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Research Article

Observation of Drilling Burr and Finding out the Condition for Minimum Burr Formation

Nripen Mondal, Biswajit Sing Sardar, Ranendra Nath Halder, and Santanu Das

Department of Mechanical Engineering, Kalyani Government Engineering College, Kalyani, West Bengal 741235, India

Correspondence should be addressed to Santanu Das; sdas.me@gmail.com

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Suppression or elimination of burr formation at the exit edge of the workpiece during drilling is essential to make quality products. In this work, low alloy steel specimens have been drilled to observe burr height under different machining conditions. Taper shank, uncoated 14 mm diameter HSS twist drills are used in these experiments. Dry environment is maintained in experiment set I. Water is applied as cutting fluid in experiment set II. In the next four sets of experiments, the effect of providing back-up support material and exit edge bevel is observed on formation of burr at the exit edge of specimens under dry and wet conditions. It is revealed that an exit edge bevel of 31 degrees with water as the cutting fluid gives negligible burr at the exit edge of the drilled hole at certain machining conditions. Use of a back-up support can also reduce drill burr to a large extent. In this paper, artificial neural networks (ANN) are developed for modeling experimental results, and modeled values show close matching with the experimental results with small deviations.

1. Introduction

Drilling is a common hole-making operation, and the majority of workpieces are subject to hole-drilling before they leave a machine shop. However, presence of burr on the drilled workpieces creates problems not only in handling, but also in the assembly line. Burrs are undesired projections attached to the edge of drilled holes. These are found to be substantially greater at exit side than entry side. Hence, elimination, or large-scale reduction, of exit burr is the necessary requirement of an industry [1–5].

Many researchers worked on burr-related problems associated with drilling and other processes and also investigated the mechanism behind burr formation. Control charts were applied by Min [6] and Kim et al. [7] for control and prediction of burr height during drilling different steels. The same technique was also employed by Lee and Dornfeld [8] for estimating burr size during microdrilling to some success. Finite element method (FEM) was used by some others [9–11] to observe stress and deformation patterns analytically to understand the reason behind burr formation. Guo and Dornfeld [9] made finite element analysis to assess the substantial reduction of drilling burr with back-up support. They also successfully did [10] this analysis to understand burr formation in stainless steels. FEM was also used by Park and Dornfeld [11] to find out the influence of exit edge angle of a specimen, tool rake angle, and back-up support on burr formation. The estimates made showed remarkable results.

An overview on different strategies to control burr was presented by some researchers [1–5, 12, 13]. Investigations on the effect of drill size [14, 15], use of drills with special geometry [16–19], effect of using different coolants, exit edge modification, and providing back-up support [20–22] were explored by other research groups. Lee and Dornfeld [8] carried out experiments on four different materials using HSS and carbide drills of varying shapes and geometry. They concluded that step drills with less step angle and step size produced quite small burr. Min et al. [20] performed experimental and analytical investigation on drilling burr formation by varying interaction angle at the exit edge. It is the angle by which work exit surface is inclined. They observed that a large interaction angle results in quite less burr due to less bending of job material to form a burr. Another group of researchers found out [19] variable feed drilling with a suitable amplitude to give high tool life with quite low burr height. Although variable feed was reported

Table 1: Experimental conditions.

Machine tool	Radial drilling machine, Make: Energy Limited, India, Model: RDH-32/930 Main motor power: 1.5 kW
Tool holder	R/L 265 ME-20 AL, Make: Sandvik Asia Limited, India
Cutting tool	Taper shank, uncoated 14 mm diameter HSS twist drill, Make: Miranda (India)
Workpiece material	Low alloy steel, hardness: 225 HB Composition: C (0.17%), Si (0.21%), Mn (0.63%), P (0.09%)
Workpiece size	100 mm × 50 mm × 6 mm
Cutting velocity	20, 25 and 31 m/min
Feed	0.032, 0.05 and 0.08 mm/rev
Environment Experiment sets	Dry and water-cooled I—Drilling in dry condition without any back-up support or edge bevel II—Drilling with water cooling without any back-up support or edge bevel III—Drilling in dry condition with a back-up support IV—Drilling in water-cooled condition with a back-up support V—Drilling in dry condition with 31° exit edge bevel VI—Drilling in water-cooled condition with 31° exit edge bevel

to reduce burr remarkably compared to that of constant feed drilling, implementation of this method needs special facility to be provided on a drilling machine.

During tool/cutter exit from the workpiece, cutting edge of the tool/cutter was observed [5–12] to have been chipped off or broken beside formation of burr/foot. This problem also was seen to reduce with the introduction of special tool geometry, suitable exit order sequence, and work edge bevel. Provision of a beveled work edge was reported to lower burr height noticeably in milling and drilling operations [12–15, 21–23] due to gradually decreasing depth of cut and the reducing need of back-up support. Suitable tool path selection also reduces burr height [24]. Significant effect of different size of drills on burr formation was observed in some other works [14, 15] under varying cutting conditions. Introduction to different shape and geometry of cutting tool was also reported [8, 17, 18, 25] to reduce burr significantly for specific applications. A typical stepped drill was tested to restrict or to remove burr effectively. For laminated composites, delamination and burr formation at interface layers were studied [26] and some conditions were reported to reduce formation of burr and to avoid delamination.

In another work, mechanism of exit burr formation during drilling of aluminium alloys was closely studied [27], and an analytical model was proposed considering the effect of temperature that matched well with experimental results. Burr size was also modeled by other researchers [28] analytically for ductile metals to make good prediction of burr formation. The nature of burr formed during drilling of small size drills under dry and minimum quantity lubrication (MQL) with water soluble oil condition was discussed [29]. They also tried to obtain good quality holes with minimum burr by using optimized tool selection. Investigation of drill burr during hole-making on low carbon steel specimens with 40 Brinell Hardness Number was carried out by Roy et al. [23]. Utility of providing a back-up support or beveling the exit edge by 31° was observed in that work. However, effect of water-cooled condition was not explored suitably with or without a bevel in this work. Providing bevel in dry condition was reported not to show remarkable reduction in burr height.

Karnik et al. [30] tried to minimize burr size in drilling stainless steel workpieces with the use of genetic algorithm (GA) and Taguchi method of designing experiments. An innovative measurement technique to find out burr height was also reported [31]. Gaitonde and Karnik [32] utilized artificial neural networks (ANN) and particle swarm optimisation (PSO) approaches for optimal selection of drilling parameters to achieve minimum burr size (height and thickness) during drilling within the domain of experiments.

Even as a lot of works have been carried out on burr, still a lot of scope remains to find out appropriate strategy to minimize burr for a particular process of machining different workpiece materials. The obbjective of the present investigation is to explore effects of different machining conditions and strategies on drilling burr formation and selection of the optimal condition to suppress burr formation significantly. 14 mm diameter holes are drilled with or without using a back-up support and bevel at the exit edge to notice formation of burr in low alloy steel specimens under dry and wet with water cooled environment.

2. Experimental Setup and Machining Condition

Experiments are conducted in this work on a radial drilling machine (Make-Energy Limited, India) under dry and wet (water cooled) conditions. Low alloy steel specimens are taken for drilling experiments using 14 mm diameter drills.

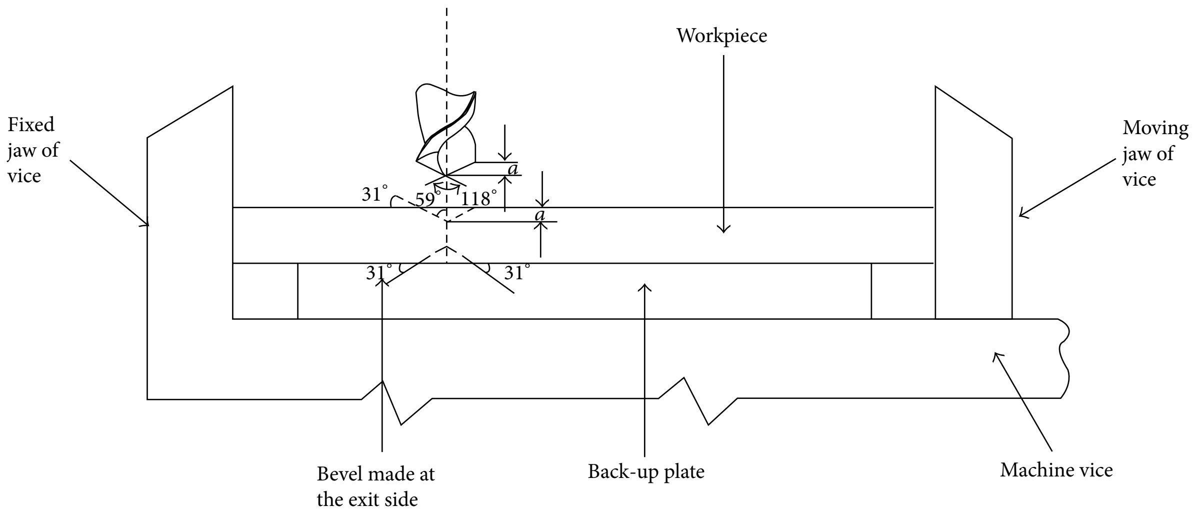

Figure 1: Schematic representation of drilling using a back-up plate and/or exit edge bevel.

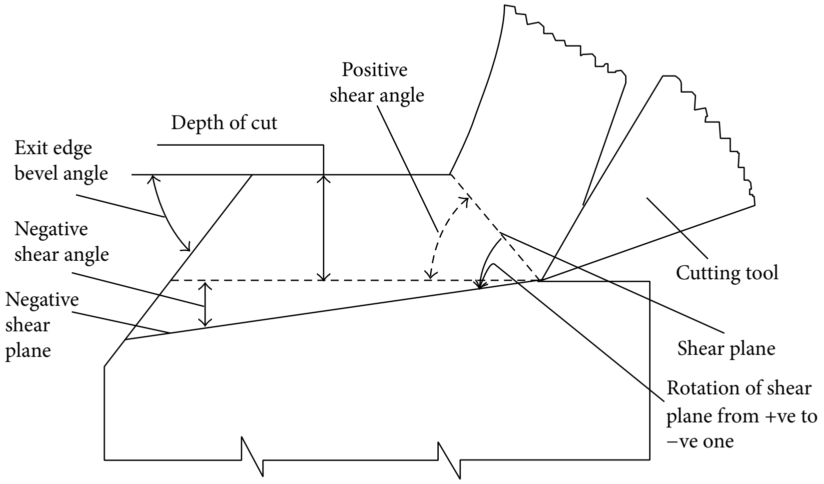

Figure 2: Schematic diagram showing orientation of positive shear plane to a negative one and exit edge bevel.

Experimental conditions are given in Table 1. Cutting velocity, V_c, and feed, S_z, are chosen within 20–31 m/min and 0.032–0.08 mm/rev, respectively. Ranges of V_c and S_z are selected considering usual industrial practice for drilling low alloy steels with tungsten grade HSS drill bit. Back-up support is provided to explore its influence on reduction of burr formation in some sets of experiments. It is done by placing similar specimens as that of the test piece with slightly less width below the test piece as shown in Figure 1 and without providing any edge bevel. Less width of the support facilitates easy clamping of test piece in a machine vice. Drilling is continued up to the middle of back-up support thickness.

Back-up plate is used to provide the required support during the tool exit and intends not to allow rotation of shear plane to a negative shear plane and suppresses bending of chip to form a burr. The shear plane rotation was reported to result in burr formation in a number of works [4, 5, 9, 13, 21]. Possible rotation of a positive shear plane to a negative one is shown schematically in Figure 2. When the tool or cutter approaches the emerging edge of a workpiece, no back-up material exits at that position to support the cutting forces exerted by the cutting tool onto the part of the workpiece. As a result, the shear plane gets oriented to the negative direction. If a back-up material is placed below the workpiece, then required support is likely to be provided by it resulting in expected reduction in the formation of burr. The effectiveness of suppressing formation of burr by using a back-up support is compared to that of using edge beveling in this work.

A bevel of 31° is provided at the rear side of the workpiece as shown in Figure 1 for experiment sets V and VI. The bevel is made with the help of drilling with the same 14 mm drill bit up to the drill point length, a, as shown in Figure 1. In this way, 31° exit edge bevel angle is made, as it is complementary to 59° which is half the point angle, 118°. Thus, no other processes are needed to produce the bevel. Only appropriate marking at the location of the bevel making with the drill is to be done. Bevel portion of the specimen is placed at the rear side of the workpiece aligning with the hole to make with suitable marking. When this exit edge bevel is used, no back-up support is provided.

Number of other parameters, such as lip clearance angle and point angle, may have an influence on burr formation, and this may be explored experimentally. However, investigation is restricted in this work to find out the effect on burr height by varying cutting velocity, feed, machining environment, and with and without the use of back-up and exit edge bevel of 31°.

Along the bevel provided at the exit edge of the workpiece, depth of cut gets gradually reduced. When the drill bit goes down along the bevel position, chip width gets reduced gradually. Correspondingly, the influence of chisel edge to deliver axial thrust causing bulging out of the thinning work material at the exit end is eliminated. When peripheral point of cutting edge of the drill bit approaches the rear end of the specimen, depth of cut reduces gradually needing correspondingly decreasing cutting force (thrust) and torque. Hence, at some bevel angle, it is expected that no substantial requirement of back-up support will be there leading to suppression of burr formation at the exit edge [4, 5, 7, 13, 20–22]. In the present work, 31° exit edge bevel is provided as it is easily achievable by using the twist drill point portion having a point angle of 118° as detailed in Figure 1. Influence of this is explored on the extent of suppressing burr formation.

Table 1 shows the detail of experimental conditions. Process parameters are selected in-line with that normally practiced in industry using standard HSS twist drills. Three levels of feed (S_z) and cutting velocity (V_c) are employed following full factorial design of experiments at each experiment set as detailed in Table 2. Hence, at each experiment set, $3^2 = 9$ tests are performed. Although a burr size may be characterized by its thickness and height, in the present work, burr height is considered to characterize a burr in line with many other works reported earlier [7, 18, 19, 27]. Burr height is measured using a vernier height gauge. Six different sets of experiments are conducted as detailed in Table 1 to find out the condition giving minimum drilling burr within the domain of experiments. Experiment sets I and II are performed under dry and wet with water cooling condition, respectively, without using any backing plate or edge bevel. Experiments with the provision of backing support are done under dry and water-cooled conditions in experiment sets III and IV, respectively. In experiment sets V and VI, drilling is carried out at respective dry and wet environments with an exit edge bevel of 31°.

3. Results and Discussion

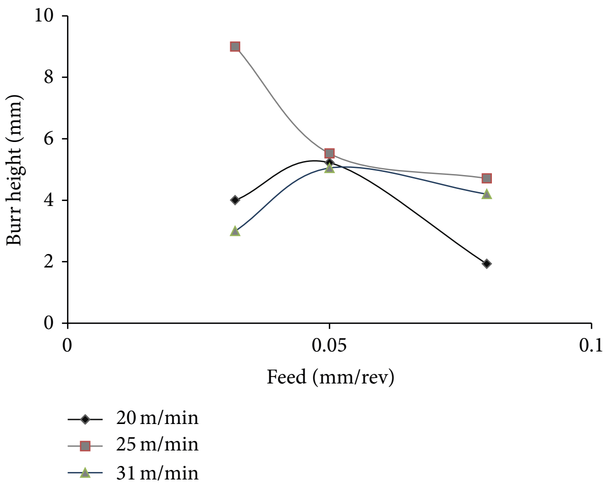

FIGURE 3: Plot of variation of burr height at different cutting velocity and feed for experiment set I.

TABLE 2: Test conditions in each experiment set.

Sl. no.	Feed (S_z) (mm/rev)	Cutting velocity (V_c) (m/min)
1	0.032	20
2	0.032	25
3	0.032	31
4	0.050	20
5	0.050	25
6	0.050	31
7	0.080	20
8	0.080	25
9	0.080	31

3.1. Discussion on the Observation of Drilling Burr at Dry Condition without Any Back-Up Support or Beveled Edge (Experiment Set I). Observation on experiments in drilling at dry condition without using any back-up support material, or edge beveling, is presented in Figure 3. Large burrs are found in these tests. Variation of burr height is noticed at different machining conditions, although no clear trend is seen with the individual machining parameters. Large size burrs are expectedly formed in these tests as no back-up support material is available at the exit edge of the drilled hole. For this, shear plane is likely to have oriented to a negative direction facilitating formation of burr as shown in Figure 2 [21, 24]. When shear plane is oriented towards a negative plane, the chip is bent downwards and can be attached to the exit edge of workpiece forming a burr. Large extent of plastic deformation under dry condition with high temperature rise may have resulted in large burrs. Corresponding photographs of burrs observed are shown in Figure 4. For experiment set I, only at a cutting velocity (V_c) of 20 m/min and a feed (S_z) of 0.08 mm/rev (test No. 7), burr height of slightly less than 2 mm is found. In all the nine tests in experiment set I, transient, nonuniform burrs are observed. Classification of drilling burr was discussed by Kim et al. [7]. They classified drilling burr as uniform, crown, transient, and uniform with drill cap.

3.2. Discussion on the Observation of Drilling Burr under Water-Cooled Condition without Back-Up Support or Edge Bevel (Experiment Set II). Experiment set II is conducted in water cooled condition without using a back-up material and

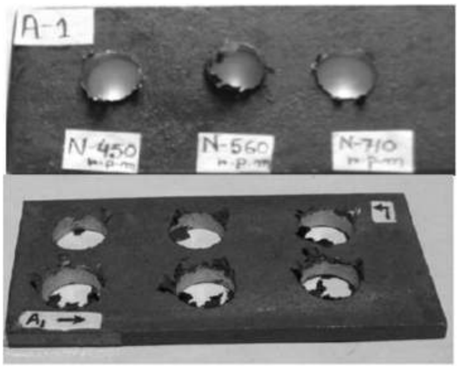

Figure 4: Photographic view of burr formed in experiment set I (left-right order: top for Sl. numbers 1–3, bottom for Sl. numbers 4–6, middle for Sl. numbers 7–9).

edge bevel. The experimental results are plotted in Figure 5 showing the variation of burr height observed under different cutting conditions. No remarkable reduction in burr height is found to be there at water-cooled condition compared to that at dry environment. At certain machining conditions, burr height is lesser with water cooling than dry condition. However, at other conditions, larger burr height is observed with water cooled condition than that with dry condition. Figure 6 shows typical burrs seen at the exit edge of the drilled holes. In this experiment set II, mainly transient burrs are observed. Water cooling is expected to reduce drilling temperature and thereby may reduce the extent of plastic deformation during drilling. However, marginal contribution of water in lubricating tool-chip-workpiece interface regions may be the possible reason behind having no significant effect of it on burr reduction. In this experiment set also, no definite trend of variation of burr height with machining parameters is noticed as that of experiment set I.

3.3. Discussion on Drilling Burr Formation with a Back-Up Support at Dry Condition (Experiment Set III). Experiment set III is performed in dry condition by providing a low alloy steel back-up support. This backing plate is similar to that of the test specimen with slightly less width to facilitate easy clamping of the test piece in a machine vice (Figure 1). This is done to render a support during tool exit, so that rotation of shear plane from positive value to a negative one about a pivot point is suppressed. With this, burr formation is expected to be restricted. Burrs formed at these conditions are observed, and the burr heights measured at different cutting velocity and feed are shown in Figure 7. Burr height observed is found to be substantially reduced with the use of back-up support at dry condition compared to that at experiment set I. The largest burr height seen in experiment set III is 0.64 mm. Figure 8 depicts the photographic view of burr formed using a back-up plate in dry condition. Transient burrs are seen in these tests around the hole exit end at few locations only.

It is seen that burr height is quite less at low cutting velocity at all the three feeds. At low cutting velocity (V_c), when rise in machining temperature, and hence, plastic deformation is less, possibility of large burr through sustained

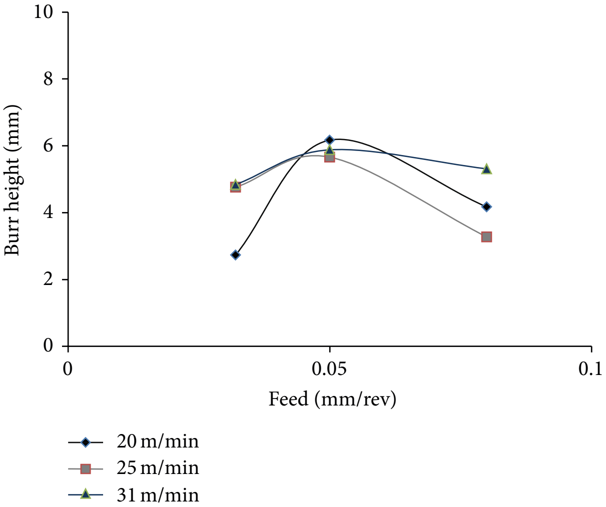

Figure 5: Plot of variation of burr height at different cutting velocity and feeds for experiment set II.

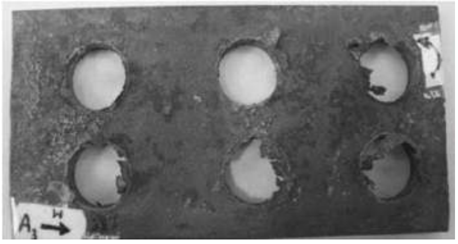

Figure 6: Photographic view of typical burr formed in experiment set II (left-right order: bottom for Sl. numbers 1–3, top for Sl. numbers 4–6).

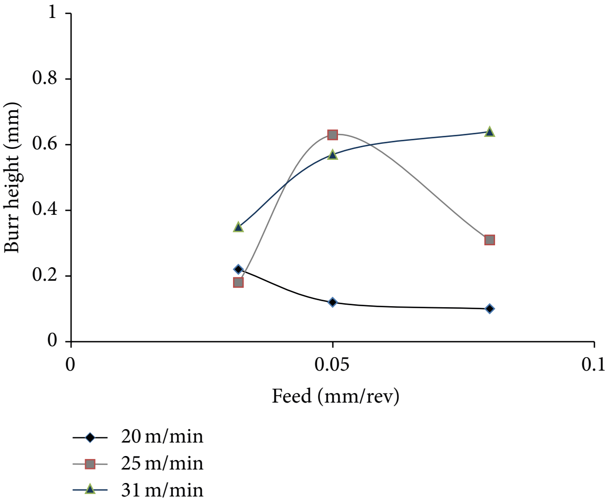

Figure 7: Plot of variation of burr height at different cutting velocity and feeds for experiment set III.

Figure 8: Photographic view of burr formed in experiment set III (left-right order: middle for Sl. numbers 1–3, top for Sl. numbers 4–6, bottom for Sl. numbers 7–9).

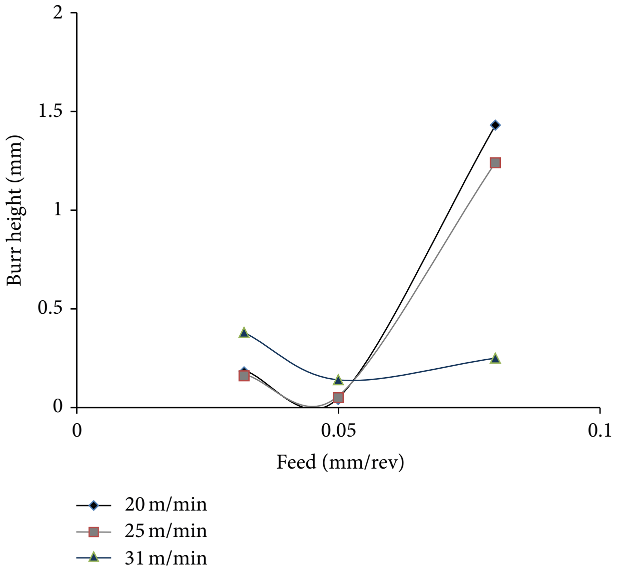

Figure 9: Plot of variation of burr height at different cutting velocity and feeds for experiment set IV.

bending is also expected to be less. Minimum burr height of only 0.10 mm is observed with the use of back-up support at dry condition at a feed of 0.08 mm/rev and cutting velocity of 20 m/min. Burr height more than 0.5 mm but less than 0.65 mm is found at some other higher cutting velocity conditions.

3.4. Discussion on Drilling Burr Formation Using Water-Cooled Condition with a Back-Up Support (Experiment Set IV). Experiment set IV is carried out with a back-up support material under water-cooled condition. Burrs formed at these conditions are noted, and the result is shown in Figure 9. Photographic views of burrs present in this experiment are shown in Figure 10. It is found that burrs are reduced considerably under this water-cooled condition using a back-up support at 0.032 and 0.05 mm/rev feed conditions. Quite less burrs as low as 0.04 mm and 0.05 mm in height are obtained at a feed of 0.05 mm/rev and cutting velocity (V_c) of 20 and 25 m/min, respectively. However, at a higher feed of 0.08 mm/rev and cutting velocity (V_c) of 20 and 25 m/min, large burr of more than 1 mm is detected. Only at one or two points, small size burrs are found in this experiment set.

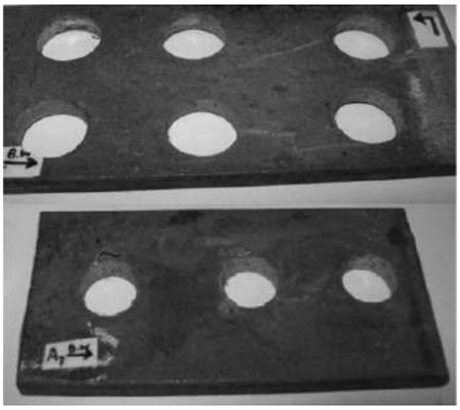

Figure 10: Photographic view of burr formed in experiment set IV (left-right order: middle for Sl. numbers 1–3, top for Sl. numbers 4–6, bottom for Sl. numbers 7–9).

Combined effect of attaching the back-up support and reduction in cutting temperature due to water cooling may have caused the formation of less burr height. The back-up support is expected to restrict the rotation of shear plane to a negative orientation as indicated in Figure 2, and to reduce burr formation significantly. Water cooling reduces cutting temperature and may have not allowed large increase in plasticity of the workpiece during machining causing less tendency of burr formation.

3.5. Discussion on Drilling Burr Formation Using Exit Edge Beveling under Dry Condition (Experiment Set V). Variation of burr height with the change in feed at three cutting velocities is plotted in Figure 11 with the provision of 31° edge beveling in dry condition. The burr formed is observed, and its photograph is shown in Figure 12. Moderate burr height less than 1 mm is formed at all the machining conditions undertaken in experiment set V. Burr size in this case is lower than that without using a back-up support or an edge bevel but higher than that using a back-up support. Gradual reduction of depth of cut along the bevel needs reducing force values and tends to reduce burr formation. At some points around the exit edge, few burrs are found to be attached. Further experiments are next performed using water-cooled condition to reduce temperature maintaining the exit edge bevel of 31° to investigate its effectiveness. This observation is also supported by somewhat similar reports made previously [15, 23, 27] under varied experimental conditions.

3.6. Discussion on Drilling Burr Formation Using an Exit Edge Bevel with Water Cooling (Experiment Set VI). Experiment

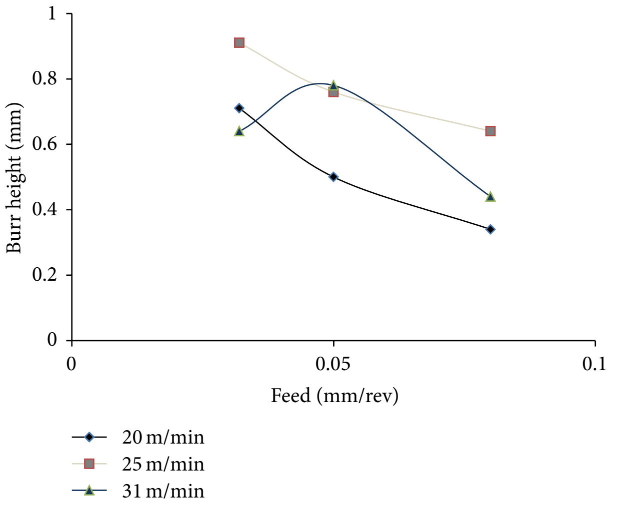

FIGURE 11: Plot of variation of burr height at different cutting velocity and feeds for experiment set V.

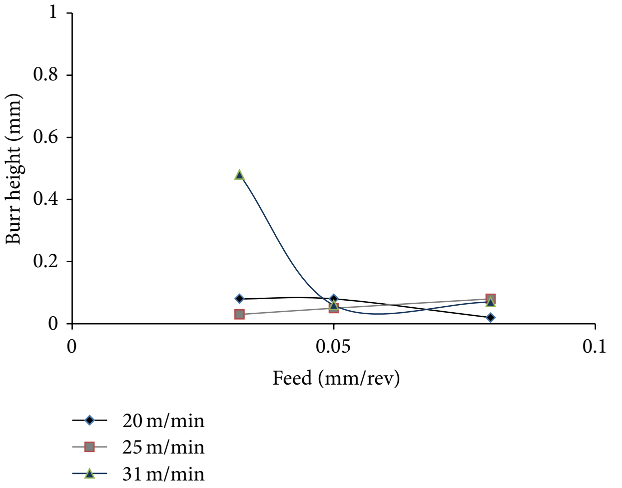

FIGURE 13: Plot of variation of burr height at different cutting velocity and feeds for experiment set VI.

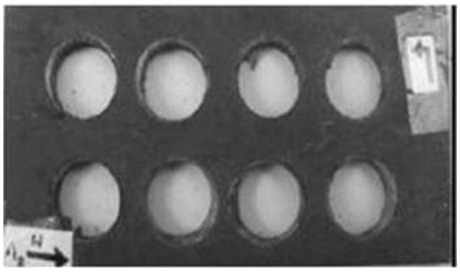

FIGURE 12: Photographic view of burr formed in experiment set V (left-right order: bottom for Sl. numbers 1–4, top for Sl. numbers 5–8, right side for Sl. number 9).

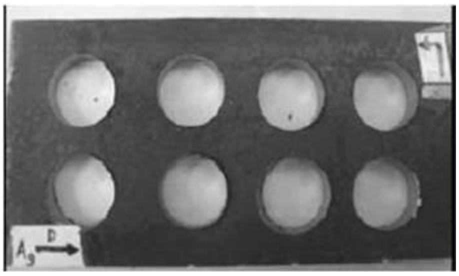

FIGURE 14: Photographic view of burr formed in experiment set VI (left-right order: bottom for Sl. numbers 1–4, top for Sl. numbers 5–8, right side for Sl. number 9).

set VI is carried out in water-cooled condition with three values of cutting velocity and feed with the provision of an exit edge bevel of 31°. Burr formation in these conditions is also observed to be similar to the other five experiment sets. Results are presented in the form of Figure 13. Quite less burr height is observed from the plot except at 31 m/min cutting velocity and 0.032 mm/rev feed condition. The photographic view of drilling burr corresponding to experiment set VI is shown in Figure 14. Tiny infrequent burr is seen around the exit edge of the drilled hole in this experiment set.

Figure 14 reveals that burr is reduced substantially by using an exit edge bevel angle of 31° at water-cooled condition. Only at a cutting velocity (V_c) of 31 m/min and feed of 0.032 mm/rev, large burr height of 0.48 mm is observed. Under other experimental conditions, low burr height of up to 0.08 mm is observed. At a cutting velocity (V_c) of 20 m/min and a feed of 0.08 mm/rev, a minimum burr height of 0.02 mm is obtained. This is the smallest height of burr seen among different sets of the present experimental work, and hence, the condition corresponding to this quite low burr can be recommended to adopt.

This small burr height may have occurred mainly due to the provision of the 31° exit edge bevel that causes gradual reduction of depth of cut when the drill approaches the rear surface of the hole. This results in gradually less requirement of cutting force during tool exiting, and therefore, needing no additional back-up support during emergence of the drill from the rear side of the job. Consequently burr formation may have been suppressed significantly as negative shear plane formation becomes less likely. Water-cooled machining conditions further help in reducing plastic deformation by taking away the heat generated and reducing the extent of burr formation. This is in line with the report on the temperature effect on burr formation [23, 27].

Burr height at the exit edge is next modeled as a function of cutting conditions with a complex nonlinear algorithm, namely, artificial neural networks (ANN), or simply neural networks (NN). Detail of the NN applied in this work is given in the following sections.

4. The Neural Networks (NN) Model Used

There are several algorithms used in a neural network. In the present work, Levenberg-Marquardt multilayer Neural Networks (NN) with back propagation training algorithm and feed forward system [32–34] are used to model burr height using the data observed. Matlab software package with neural network toolbox is utilized in this work. In this algorithm, an iterative gradient method is employed to compute connection weights corresponding to minimum total mean-square error between the obtained output of the multilayer network and the target output. Multilayer NN consists of an input layer, one or more hidden layer(s) and an output layer [32, 33]. The neural network structure used in the present work is shown in Figure 15, where there are one input layer having five input nodes, a single hidden layer, and an output layer with one output node. Cutting velocity, feed, use of coolant, back-up support, and edge bevel comprise of the input layer, and burr height is there as the output node. The NN algorithm used in this work is detailed elsewhere [34].

5. Using the NN for Testing and Experimental Validation

The neural networks (NN) are first trained with a training data set. There are total 54 experimental datasets. These datasets are shown in Table 3. Train ratio chosen is 80/100 which means that 44 datasets (i.e., 80% of 54 datasets) are used for training (1st columns Sl. number 1 to 44). A validation ratio of 10/100 is used, meaning the use of 5 samples (10% of datasets) for validation (1st columns Sl. numbers 45 to 49). Testing ratio of 10/100 is selected in this work that means 5 sample data (10% of datasets) are to be used for testing (1st columns Sl. numbers 50 to 54). Training sample data are required for determining weights of the network during training. Validation of sample data is used to measure network generalization and to halt training when generalization stops improving. The testing sample data have no effect on training. They provide an independent measure of network performance during and after training. The training dataset consists of 44 sets of sample data consisting of normalized datasets of input data and the corresponding output data. The normalizing factor considered is $(x_{\text{in}}/x_{\text{max}})$ where x_{in} is input data and x_{max} is the maximum value data. The five input variables are cutting velocity, feed, use of coolant, use of a back-up support, and provision of exit edge bevel, and the output is experimentally observed burr height at the exit edge. For use of NN training, dry condition, use of no back-up, and no edge bevel of the work piece are assigned 0 values as the input, and water-cooled condition, use of back-up support, and 31° edge bevel angle of the workpiece are assigned a value of 1 each.

ANN-based burr size modeling is done in MATLAB software package using neural network toolbox. Levenberg-Marquardt multilayer neural networks (NN) with back propagation training algorithm are employed in this work. Maximum number of epochs chosen is 1000. Initial and maximum values of mu (a factor promoting convergence of a network by a typical iterative method) are 0.001 and 10^{10} with the decreasing and increasing factors of 0.1 and 10, respectively. Minimum performance gradient (MSE) considered is 10^{-7}.

The number of hidden neurons chosen in each hidden layer is (2 × input + output). Considering 1 hidden layer, the total number of hidden neurons becomes 11 for an optimum structure of NN [33, 34]. During network analysis, it is found that in general, increasing the hidden layer from 1 to 3 results in little change; the network becomes too complex to solve the problem, and so, the number of hidden layer is usually taken as 1 and the number of hidden neurons can be chosen to be 11 as an optimum one. After training of the NN, all of the 54 sample datasets are used for getting the output. The estimated burr height, thus obtained, and the error of estimation are shown in Table 3 in the last two columns beside the input dataset.

The comparison of experimental findings and neural network estimates of burr height is displayed in Figure 16, and percentages of error between experimental values and model estimates are shown in Figure 17. It is found that the NN model estimates are having quite close matching with the experimental data, barring few deviations, and showing the effectiveness of the NN algorithm for modeling the input-output system to outline the possibility of estimation of burr height within the experimental domain. Occasionally, only small deviations are observed between the estimates and measured burr height. This may be due to the inherent experimental variability of the machining system and possible existence of high degree of nonlinearity in the system. It is clear from Figures 16 and 17 that model estimates deviate more when burr height is noticeably high. In the case of experiments using back-up support, or edge bevel with the use of water cooling environment that gives remarkably less burr height, estimation error is quite less. ANN was employed in earlier works [30, 32] successfully to model and estimate burr size. In line with this, finding out the condition to reduce burr height significantly is likely to be facilitated by the proposed modeling technique.

6. Conclusions

From the present work with 14 mm diameter HSS twist drills for making holes in low alloy steel specimens, conclusions drawn are given below.

(i) Usual drilling under dry condition shows large burr formation at the exit edge. Applying water as the cutting fluid does not yield remarkable results in reducing burr height. Absence of back-up support or bevel during tool exit may have resulted in formation of large burr both in dry and wet conditions.

(ii) Use of a back-up support reduces burr height substantially within the domain of experiments conducted due to less possibility of negative orientation of the shear plane. Use of water is found to reduce burr height further at these experimental conditions. This may be due to lowering of temperature, and hence, lessening plasticity of workpiece.

(iii) Use of 31° exit edge bevel, made with a standard twist drill of 118° point angle, causes significant reduction in burr height in most of the cutting conditions. Use of water cooling minimizes burr height to a great extent. Slow gradual reduction of depth of cut along the bevel causes decreasing requirement of cutting

Table 3: Training dataset for neural networks (NN) and estimated burr height.

Training data number	Cutting velocity, V_c (m/min)	Feed (mm/rev)	Cooling applied	Use of back up plate	Edge beveliing	Measured burr height (ΔM) (mm)	NN estimated burr height (ΔS) (mm)	Percentage of predication error $\frac{\Delta M - \Delta S}{\Delta M} \times 100$
1	20	0.032	0	0	0	4	4.178	−4.45
2	20	0.032	1	0	0	2.73	2.794	−2.34432
3	20	0.032	0	1	0	0.22	0.214	2.727273
4	20	0.032	1	1	0	0.18	0.192	−6.66667
5	20	0.032	0	0	1	0.71	0.818	−15.2113
6	20	0.032	1	0	1	0.08	0.074	7.5
7	20	0.05	0	0	0	5.22	5.047	3.314176
8	20	0.05	1	0	0	6.17	5.938	3.76013
9	20	0.05	0	1	0	0.12	0.132	−10
10	20	0.05	1	1	0	0.04	0.0393	1.75
11	20	0.05	0	0	1	0.5	0.49	2
12	20	0.05	1	0	1	0.08	0.076	5
13	20	0.08	0	0	0	1.93	2.092	−8.39378
14	20	0.08	1	0	0	4.17	3.075	26.25899
15	20	0.08	0	1	0	0.1	0.109	−9
16	20	0.08	1	1	0	1.43	1.373	3.986014
17	20	0.08	0	0	1	0.34	0.429	−26.1765
18	20	0.08	1	0	1	0.02	0.024	−20
19	25	0.032	0	0	0	7	6.625	5.357143
20	25	0.032	1	0	0	4.76	4.894	−2.81513
21	25	0.032	0	1	0	0.18	0.219	−21.6667
22	25	0.032	1	1	0	0.16	0.159	0.625
23	25	0.032	0	0	1	0.91	0.791	13.07692
24	25	0.032	1	0	1	0.03	0.027	10
25	25	0.05	0	0	0	5.52	5.66	−2.53623
26	25	0.05	1	0	0	5.66	6.044	−6.78445
27	25	0.05	0	1	0	0.63	0.568	9.84127
28	25	0.05	1	1	0	0.05	0.041	18
29	25	0.05	0	0	1	0.76	0.664	12.63158
30	25	0.05	1	0	1	0.05	0.047	6
31	25	0.08	0	0	0	4.71	4.246	9.85138
32	25	0.08	1	0	0	3.27	3.718	−13.7003
33	25	0.08	0	1	0	0.31	0.362	−16.7742
34	25	0.08	1	1	0	1.24	1.25	−0.80645
35	25	0.08	0	0	1	0.64	0.523	18.28125
36	25	0.08	1	0	1	0.08	0.079	1.25
37	31	0.032	0	0	0	3	3.823	−27.4333
38	31	0.032	1	0	0	4.84	5.052	−4.38017
39	31	0.032	0	1	0	0.35	0.368	−5.14286
40	31	0.032	1	1	0	0.38	0.331	12.89474
41	31	0.032	0	0	1	0.64	0.732	−14.375
42	31	0.032	1	0	1	0.48	0.471	1.875
43	31	0.05	0	0	0	5.05	4.479	11.30693
44	31	0.05	1	0	0	5.88	6.255	−6.37755
45	31	0.05	0	1	0	0.57	0.472	17.19298

Table 3: Continued.

Training data number	Cutting velocity, V_c (m/min)	Feed (mm/rev)	Cooling applied	Use of back up plate	Edge beveliing	Measured burr height (ΔM) (mm)	NN estimated burr height (ΔS) (mm)	Percentage of predication error $\frac{\Delta M - \Delta S}{\Delta M} \times 100$
46	31	0.05	1	1	0	0.14	0.139	0.714286
47	31	0.05	0	0	1	0.78	0.734	5.897436
48	31	0.05	1	0	1	0.48	0.358	25.41667
49	31	0.08	0	0	0	4.2	4.64	−10.4762
50	31	0.08	1	0	0	5.31	5.27	0.753296
51	31	0.08	0	1	0	0.64	0.452	29.375
52	31	0.08	1	1	0	0.35	0.449	−28.2857
53	31	0.08	0	0	1	0.44	0.423	3.863636
54	31	0.08	1	0	1	0.07	0.079	−12.8571

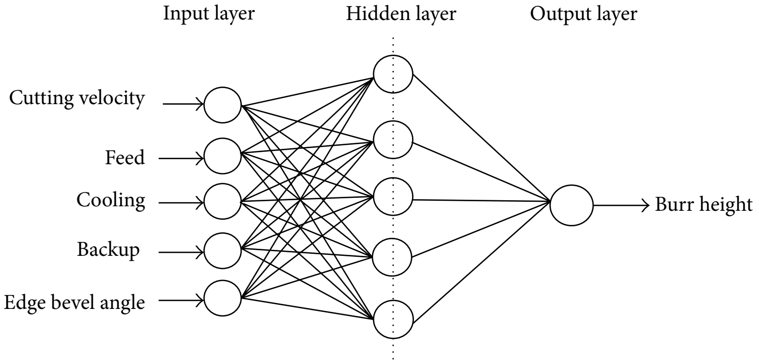

Figure 15: Architecture of artificial neural networks used.

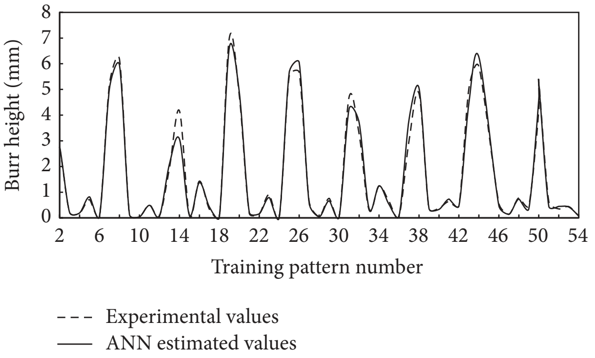

Figure 16: Experimental and ANN estimates of burr height for training patterns.

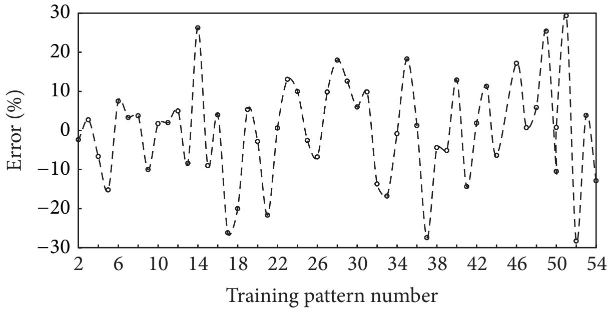

Figure 17: Experimental and ANN estimates of burr height in percentage of error.

force/torque needing reduced back-up support. This possibly causes suppression of burr formation to a large extent. Application of water cools down the tool and workpiece. This reduces plastic deformation resulting in further lowering of the chance of formation of large burrs.

(iv) Within the experimental domain, hole-making at cutting velocity 20 m/min and feed 0.08 mm/rev using 14 mm drills and 31° exit edge bevel gives minimum burr under water-cooled condition. In this case, burr height as low as 0.02 mm is achieved. Hence, this condition may be recommended to obtain negligible burr.

(v) The three-layer neural networks algorithm is applied to model the experimental data, and the model estimates are seen to have close matching with the observed burr height with small deviations, thereby showing the possibility of using the model for estimation of burr height within the domain of experimentation.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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