taguchi analysis suggests that both JH and IANG each had a 33.3% effect on the output and that their interaction had a 33.3% effect, other parameters having no effect on the output at their selected levels.

Fig. 3. The effects of the most influential variables on the main output.

The confirmation experiment was conducted with the most influential independent variables JH and IANG in a fully-crossed 3-level, 9-run experimental design for a total of 36 runs. The outputs were measured in the same way. The analysis confirms that JH, IANG and their interaction had effects on the main output as illustrated in Figs. 3 and 4. The analysis shows that the output was '1' only when JH was $h/2$ and IANG was 0° , at all other conditions the output being '0'.

5.2. Deburring experiment series II

The second series of experiments was conducted with five independent variables in a fully-crossed 2-level, 8-run experimental design for a total of 32 runs. The size of the radius generated was measured using an optical profile projector. The size of radius generated was found to have a maximum value of the burr root thickness. The data obtained were analysed to distinguish the relative influence of each independent variable on the size of the radius generated at the edge. Results of ANOVA suggest that the SOD had the maximum influence on the size of the radius generated, the influence of all other parameters being insignificant. Table 4 shows the percentage effect of each variable on the

Fig. 4. AS for Fig. 3.

Table 4
ANOVA results

Variable	Influence (%)
SOD	88.3
NPR	0.3
MR	2.7
ASIZE	0.3
Time	2.7
Error	5.7

output. The interaction effects between the five independent variables were evaluated and it found that they did not play a significant role in affecting the radius generated, hence they are not presented here.

Based on the experimental data set, a model for the size of radius generated was determined, the coefficients of the regression being presented in Table 5. The model is based on 32 radius measurements and, as previously mentioned, the model accounts for first order main effects only. The estimated and measured values of the confirmation experiments are given in Table 6. As can be seen, a reasonable correlation exists between the measured and predicted values.

6. Discussion

The following discussion with the aid of Tables 7 and 8 illustrates the influence of the independent variables on deburring. It was noted throughout the studies that burr was removed and a convex edge was generated only when the IANG was 0° and JH was $h/2$. When the JH was less than $h/2$, some portion of the specimen was machined off along with the burr and a concave radius or taper was generated on the specimen, depending upon the level of the other variables. When the JH was more than $h/2$, or when the IANG was other than 0° with the JH level at $h/2$, the burr became bent and was not removed from the specimen. Other variables did not influence the burr removal.

6.1. Jet height

Table 7 shows the effect of JH on burr removal, whilst Table 8 shows the effect of JH on the type of edge generated. Burrs were removed for all the levels of IANG when JH was 0. This is due to the burr root lying within the jet, this causing the complete removal

Table 5
Regression coefficients

C_0	C_1	C_2	C_3	C_4	C_5
0.077262	0.000893	0.25	0.070833	0.004167	-0.000625

Table 6
Edge radius results

SOD	Predicted	Measured	
2	0.23	0.2	0.3
4	0.37	0.4	0.4
6	0.51	0.48	0.5
8	0.65	0.6	0.6

of burr. The burr was also removed when JH was $h/2$ and IANG was 0° . In this case, as the burr root lies tangential to the jet, ignoring the expansion effect of the jet, the removal of the burrs was ensured. In all other cases, the burr became bent and was not removed. Hence, burr removal is possible only when the JH is less than $h/2$. When JH was 0 and IANG was 0° , a concave type of edge was produced and when IANG was greater than 0° , a tapered edge was produced. The required type of edge was produced only when JH was $h/2$ and IANG was 0° .

6.2. Impingement angle

Tables 7 and 8 show the effect of IANG on burr removal and the type of edge produced. From Table 7, it can be seen that burr removal was ensured for all levels of IANG when JH was 0 and for 0° IANG with $h/2$ equal to JH, the reason being that the root of the burr lies within the jet. In all other cases, the burrs became bent and were not removed.

6.3. SOD

The effect of SOD on burr removal is shown in Table 9. When the SOD increases beyond a particular value, 8 mm in this case, the removal of burr was not ensured. This is most likely due to the increased effect of jet expansion at larger values of SOD. As the SOD increases beyond 8 mm, the energy of the exterior of the jet decreases to levels which are below those necessary to remove material at the root of the burr. Hence to achieve burr removal, the SOD should be maintained below the threshold value.

Table 7
Effects of JH and IANG on burr removal

IANG	Jet height		
	0	$h/2$	$3 h/2$
0	1	1	0
15	1	0	0
30	1	0	0

1, Deburred; 0, not deburred.

Table 8
Effects of JH and IANG on type of edge generated

IANG	Jet height		
	0	$h/2$	$3 h/2$
0	b	a	—
15	c	—	—
30	c	—	—

a, Convex radius; b, concave radius; c, taper.

6.4. Size of radius generated

The following discussion with the aid of Table 4 and Fig. 5 illustrates the influence of the independent variables on the size of radius generated whilst deburring. Results from the Taguchi analysis of Table 4 show that the percentage effect of the SOD on the size of the radius generated was very high, i.e. 88.3%, the influence of all other variables being insignificant. From Fig. 5, drawn from the data of confirmation experiment, it can be seen that the size of the radius generated increases with the SOD. After the threshold value, 8 mm in this case, the burrs were not removed and hence no edge radius was generated. Further, the size of the radius generated was restricted to the root thickness of the burr, this most likely being due to the primary erosion removing the burr and the secondary erosion causing the generation of the radius at the edge. When the burrs were completely removed up to the root thickness, both primary and secondary erosion ceases and the process of generating the radius stops limiting the size of radius to the root thickness of the burr.

7. Conclusions

The primary objective of this study was to obtain a measure of the influence of the AJM parameters on the deburring process of stainless steel specimens. Through a Taguchi experimental design and analysis of the deburring results, the following conclusions are drawn. (1) Abrasive jet deburring has the advantage over manual deburring methods of generating an edge radius automatically. This increases the quality of the deburred components. (2) The process of removal of burr and the generation of a convex edge were found to vary as a function of the parameters jet height and impingement angle, with a fixed SOD. The influence of other

Table 9
Effects of SOD on deburring

SOD	2	4	6	8	10	12
Deburred?	1	1	1	1	0	0

Fig. 5. The effect of the SOD on the radius generated.

parameters, viz. nozzle pressure, mixing ratio and abrasive size were found to be insignificant. (3) The process of removal of burr was found to take place within a limited value of SOD. (4) The SOD was found to be the most influential factor on the size of the radius generated at the edges. (5) The size of the edge radius generated was found to be limited to the burr root thickness. (6) The burr becomes cut off at the root and hence the deburring time has no effect on the eventual burr height. (7) A statistical model for the size of the radius generated has been developed based on a regression technique. The model successfully predicts the size of the radius generated on stainless steel specimens and can be used for deter-

mining the deburring parameters for a tailored edge radius.

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