Potential Prediction of Burr Formation in Drilling Based on Acoustic Emission

Z. Katz and N.A. Lukoto*

A method for predicting burr formation in drilling using an acoustic emission (AE) based technique is proposed and tested. The model development is based on drilling with and without burrs using standard twist drills. The objective of the work is to enable on-line prediction of burr formation and appearance. Tests were performed in aluminium and steel. Data obtained was analysed and compared. The experimental set-up is described and the analysis of AE signals is explained, formulated and applied. From the analytical model, the effects of drilling conditions such as feed, work piece material and drill diameter were studied. This resulted in the establishment of empirical type AE equations which incorporate drilling parameters. The ability of burr prediction can be used to control drilling parameters on-line, according to AE values.

Key Words:

Acoustic emission (AE), burrs, drilling

1. Introduction

The drilling burr formation is one of the most common encountered problems in the drilling process, especially in the era of factory automation and advanced systems technology [Kim and Dornfeld, 2000, Takeyama and Kato, 1991].

Burrs are among the most troublesome obstructions to high productivity, accuracy, assemble ability and automation of machining processes in manufacturing industry [Gilespie, Blotter,1976]. As a result, deburing and burr minimization technology have become more important. The basis of strategies to reduce or prevent burr formation is a clear understanding of the mechanism of the burr formation (Hashimura, Chang and Dornfeld, 1999)

Many experimental and theoretical research on drilling burrs have been conducted {Nakayama 1987]. In such studies, a key research task is to investigate the relationship between drilling conditions and geometrical features of drilling burrs (Kim and Dornfeld, 2000, Nakao and Watanabe, 2004, Choi, Min and Dornfeld, 2004).

Selecting process parameters according to workpiece material and hole quality requirements, is critical for the minimization or prevention of burr formation. However, analytical models for the interaction between process conditions, material properties and burr formation are limited. Some analytical models and several empirical models from extensive experimental tests have been developed for several materials (Katz and Lukoto,2004, Choi, Min and Dornfeld, 2004).

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Acoustic emissions based techniques, because of their sensitivity to displacement or velocity, can detect the released energy and are the most promising for non-destructive investigation of mechanical systems. An AE signal generated in a metal, conveys useful information about the fatigue behavior of a specimen (Emamian, Kaveh and Tewfik, 2000).

The level of AE signal measured, could recognize the events as they happen to the workpiece and tool during machining. This is usually differentiated when other parameters exceeds the predetermined threshold (that is the value that usually determines the expected results). The level of AE signal would, however, most likely depend on the cutting conditions, the combination of tool and work material, and the sensitivity of the measuring equipment (Moriwaki, Tobito 1990).

As waves propagate in metals under stress, the frequency at which the waves propagate leads to the possibility that in machining, wave propagation can be used as a means to study processes such as burr formation. Acoustic emission data are digitized, stored in permanent recording of tests, and used at anytime for re-evaluation.

The first reports on applied acoustic emission to monitor the machining processes were those of Iwata and Moriwaki, 1977. Their studies examined the sensitivity of AE root-mean square (RMS) energy and other AE signal parameters(frequency, intensity) to progressive flank wear in turning. Since these initial reports, continuing studies have established the effectiveness of AE-based sensing methodologies and techniques for tool condition and cutting process monitoring (Hutton, Fu, 1999).

2. The experimental setup

The experimental setup (Figure 1) was designed to secure the workpiece to the surface and to protect it from producing unnecessary background noise by rubber tap washers. The AE sensor was secured to the surface of the workpiece (a circular plate). The sensor was mounted in the center of the workpiece to be closer to the AE source and to acquire proportionality of measurements. The workplate was fixed on 4 points, equidistant to each other. AE signals could be greatly attenuated by the length and number of joints within the transmission path and the mounting location of the sensor.

All experiments were carried out using 8 mm, 10 mm and 12 mm

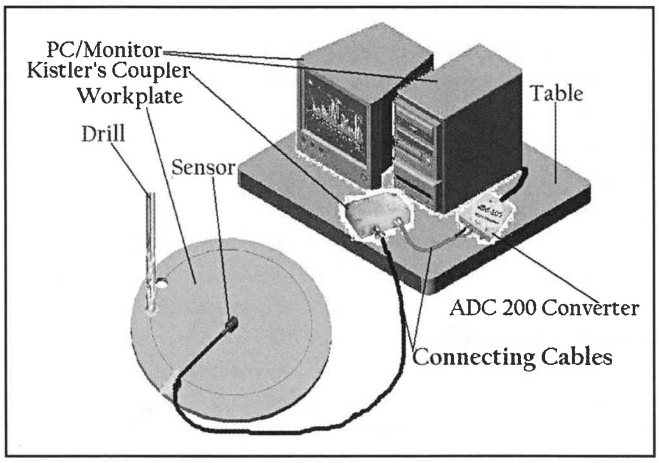


Figure 1: Experimental set-up

diameter high-speed steel conventional drills. A Kovosvit, VO32 radial drilling machine was used for drilling.

The work piece materials selected were AISI 1015 steel and aluminium grade 6082.

Each work piece has 400 mm in diameter and 10 mm thickness. The drilling tests were carried out in a test rig designed to carry a workpiece disk. Rubber tap washers were used to separate the workpiece material from any contact with the rig, thus reducing external noise effects to minimal. All drilling tests were conducted in dry conditions.

The Kistler's acoustic emission (AE)-piezotron coupler supplies the sensor and processes sound emission signals. Two output analogue signals AE-Filter and AE-RMS are transferred to the computer via the ADC converter. A Kistler's AE sensor type 8152 B was used.

Pico ADC 200 converter feeds the converted AE signals values to a computer for the examination of their characteristics of the AE signals measured through a windows based oscilloscope and data recorder.

Signals were amplified with a gain of 10 or 100 dB. 18 holes are drilled on a steel plate/workpiece before the drill replacement and 36 holes are drilled on aluminium plate before the drill is replaced. This is done to allow the drill usage for less than 1% of its total life so that the results are not affected by the propagation and influence of the tool wear.

Prior to the actual drilling of the workpiece, the AE RMS and AE filter were sampled and recorded from 3 mm before the drill penetration in the workpiece, to about 5mm after that. This was done to allow signals to adequately represent the burr formation process from its initial stages.

Drilling conditions were varied in accordance with speed, feed, drill diameters and work piece material. The experiments were divided in two phases: drilling with burrs and drilling without burrs. The differences and similarities are essential for the prediction of burrs.

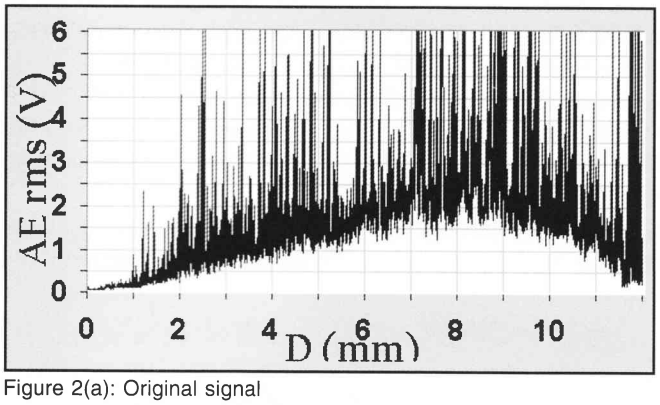


Figure 2(a): Original signal

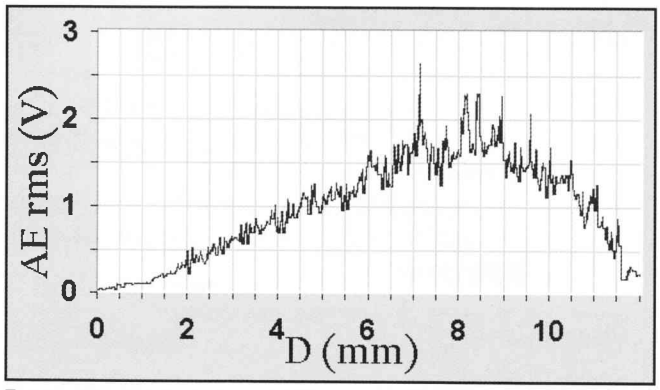


Figure 2(b): Original signal [drilling noise filtered out]

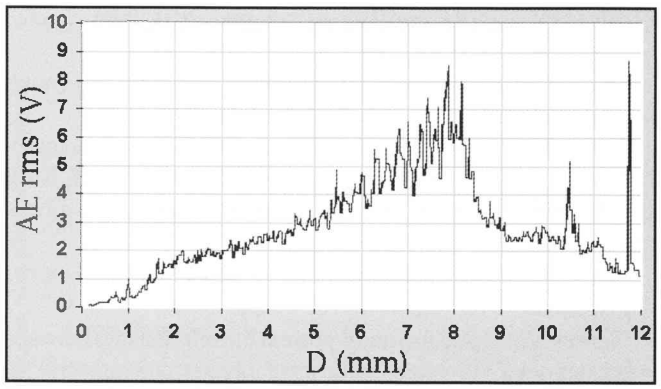


Figure 3 (a): Aluminium plate at 900rpm

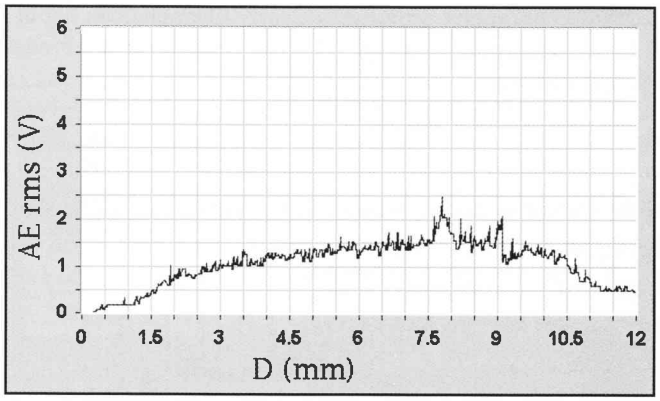


Figure 3 (b): Aluminium plate at 450rpm

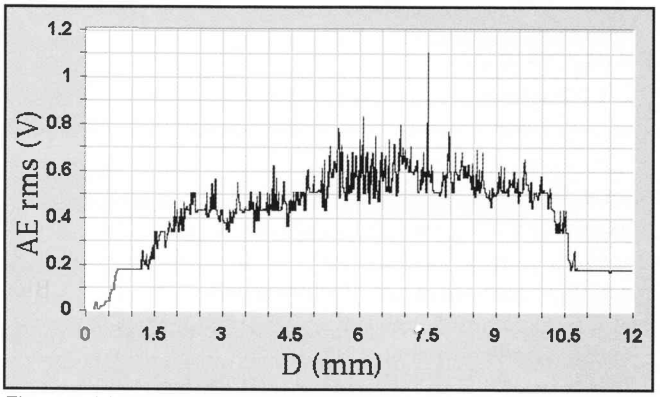


Figure 3 (c): Aluminium plate at 900rpm

3. The proposed prediction model

To address critical problems related to the prediction of burr formation, acoustic emission (AE) based techniques are viable sensing methods. The experimentation reported in this paper is divided in two phases. The first phase is aimed at understanding drilling with burrs formation. The second phase requires drilling of more holes until there are sufficient burrless holes. The AE RMS for both phases is then compared to establish a pattern, similar or different, typical for the two phases. The phases are further expanded to include two workpiece material materials; AISI 1015 steel and 6082 aluminium to establish the effects of material properties.

3.1 Experimental results and analysis

The experimental results expressed in terms of AE RMS values as recorded during the drilling operations, vary according to the specific drilling parameters used. The difficulty in comparing and analyzing AE RMS signals as recorded is evident from Figure 2(a). Therefore the minimum values of the continuous

signals of the acoustic emission as in Figure 2(b), were selected for the analysis and interpretation of results.

Figure 2(a) shows the original signal and Figure 2(b) shows the minimum average of the original signal.

Figure 2(b) shows the averages calculated using data modified by the moving minimum function indicating the AE RMS signal that is very useful for experimental studies in burr formation.

The noise caused by drill rubbing on the material is therefore removed.

Figures 3(a), 3(b), 3(c) and 4 present the relationship between speed and AE RMS values at a constant feed (0.03 mm/rev) for steel and aluminium. The acoustic emission configuration according to the speed variation is clearly illustrated. At about 7.75 mm depth of drilling (D), AE RMS peaks were observed at 900 and 450rpm.

The AE RMS peaks (maximum values readings) increase as the speed is increased. At 355 rpm such peaks disappeared.

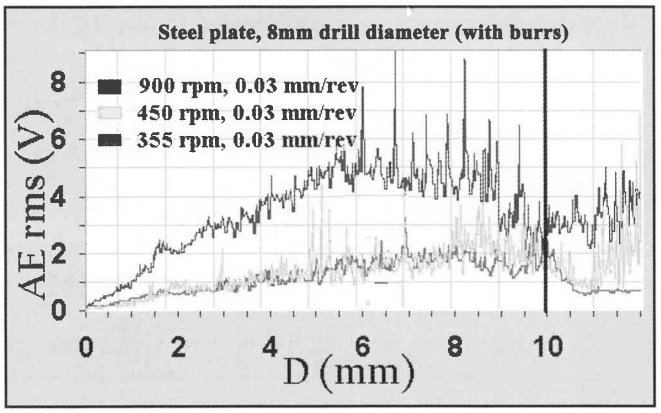


Figure 4: Impact of increasing speed for drilling of steel

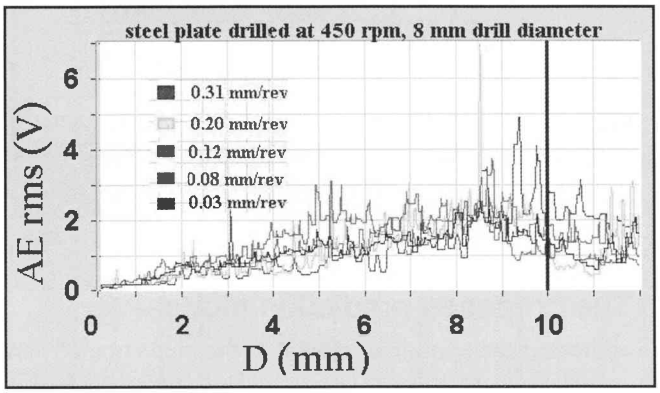


Figure 5: Typical effects of feed variation during the drilling of steel

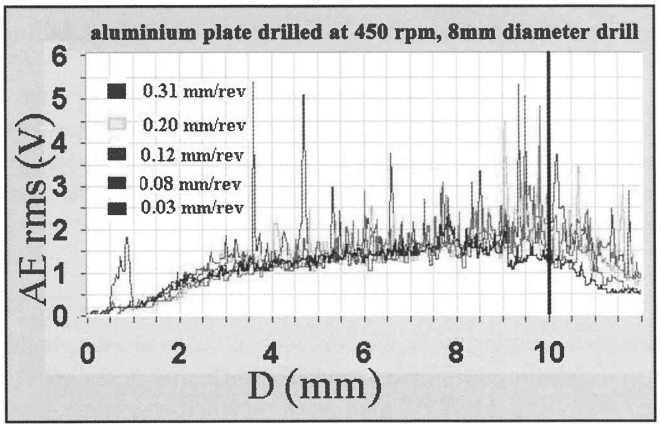


Figure 6: Typical effects in drilling of aluminium as feed is varied.

For both steel and aluminium workpieces, the AE RMS values increase as speed increases. The main differences are in the AE RMS values and the points of the maximum AE RMS values (depth of drilling).

Figures 3, 4, 5 and 6 illustrate the effects on AE RMS when drilling conditions were varied for both aluminium and steel.

The AE plots trends are presented by polylines which represent the averages in each plot (similar to the one shown in figure 7). The maximum AE RMS for each drilling conditions is represented by its locus curve as in figures 7(a), 7(b) and 7 (c).

In Figure 7(a) the maximum AE RMS increases as feed is increased.

These polylines trend-curves have unique maximum AE RMS points at distances between about a half to three-quarter of the depth of drilling (D), depending on the drilling conditions or material properties.

Figure 7(b) is derived from such trend-curves and drilling conditions that make up Figure 7 (a) and represents a typical empirical surface for AE behaviour.

The contour plot (Figure 7 (c)) determines the locus of maximum AE RMS by connecting the points for a maximum AE RMS as feed is increased.

The proposed model for prediction of burr formation involves the development of the locus of the maximum AE RMS for both aluminum and steel at various drilling conditions. The conditions for burrless drilling and drilling with burrs were then compared. Figure 8 shows the dependence of AE RMS on feed (f), speed (n) and depth of drilling (D).

3.2. Drilling Parameters

Due to the complexity of the drilling burr formation process, it is very difficult to develop accurate analytical models. Drilling burr formation is affected by material properties, drilling conditions and drill geometry and several other potential variables in a complex non linear way.

In this work, the drill geometry was fixed and the only variable related to the drill was its diameter. Other parameters are related to the feed rate (feed and speed). The AE RMS relates to the direct effects of the plastic deformation of the material in the various stages of drilling. From experiments it is observed that increasing feed rate in drilling tends to increase the AE RMS values.

Experiments have revealed that AE RMS is a function of feed rate and depth of cut and can be expressed in the form of

$$Max\text{-}AE_{rms} = \psi(f,D) \quad (1)$$

or

$$Max\text{-}AE_{rms} = k \times f^{a} \times D^{b} \quad (2)$$

Where Max-AE_{rms} is defined as the AE RMS values at the locus of the maximum AE RMS. The feed rate (f) and depth of drilling (D) are independent variables. The effect of changes in the feed rate on the AE RMS can be evaluated with constant depth of drilling, and then the influence of the feed rate on the AE RMS is be expressed as

$$Max\text{-}AE_{rms} = C_a \times f^{a} \quad (3)$$

where: $C_a = k \times D^{b}$

Similarly, the effect of changes of the depth of drilling, D (mm) on the AE RMS is evaluated by holding feed rate constant. The influence of the depth of drilling on the AE RMS can be expressed as

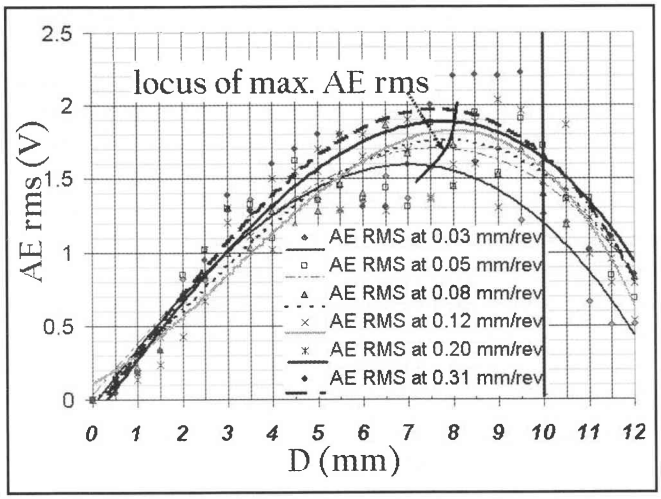


Figure 7(a): The represantation of the locus curve for aluminium plate drilled at 450 rpm, 8 mm drill diameter

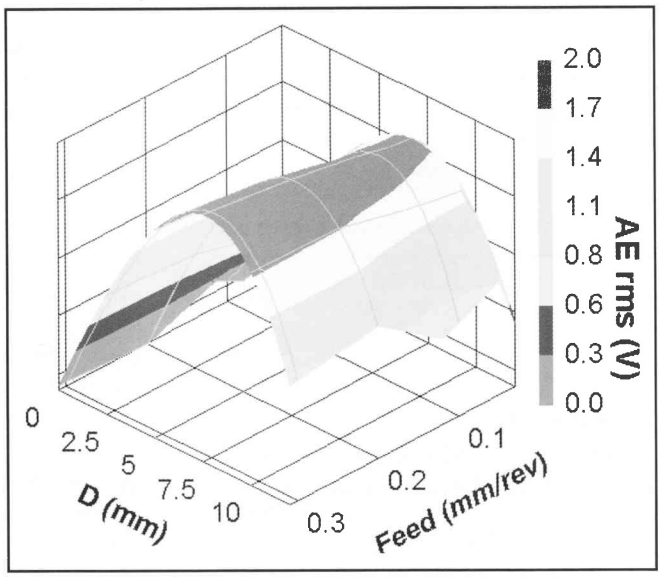


Figure 7(b): 3D represantation for aluminium plate drilled at 450 rpm, 8 mm diameter

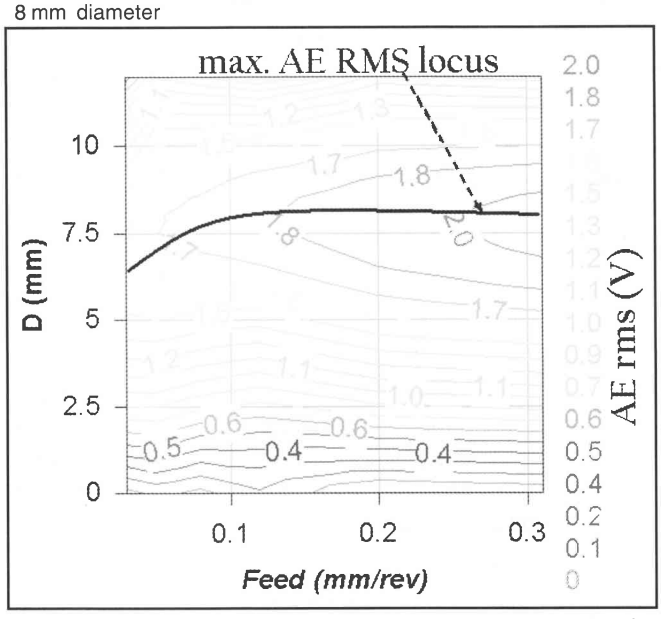


Figure 7(c): Contour plot showing the locus of maximum ae rms for drilling of aluminium

$$Max\text{-}AE_{rms} = C_b \times D^b \quad (4)$$

Where: $C_b = k \times f^a$

3.3. Control Boundaries for burr formation

The classification of the control boundaries were made according to the drill sizes used (8 mm, 10 mm and 12 mm). Each classification is representing the three conditions (Figure 9), which are most likely to create burrs, conditions for burrless drilling and conditions for general drilling (Intermediates between drilling with burrs and drilling without burrs). Signal appearing on the general drilling boundary area indicates the higher than expected AE RMS values. Drilling conditions should be changed to lower values of the AE RMS to achieve burrless drilling.

Table 1 shows an set of constants obtained from experimental data for the classification of burrs formation.

k, a and b were found empirically for the different cases.

8 mm drill	Steel	Aluminium
Drilling Constants		
Drilling with burrs		
k	0.0006	0.0014
a	2.542	0.0993
b	0.7018	1.8357
Drilling without burrs		
k	0.0057	0.0412
a	1.7183	0.7441
b	0.7391	0.9447

Table 1: Empirical values for model's constants

Figure 9 is obtained from equations 3 and 4 and their combination produces equation 2. Figures 10 and 11 show 3D plots (steel work-piece drilled with and without burrs formation).

It has been verified experimentally that drilling with burrs produces a higher intensity of AE RMS signal than drilling without burrs. Conditions for burrless drilling will then always

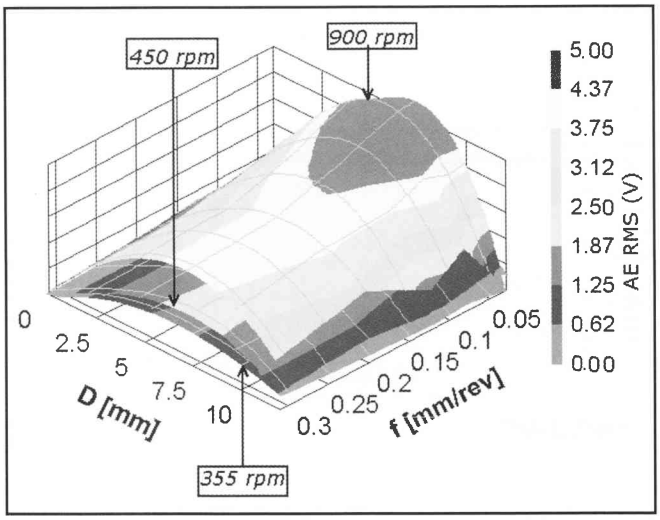


Figure 8: 3D represantation of ae rms in aluminium with 8 mm d drill (with burrs)

form an important boundary for prediction of burr formation.

The flowchart in Figure 12 illustrates how a burr formation prediction process can be applied in an automated system. Inputs are feed rate (f) and drill diameter (d). The boundary conditions can be validated by comparing them with the experimental results. An example of an analytical model for predicting burr formation is shown in Figure 13.

In order to show the validity of the proposed model for prediction of burr formation, experiments were conducted to investigate the influence of feed rate and drill diameters.

Figure 13 shows the experimental data that validates the analytical model to predict burr formation. It covers data for only one particular case (drilling at 21.3 mm/min) whereas figures 10 and 11 covers data for all the cases involving 8 mm drill and a 10 mm thick AISI 1015 steel work piece.

Burrs may form in a metal due to various reasons. When the material is drilled at low feed and high speed, the time to drill the hole through the work piece material is longer and the temperature increases rapidly to reach hardening stage temperatures. When a new hole is being drilled within the close proximity to the hole drilled at a higher speed, and at very low feed, temperature of the work material in this vicinity tends to increase more rapidly than when the feed is higher and speed lower.

Figures 14 and 15 show that an increase of the drill diameter has an effect on AE RMS due to the fact that the volume of material to be removed is increased and more energy is required. This is also proved experimentally as indicated previously.

4. Summary

The concept of possible prediction of burr formation and burrless condition in drilling was presented. The experiments proved that burrless drilling as a similar process as is drilling with burrs, because both are subject to variation in drilling conditions.

The proposed model has shown good quantitative predictions for a range of drilling conditions.

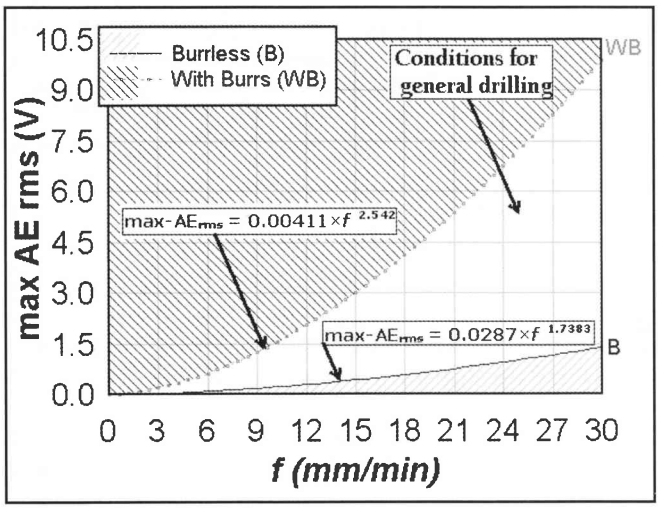
The dependence of AE RMS signals on drilling parameters and work material, establishes a pattern were burrless drilling and drilling without burrs can be defined.

Simpler empirical equations including most practical variables in the experimental analysis have been presented.

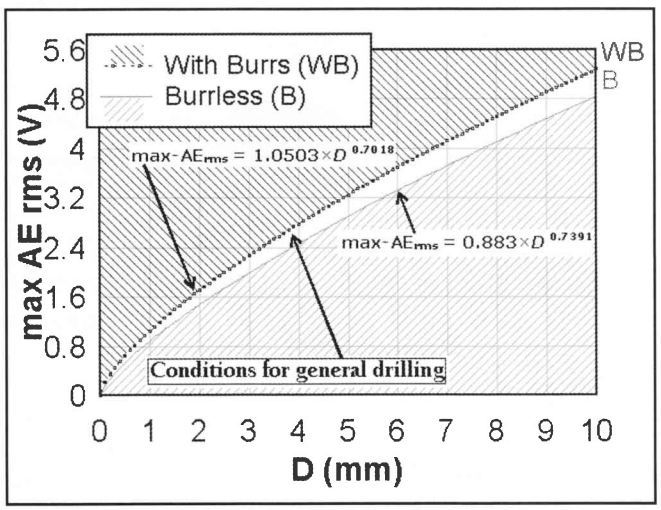
The empirical results confirm that each test can be examined independently and prediction of possible burr formation conditions can be done on-line.

The experimental procedure and the empirical results are indicative of the relationships between the variations of drilling parameters and the burrs formation and behaviour. The results clearly point to the specific behaviour of the recorded acoustic emission values and process variables such as feed rate, speed, diameter and work piece material (Figures 13,14,15 etc.).

In a practical manufacturing environment, those relationships could be used on line for control and optimization of parameters for the reduction or avoidance of burrs formation in drilling.



(a) Constant depth of drilling



(b) Constant feed rate

Figure 9: Control boundaries plot for steel , 8 mm drill diameter

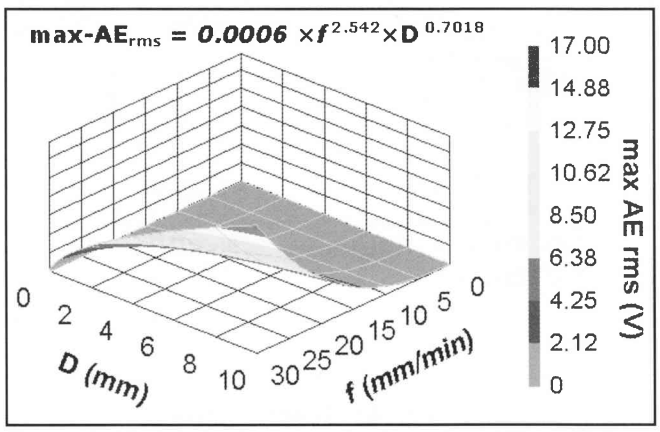


Figure 10: 3D plot showing ae rms values when drilling with burrs (8 mm drill)

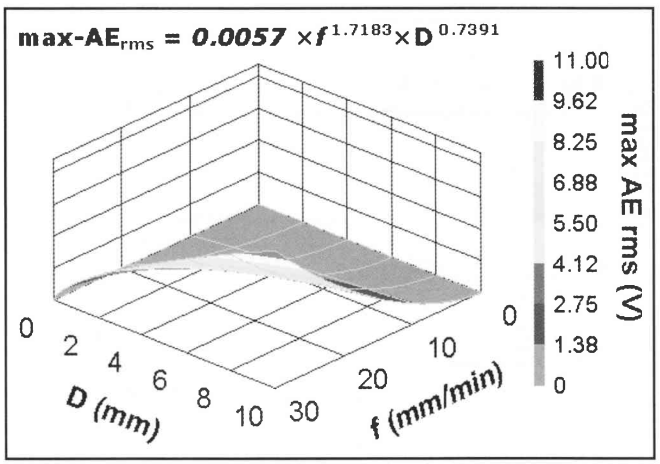


Figure 11: 3D plot showing ae rms values for burrless drilling of steel(8 mm drill)

4.1 Advantages of the model

AE RMS data are digitized and stored on a computer, providing permanent recording for the test results to be used at anytime for re-evaluation and post processing analysis.

The AE RMS data may appear as points, each representing a sample. Few of those samples are scattered above the normal average and can be easily isolated. Programming and statistical analysis is possible to remove the undesired signals to achieve clearer results. Because of the fast detection rate of AE signals, rapid detection of burr formation or appearance is practically possible.

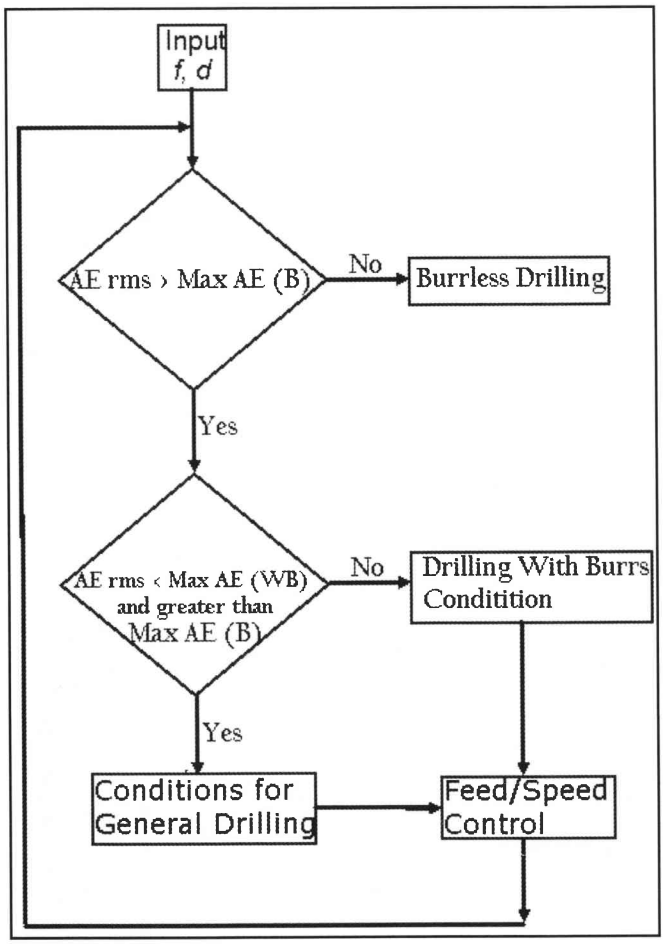


Figure 12: Flowchart for the basic model for burr prediction

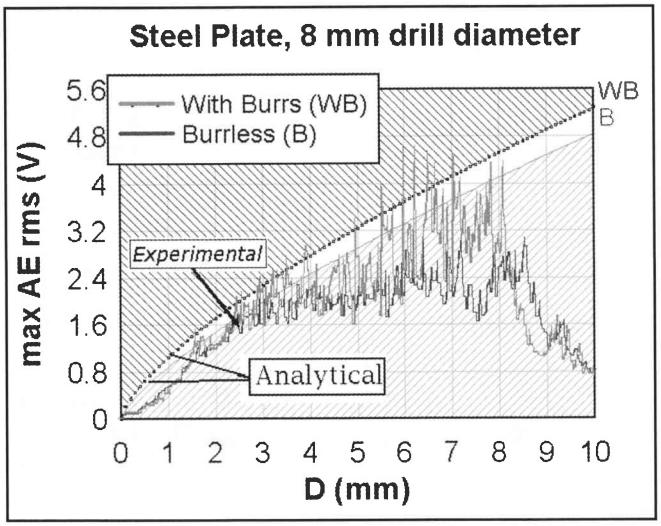


Figure 13: Comparisons of analytical and experimental data (drilled at 21.3 mm/min)

4.2 Disadvantages of the model

Currently, there are no general standards that deal with burr formations. Many researched have tried often to use the thrust force, as a way of trying to find a more acceptable basic reference parameter.

At high feed rates, the sampling rate is reduced and the AE RMS may be limited because of the instrument's AE RMS output voltage limits. Figure 16 shows a case where AE voltage is limited to 9.4 V and no signal above that figure could be recorded unless special setting is made to the measuring instrument.

Figure 17 indicates the decrease in sampling rate as the feed rate is increased.

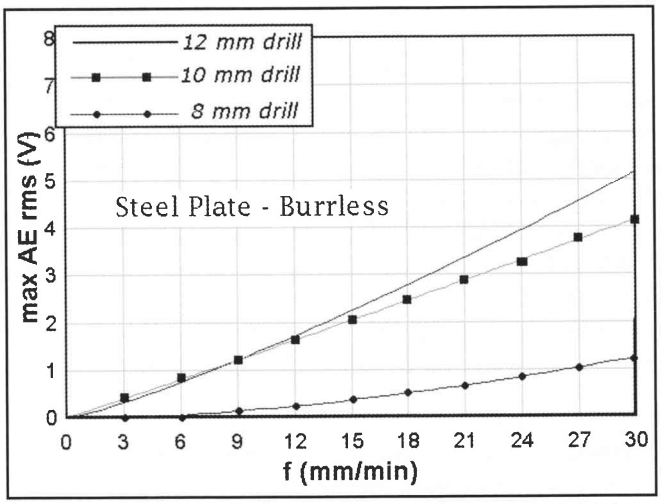


Figure 14: The effect of drill diameter for drilling aisi 1015 steel

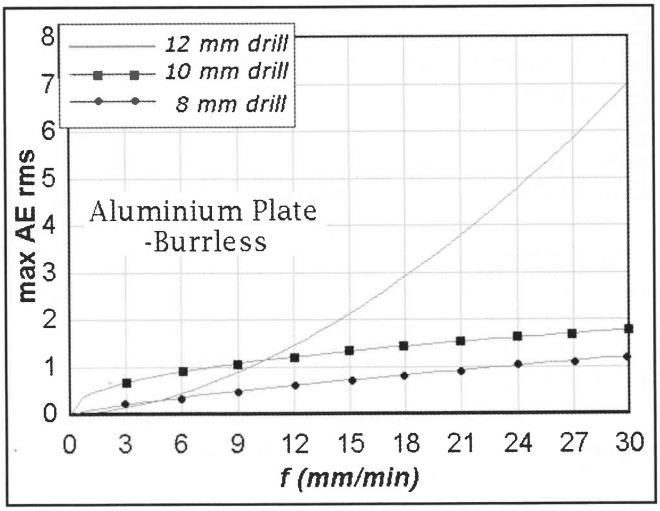


Figure 15: The effects of drill diameter for drilling type 6082 aluminium

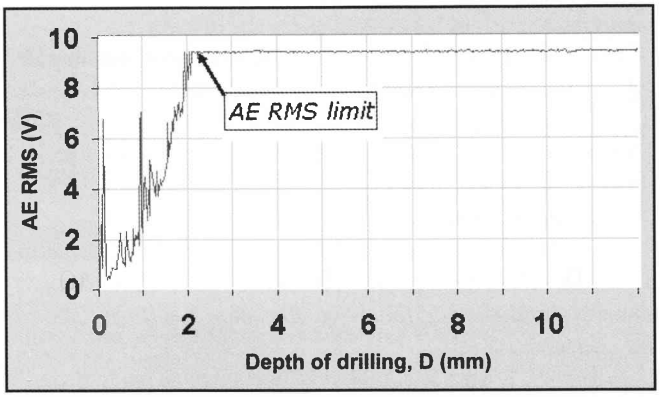


Figure 16: AE rms when drilling aluminium plate at 140 (mm/min)

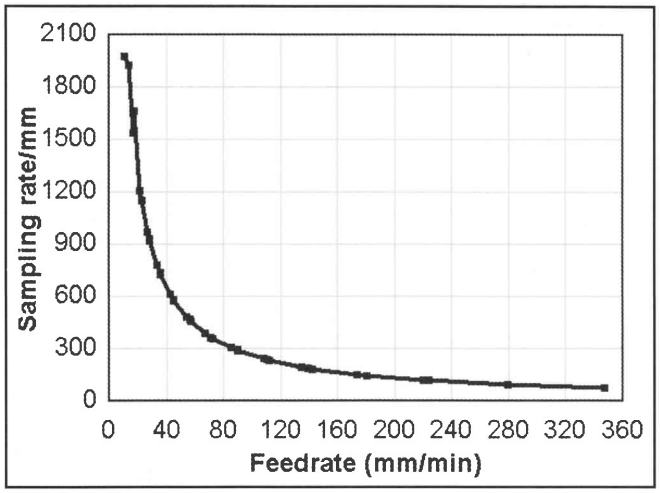


Figure 17: Sampling rate vs feed rate

5. Conclusions

A model for predicting burr formation presented in this work, indicates that drilling parameters can be automatically adjusted on line according to AE RMS used to detect conditions for burr formation.

Further study is required to understand the effect of feed-rate of same magnitude but with different feed and speed.

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