Eng. &Tech.Journal, Vol.34,Part (A), No.6,2016

Burr Formation Mechanisms During Drilling Operations Of Low Carbon And Stainless Steels

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Received on:7/9/2015 & Accepted on:20/1/2016

ABSTRACT

In drilling operations, burrs cause many problems for product quality and functionality. Therefore, understanding of burr formation mechanism is essential in order to reduce the deburring cost by reducing burr formation. Also, to avoid or minimize the burr formation during drilling, it is necessary to realize the relationship between the burr formation mechanism and the cutting parameters involved in the machining operations. Therefore, this research is an attempt to investigate experimentally the influence of using a wide range of cutting speeds, feed rates, and depth of cuts on the burr formation mechanism in drilling operations of low carbon and stainless steels plates using HSS cutting tools and cutting fluids. Additionally, this study was focused on the effect of these cutting parameters on the burr size and type. Thus, the average heights of exit formed burrs were measured at different machining conditions. Two types of burr mainly formed and observed (transient and uniform burrs) during drilling both steels. Accordingly, two types of burr formation mechanism related to these observed types of burr were explained. It was found that the average burr height for both steels generally reduced with increasing cutting speeds and feeds due to the change of burr type from a transient burr at lower cutting speeds and feeds to a uniform burr with and without a drill cap at higher speeds and feeds. Finally, no crown burr type formed and observed during drilling both steels in comparison with previous works.

Keywords: Drilling Operation, Burr Height, Burr Formation Mechanism, Low Carbon steel, Stainless Steel

INTRODUCTION

Machining burrs are considered as unwanted materials or undesired projections remaining after almost all machining operations, including drilling, milling, and turning. They form in these operations at the exit of a cutting edge upon completion of a machining operation as a result of plastic deformation of metals, incurred by the cutting edge. Burr formation at the end of a cut is a phenomenon similar to the formation of chips. Its formation not only degrades part accuracy and quality but also hampers part handling and assembly. So, they usually reduce the quality of the material parts and may cause interference with subsequent assembly operation. Because of their sharpness, burrs can be hazard to personnel [1].

There are many solutions and attempts that have been made regarding the burr formation problems, but none of them offers a complete solution. Therefore, many parts in the automotive and aerospace industries require deburring, which is a tedious, non-productive process that consumes 15-30% of the total machining cost. Therefore, burr elimination and minimization are gaining increased importance in industry and research **[1].** Thus, efforts in the field of deburring have been intensified lately. Due to increasing costs and higher quality requirements in manufacturing, there is a need for deburring procedures that are fast and of high quality, at reasonable costs. Also, due to increasing demands on high part accuracy and low production time, there is a great deal of interest around the world in studying the mechanisms of burr formation **[2]**, the strategies for burr prevention **[3],** and the methods for deburring.

Burr sizes must be controlled for the optimal choice of a deburring process or cutting parameters for burr minimization. One of the ways to solve this problem is to make analytical models **[4-9]** of burr formation processes. However, this approach requires a clear understanding of burr formation mechanism, which can be attained by experimental observations of burr development process. Burrs are formed when a drill enters and exits the hole. Burr is a plastically deformed material generated during cutting. The drilling process produces burrs on entrance and exit surfaces of the workpiece. The entrance burr forms on the entrance surface as material near the drill undergoes plastic deformation. The exit burr is a part of the material extending off the exit surface of the workpice. It is important as it is larger than the entrance burr in size and is most difficult to remove causing deburring problems. The magnitude of burr can be defined by its height. Therefore, the present work of this paper has only concentrated on the exit burr as in previous studied that have focused their attention on the exit burr **[10, 11].**

Exit burrs have been previously classified into different types by many researchers **[12-14]** during drilling various materials, such as titanium, aluminum, brass, low carbon steel, and stainless steel alloys at different cutting conditions. In conventional drilling, the feed and speed assist to establish the shape and the sizes of the exit burrs. In drilling low carbon and stainless steel alloys **[12],** three main types of exit burr have been recognized as uniform burrs, transient burrs, and crown burrs, as shown in **Fig.(1).** A uniform burr is usually formed at low feed rates and speeds and is generally small having a uniform cap along the hole perimeter, whereas a crown burr is generally formed at higher feeds and speeds and is characterized by large flake. A transient burr (uniform burr without cap) is a blend or more like a combination of uniform burr and crown burr.

It is important to study experimentally the mechanism of the exit burr formation to develop the effective drilling technique. The process of drilling exit burr formation can be divided into following three different stages: work material plastic deformation, bulge development at the bottom surface of the workpiece, and tearing the material beneath the chisel edge due to the maximum elongation and bending the remaining material to become the burr, as shown in **Fig.(2) [15].** Min et. al. **[16]** explained the mechanism of burr formation in drilling low alloy steel, AISI 4118. As the drilling depth increases, the deformation accumulated at the bottom of the hole also increases.

Previously, different models have been developed to determine the burr formation mechanism in orthogonal cutting in drilling different materials. In Park's model **[17]** using a two-dimensional finite element method in drilling stainless steel 304L, the burr formation mechanism was divided into four stages: burr initiation, development, initial fracture, and final development of burr. Guo and Dornfed **[6]** described the burr initiation stages by using a finite element model and concluded that when the drill tip approaches the bottom edge of the workpiece, the burr initiation stage begins with local plastic deformation. Later, Dornfeld **[7]** proposed a new model that considers more parameters and classified the burr formation mechanism into four stages: initiation, development, pivoting, and final burr formation. While in recent models **[18-20],** the burr formation mechanism was divided into five categories. The stages are: steady state drilling burr, initiation, development, initial fracture, and final burr, respectively, as shown in **Fig. (3).**

Quantitatively, particular attention has been focused on burr formation mechanism and analysis in previous studies **[21]** during drilling and milling operations of aluminum and its alloys, since they are considered easy-to-machine materials. However, a few researches **[22, 23]** have been carried out to study the burr formation mechanism during drilling and milling operations of low carbon and stainless steel alloys. Therefore, the aim of this research is to establish the link between the burr formation mechanism and burr characteristics (its shape and size) at different cutting conditions. So, this paper is devoted to the study experimentally some aspects of the burr formation process in drilling operations of low carbon and stainless steel alloys at different cutting parameters (cutting speeds, feed rates, and depth of cuts) to understand the burr formation in the simple case and to describe the burr formation mechanism.

Burr formation is normally considered as a very complicated process in metal cutting, and its formation mechanism has not yet been fully revealed. In recent years, some researchers **[5-7]** have started to study the burr formation mechanism by using the finite element method to simulate, analyze, and model the burr formation processes. However, there have been some studies on the burr formation mechanism which are dependent on the experiment. Also, only a few studies **[8, 9]** have been carried out on the mechanism of burr formation and the influence of the cutting parameters to assist in the reduction of burrs and the production of free burr components. Therefore, the aim of this research is to establish the link between the burr formation mechanism and burr characteristics (its shape and size) at different cutting conditions. So, this paper is devoted to the study experimentally some aspects of the burr formation process in drilling operations of low carbon and stainless steel alloys at different cutting parameters (cutting speeds, feed rates, and depth of cuts) to understand the burr formation in the simple case and to describe the burr formation mechanism.

Experimental Work

The work materials investigated in this work are hot rolled low carbon steel (LCS), St37, and cold rolled stainless steel (SS), AISI 316 and both materials are in the annealed condition. These materials were selected because they are widely used in industry for production purposes by drilling operations. They are supplied with the chemical compositions and mechanical properties given in **Table (1)** and **Table (2)**, respectively. Two rectangular plates were prepared from these materials for drilling tests to study the burr formation mechanisms in drilling operations. The dimensions of each plate are 200 mm length, 130 mm width, and 9 mm thickness. Prior to testing, these plates were surface cleaned by a face milling operation to remove the surface oxide and to flatten the upper and lower surfaces for each plate for measuring purposes.

Drilling tests for both low carbon and stainless steel plates were first carried out using 12.5 mm diameter high-speed steel (HSS) conventional twist drills in order to obtain burrs with larger sizes for measuring purposes at different cutting speeds and feeds.

All drilling tests were performed on a CNC drilling machine WMW Machinen-kuzzeichen. A water-soluble coolant (a soluble oil, which is an oily emulsion freely miscible in water) was used as the cutting fluid during drilling low carbon and stainless steels. This cutting fluid is commonly used as a coolant for lubricating and cooling purposes by reducing the harmful influences due to friction and high temperatures during drilling processes**.**

The cutting conditions considered in drilling tests were cutting speed and feed. The cutting parameters ranges used in this work are listed in **Table (3)** for drilling stainless steel and low carbon steel, respectively. These parameters were selected according to the past experience of using high-speed steel (HSS) cutting tools and also to the general recommended working ranges given for speeds and feeds used for these tools in drilling operations of low carbon and stainless steels **[24].** During each test, only one parameter was varied at a time the one under study its effect on burr formation and its size, while the other parameters were kept unchanged.

Burr measurements are considered one of the main challenges in burr research due to their complex and irregular shape and size. It is usually very difficult to be measured accurately.

Therefore, burr values are collected from the edge surface of a workpiece for burr height and thickness by dividing the surface into several parts. In each of these parts, the distance of the highest peak to the deepest valley is measured. Then, the average of these is taken. This gives a good picture of the achieved edge quality in the direction of the burr height and thickness **[25].**

There are several methods available to measure the geometry of the burr specifically burr height and thickness since they are the most frequently and easily measured burr quantities **[14].** These methods can be divided into contact and non-contact method. Generally, in a contact method, a stylus and height gaga are used to measure the burr geometry **[26],** whereas, the non-contact method is subdivided into optical **[14],** optimal CMM, laser and white light method **[27],** and the image processing technique **[28, 29].**

For a given set of cutting conditions, the burr size obtained in drilling tests was highly variable. Then, the average heights of the exit burrs produced in drilling were measured. A large number of measurements were made for each single test in order to obtain reliable results. The burr height was used as a burr size indicator in the present study to take easily a large number of measurements. At the hole exit, the height of the burr was measured with a CMM measuring machine (resolution of 0.001 mm). The stylus was first referenced to the plate surface next to the hole. Then, the stylus was swept slowly towards the periphery of the hole till reaching the top of the burr. The largest value registered on a digital display was taken as the burr height at that point. Eight points were taken on the border of the hole at 45^{o} angles. Differently from the described systems used by others, the stylus of the machine can deform the burr and lead to small errors that are neglected here. Therefore, the results reported were the average of 8 measurements for the height of the exit burrs formed at different positions for each hole in the drilling tests.

Results and Discussion

Burr Formation Mechanism In Drilling Tests

All experimental drilling tests of stainless and low carbon steels were conducted using the approach of changing one variable (either cutting speed or feed) at a time, as shown in the photographs in **Figs. (4) and (5),** respectively. In the present work, two types of exit burrs mainly formed during drilling stainless steel (AISI316) and low carbon steel (ST37) at different cutting speeds and feeds. These are: a transient burr type and a uniform burr type with or without a drill cap. Therefore, two types of burr formation mechanism can be explained in terms of the applied cutting conditions, since the transient burr type formed at lower cutting speeds or feeds, whereas the uniform burr type formed at higher cutting speeds or feeds after drilling both steels.

The burr formation mechanism of the transient burr at lower speeds or feeds involves the following stages, as manifested in the photograph in **Fig.(6)** :

i) First stage initiates due to plastic deformation by the exerted thrust force, distorting the shape of the material.

ii) Second stage starts with a fracture by the crack initiation due to the excessive thrust force with induced tensile stress in the material that contacts the drill cutting edge.

iii) Third stage in which the transient burr formed around the exit hole edge, producing a rigid higher burr around the hole edge. Sometimes, this burr breaks into small pieces that either remained adhered to the exit surface or detached away. This observation agrees with that seen in Ref. [14].

While, the burr formation mechanism of the uniform burr type formed at higher speeds or feeds include the following stages, as shown in the photograph in Fig.(6):

i) First stage begins with a primary shape distortion of the material due to the effect of thrust force associated with the heat generated during the drilling process.
ii) Second stage commences with a crack initiation, ending with a fracture by bending stress either at the front of the tool bit (forming a uniform burr without a drill cap) or around the exit hole edge (producing a uniform burr with a drill cap adhered to the exit surface).
iii) Third stage in which burr formed around the exit hole edge, leading to a drill cap formation. This observation is similar to that noticed in Ref. [14].

Effect of Cutting Conditions on Drilling Burr Formation Mechanism:

Effect of Cutting Speed

Drilling tests were conducted to drill both stainless steel and low carbon steel test specimens at five different cutting speeds, while the feed was kept constant during each test. At the end of each test, the average burr height was measured, and the type of burr was identified according to its formation mechanism. The photographs shown **in Fig.(4)** and **Fig.(5)** exhibit the drilling burrs formed in stainless steel and low carbon steel, respectively. The effects of increasing cutting speed on the average burr height at a constant feed in drilling both materials are depicted in **Fig.(7)** and **Fig.(8)**, respectively. These figures indicate that the average burr height for both steels is generally reduced with increasing drilling speed due to the variation of burr type from a transient burr at lower cutting speed to a uniform burr with a drill cap at higher speed.

This result is attributed to the difference in the burr formation mechanism at lower and higher cutting speed. At lower cutting speed, the transient burr type with larger size formed due to the crack initiation by plastic deformation caused by the excessive thrust force, leading to fracture occurrence in the material in front of the drill tool bit or alongside the tool cutting edge. While, at higher cutting speed, a uniform burr type with a drill cap in smaller size formed by the crack initiation due to the influence of both higher plastic deformation caused by excessive heat generated during cutting and thrust force, resulting in a fracture in the material around the exit hole edge and leading to a drill cap formation either adhered to the exit surface or detached away, forming a uniform burr type without cap. Therefore**,** it can be concluded that the heat generated during cutting associated with the thrust force with increasing cutting speed plays a big role in varying the type of formed burr from a transient type to a uniform type, and this, consequently, changes the burr formation mechanism. It should be pointed out that in the present work, no crown burr type such that seen in Ref. [14] formed at the end of all drilling tests over the whole cutting speed range used for each material, due to most likely the ductility effect of both steels.

Effect of cutting feed

The test specimens of stainless steel and low carbon steel were drilled at different five feeds, whereas the cutting speed was remained unchanged during each test (see the photographs in **Fig.(4)** and **Fig.(5)**), respectively. For both materials, the average burr height was measures at the end of each test, and the type of formed burr was identified. The influence of feed on the average burr height in drilling both steels at a constant cutting speed are illustrated in **Fig.(9)** and **Fig.(10)**. It can be seen from these figures that the average burr height reduced with increasing cutting feed, and the type of burr varied from a transient burr type at lower feeds to a uniform burr type with a drill cap at higher cutting feeds.

This finding is ascribed to the difference in the burr formation mechanism at lower and higher cutting feed. Cutting at lower feed means exerting less thrust force and less material to be removed (e.g., lower chip thickness). Thus, the crack will initiate by plastic deformation of the thinnest part of the removed material by tensile stress. This will result in a fracture which is most likely at the drill cutting edge, leading to formation of a transient burr type with larger size. In contrast, drilling at higher cutting feed refers to excessive thrust force to be exerted and more material to be removed (e.g, higher chip thickness). Therefore, the crack initiates by severe plastic deformation of the material, causing a fracture by bending stress either at the front of the drill tool bit (in case of formation of a uniform burr type without cap) or near the exit hole edge (in case of formation of a uniform bur type in smaller size with a drill cap adhered to the exit surface). Accordingly, it can be deduced that the exerting thrust force associated with type of the induced stress with increasing the cutting feed has a major influence on the type of formed burr form a transient burr type to a uniform burr type with or without a drill cap, and this will alter the burr formation mechanism during drilling both at lower and higher speed. No crown burr type was formed and observed during drilling both steels over the entire feed range utilized for each material, and that could be owing to the ductility influence of both alloys.

CONCLUSIONS

1-Two types of exit burrs mainly formed during drilling stainless steel (AISI316) and low carbon steel (ST37) at different cutting speeds and feeds. These are: a transient burr type and a uniform burr type with and without a drill cap.

2-Two types of burr formation mechanism were explained in terms of the applied cutting conditions; transient burr type formed at lower cutting speeds or feeds, and uniform burr type formed at higher cutting speeds or feeds after drilling both steels.

3-The average burr height for both steels generally reduced with increasing drilling speed due to the variation of burr type from a transient burr at lower cutting speed to a uniform burr with a drill cap at higher speed.

4-The average burr height of both steels reduced with increasing cutting feed, and the type of burr varied from a transient burr type at lower feeds to a uniform burr type with a drill cap at higher cutting feeds.

5-No crown burr type formed and observed during drilling both steels over the entire feed and speed ranges utilized for each material as compared with previous works, and that could be due to the ductility role of both alloys.

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Table (1): Chemical compositions of the work materials (produced by the material manufacturers in wt% for each element)

Work material type	%C	%P	%S	%Mn	%Si	%Cr	%Ni	%N
Low carbon steel (ST37)	Max 0.17	Max 0.045	Max 0.045	Max 1.25	Max 0.045	~	~	Max 0.01
Stainless steel (AISI316)	Max 0.08	Max 0.045	Max 0.030	Max 2.00	Max 0.75	18.00 – 20.00	8.00 – 12.00	Max 0.10

Table (2): Mechanical properties of the used work materials

Property / Material	Yield strength (MPa) min	Tensile strength (02%proof) (MPa) min	Elongation (% in 50 mm) min	Brinell (HB) Hardness max
Stainless Steel (AISI316)	205	515	40	217
Low Carbon Steel (ST37)	210	380	25	108

Table (3): Cutting conditions used for drilling operation.

Material	Cutting speed (m/min)	Feed (mm/rev)
Stainless Steel (AISI316)	3.5 – 13.9	0.08 - 0.31
Low carbon steel (ST37)	7.0 – 27.8	0.22 - 0.90

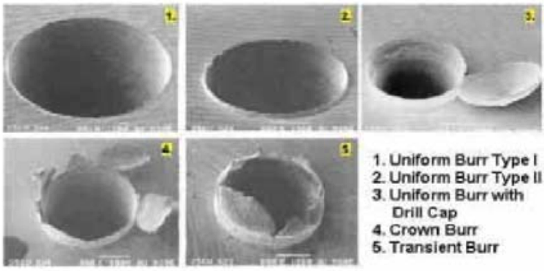


Figure. (1) Main types of drilling exit burrs [14]

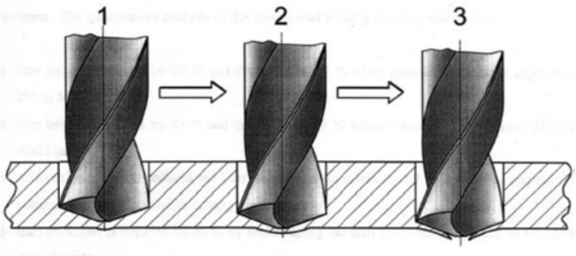
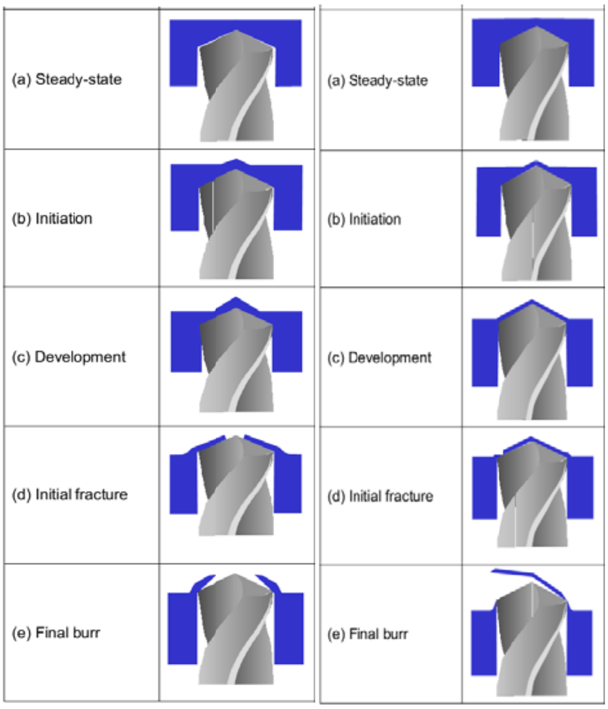


Figure. (2): Burr formation mechanism of drilling exit burr [15]



(a) (b)

Figure. (3) Burr formation mechanism stages of (a) a uniform burr and (b) a crown burr in drilling AISI 304L [11]

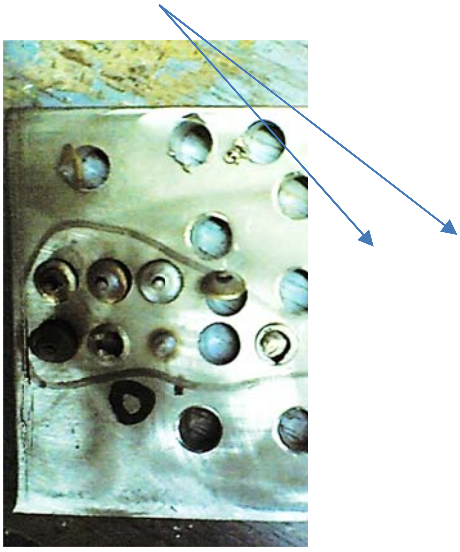


Figure. (4): Photographic

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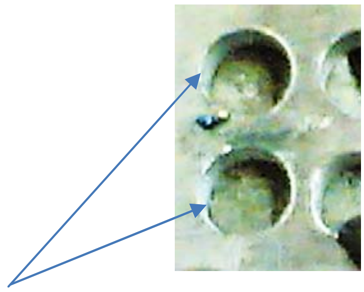

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