AN EXPERIMENTAL STUDY OF BURR FORMATION IN DRILLING AND SLOT-END MILLING OPERATIONS

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الخلاصة

يشمل هذا البحث دراسة عملية لتأثير عوامل القطع الرئيسة على تكوين البروزات الناشئة وانواعها في عمليات التثقيب والتفريز النهائي للمجاري عند تشغيل الصلب الواطئ والصلب المقاوم للصدأ بأستخدام عدد القطع من الصلب عالي السرعات وسائل التبريد. وتم التركيز على علاقة نوع البروز الناشىء ومقاسه مع عوامل القطع. ولهذا فقد تم تطبيق مديات واسعة من سرع القطع ومعدلات التغذية وأعماق قطع لغرض الحصول على أمثل ظروف قطع. وتم قياس أرتفاع البروزات الناشئة وتحليلها عند مختلف ظروف التشغيل لأيجاد تأثير سرعة القطع، معدل التغذية، وعمق القطع على تكوين البروزات الناشئة ومقارنة النتائج التي تم الحصول عليها للصلب الواطئ الكاربوني مع تلك الخاصة بالصلب المقاوم للصدأ. وأستخدمت أقطار مختلفة من المثاقب من نوع الصلب عالي السرعات لملاحظة تأثيرها على تكوين البروزات الناشئة وأعطت القياسات الكمية لأرتفاع البروز الناشئ معلومات مفيدة بسبب تكوين بروزات ناشئة صغيرة وكبيرة منتظمة نسبيا تحت هذه الظروف.

ABSTRACT

This paper presents the results of an experimental study on the influence of the main cutting parameters on burr formation and its types in drilling and slot-end milling operations to machine low carbon and stain -less steels using HSS cutting tools and cutting fluid. Particular attention was focused on the relation between the burr type and size and cutting parameters. Therefore, a wide range of cutting speeds, feed rates, and dept of cuts were investigated to explore the optimum cutting conditions. Burr heights were measured and anal- lyzed at different machining conditions to determine the effect of the cutting speed, feed rate, and depth of cut on burr formation. The data obtained for low carbon steel were compared with those for stainless steel. Different diameters of HSS twist drills were used to observe their effects on drilling burr formation. The quantitative measurements of burrs height yield much useful information because relatively uniform small and large burrs were formed under these conditions.

KEYWORDS

Burr Formation, Drilling and Slot-End Milling operations, Low Carbon and Stainless steels

INTRODUCTION

Burr can be produced with different machining processes like drilling and milling. It has been defined as an undesirable projection of material beyond the edge of the workpiece due to plastic deformation during machining. In machining, burrs cause several problems for product quality and functionality as they interfere with the assembly of parts, jamming of parts, misalignment, and short circuits in electrical components. It may also reduce the fatigue life and cause safety hazards.

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 apart of the material extending off the exit surface of the workpiece. Because the exit burr is larger than the entrance burr, this study has only focused on the exit burr. A drilling burr has several different shapes depending on parameters such as workpiece material property [1,2], drill geometry [2,3,4], exit surface angle [5], and process conditions [1,6]. Milling burrs are likely to form along the edges where the tool leaves the work part, namely exit burrs that must be removed by deburring processes to allow the work part to meet specified tolerances. Exit burrs formation in milling process are determined by several parameters including cutter geometry, work part geometry, and material properties, cutting conditions [7], and selected tool feed direction [8].

During metal cutting, the existence of burr not only reduces the dimension and accuracy of the workpiece., but also increases the manufacturing cost. Presently, the burr has been the most troublesome obstruction to high productivity and automation of machining process. Accordingly, for manufacturing advanced precise components, deburring operations are required to remove the burrs. However, in the machining operations the cost of deburring can reach 30% of the total machining cost. Therefore, much work has been carried out aiming to reduce the cost and time consuming of deburring. Research is still going on to improve and automate the deburring processes since fitting a deburring process into FMS with high efficiency and full automation is a difficult problem [9]. Also, understanding of burr formation and mechanism is essential in order to reduce deburring cost by reducing burr formation. In contrast, a few studies have been performed to determine the influence of cutting parameters to assist in the reduction of burrs and the production of free burr components. Thus, to avoid or minimize the burr formation during machining, it is necessary to understand and to have a deeper knowledge on the relationship between the burr formation and the parameters involved in the important machining operations like drilling and milling which are most widely used material removal processes.

Much research has been focused on macro-scale burr formation in drilling and face milling [7,10] but a few researchers have worked on burr formation in slot-end milling processes. Many studies have been conducted on the machinability of carbon steels but few of them concentrates on the problem of burr formation. This paper presents the results of an experimental study on the influence of the main cutting parameters on burr formation and its types in drilling and milling operations to machine low carbon and stainless steels using HSS cutting tools and cutting fluid. Particular attention was focused on the relation between the burr type and size and cutting parameters. Therefore, a wide range of cutting speeds, feed rates, and depth of cuts were investigated to explore the optimum cutting conditions.

Burrs height were measured and analyzed at different machining conditions to determine the effect of the cutting speed, feed rate, and depth of cut on burr formation. The data obtained for low carbon steel were compared with those for stainless steel. Different diameters of HSS twist drills were used to observe their effects on drilling burr formation. The quantitative measurements of burrs height yield much useful information because relatively uniform small and large burrs were formed under these conditions.

EXPERIMENTAL PROCEDURE

Nomenclature of burrs studied in drilling and end milling operations

This study concentrates on the formation of burrs in drilling and milling operations. Regarding drilling operation, the entrance(minor) and exit (major) burrs positions are on the entrance and exit surfaces, respectively, as shown in **Fig,(1)**[11]. The entrance burrs are generally very small in sizes in comparison with exit burrs at different cutting conditions. While end milling operations produced burrs as shown in **Fig.(2):** burr on the top edge (burr1), exit burrs in the feed direction (burr3 and burr5) as classified and defined by Gillespie [10], and identified experimentally by Olevera and Barrow [7]. The sizes of Burr3 and burr5 were found too small to measure as compared to that size for Burr1. However, this investigation focused only on exit burr in drilling operations and on Burr1 in milling operations because these burrs are larger in sizes and quantity than others and for deburring purposes, they are considered the most important. Burr9 (a rollover burr)does not exit since it is normally formed by the side and end of the face milling cutter, as the tool exits the workpiece over the edge. This burr is actually a series of similar burrs, where each tooth produces a complete burr.

Work materials

The work materials investigated in this work are hot rolled low carbon steel (LCS), St37, and cold rolled stainless steel (SS), AISI316 and both materials are in the annealed condition. These materials were selected because they are widely used in industry for production purposes by drilling and milling operations. They are supplied with the chemical compositions and mechanical properties given in **Table (1)** and **Table (2),** respectively. Rectangular blocks 200 mm in length, 140 mm in width, and 15 mm thickness from these materials were used for studying the burr formation in drilling and milling operations.

Cutting Tools

Firstly, drilling tests were carried out using different high-speed steel (HSS) conventional twist drill diameters (5, 7, 9, 11, and 12.5 mm) in drilling the LCS block at constant medium spindle speed (500 rpm) and lower feed (0.03 mm/rev) to indicate the influence of the drill diameter on the burr formation and its size.

Secondly, other drilling tests were made using only a HSS twist drill of 12.5 mm in diameter in order to obtain burrs with larger sizes for measuring purpose at different cutting speeds and feeds.

Finally, slot-end milling tests were carried out using a HSS end mill of 10 mm in diameter in milling LCS, and SS blocks for burr formation and measuring purposes. Each test consisted of machining of a slot of 50 mm length for different cutting speeds, feeds, and depth of cuts.

Machine Tools

All drilling tests were performed on a CNC drilling machine while end milling tests were performed on a CNC vertical milling machine. A water-soluble coolant (a soluble oil, which is an oily emulsion freely miscible in water), was used as the cutting fluid during drilling and milling low carbon and stainless steels. This cutting fluid is commenly used as a coolant for lubricating and cooling purposes by reducing the harmful effects of friction and high temperatures during drilling and milling operations [12].

Cutting conditions

The cutting conditions considered in drilling and end milling tests were cutting speed, feed rate, and depth of cut. The cutting parameters ranges used in this work are listed in **Table (3)** and **Table (4)** for drilling and slot-end milling stainless steel and low carbon steel, respectively. These parameters were selected according to the prast experience of using high-speed steel (HSS) cutting tools and also to the general recommended working ranges given for speeds, feeds, and depth of cuts used for these tools in drilling and milling operations of low carbon and stainless steels[13]. 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

There are several quantities for burr measurement: burr height, burr thickness, burr volume, and hardness [12]. Burr height and thickness are the most frequently and easily measured burr quantities. There are several methods [15] to measure burr height and thickness, such as contact method, optical microscope method and optical coordinate measurement machine (CMM) method. A surface profilometer, which is usually used for measuring macro-scale surface finish is normally used to measure burr height. Recently, the laser is also used to measure burr height.

For a given set of cutting conditions, the burr size obtained in drilling and end milling tests was highly variable. Then, the average heights of the exit burrs produced in drilling and milling 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. The height was measured with a dial gage indicator with accuracy of +/- 0.005 mm. The results reported were the average of 8 to 9 measurements for the height of the exit burrs formed at different positions for each hole and slot in both drilling and slot-end milling tests.

RESULTS AND DISCUSSION

Burr formation and observation in drilling tests

The exit drilling burr has different shapes and sizes depending on the cutting conditions used. From deburring cost point of view, it is important to consider both burr shape and size. **Figures (3)** and **(4)** show burr shapes observed in drilling stainless and low carbon steels, respectively. Three types of burrs formed in drilling both materials. These are uniform burr with a drill cap, uniform burr without a drill cap (transient burr), and crown (petal) burr. These types of burrs are uniform for both materials and they have a relatively small and uniform burr height and thickness around the hole periphery. Furness [16] previously proposed burr formation mechanisms for drill cap and crown burr types matched with corresponding pictures from high-speed video during drilling low carbon steel AISI 1018.

Uniform burr with a drill cap formation

The whole work of the current paper is focused on the formation of the drilling exit burrs since the entrance burrs are generally very small in sizes and difficult to measure when compared with exit burrs at different cutting conditions used for drilling low carbon and stainless steels.

A uniform burr with a drill cap is formed in the final step of drilling and can either remain attached to the workpiece [**Fig.(3)**] or be separated at drill exit [**Fig.(4)**]**.** The formation of the drill cap at the final step depends on the material ductility and process conditions. The most common burr type for ductile material is the uniform burr with a drill cap. In most cases, with reasonable combination of cutting conditions, initial fracture occurs at the outer cutting edge region, not near the drill center, creating a drill cap [1].

Kim et al [2] stated that the drill cap is first formed by plastic deformation of the work material under the chisel edge depending on the drilling thrust force. With drill advancement, the plastic deformation zone expands from the center to the edge of the drill. Finally, the drill cap is created by initial fracture occurs at the end of the cutting edges. The remaining material is then bent and pushed out ahead of the drill to form this type of burr.

Kim and Dornfeld [1] has proposed an analytical model for drilling burr formation mechanism in ductile materials to predict the final burr size of the uniform burr with a drill cap. However, this type of work is beyond the scope of this paper which only focuses on the influencing cutting parameters (cutting speed, feed, and depth of cut) in drilling and milling operations as well as effect of using different drill diameters.

Kim [6] in his preliminary experiment to investigate drilling burr formation on titanium Ti-6Al-4V has also observed a uniform burr with a drill cap during all conditions used. Typical burr shapes identified formed in most cutting conditions were rolled-back burr and leaned-burr. The level of rolling back seemed to be proportional to feed rate and spindle speed. Crown burr that are formed in high feed rate in steel were never formed. Thermal effect caused by the friction heat is believed to have influenced the types of burrs because of low thermal conductivity of the material and no usage of coolant.

In drilling 304 stainless steel, Guo and Dornfeld [17], have proposed and divided burr formation mechanism into four stages: initiation, development, pivoting point, and deformation stages with cap formation.

Uniform burr without a drill cap (transient) burr formation

As shown in **Fig.(3),** this type of burr formed in the transient stage between uniform burr with a drill cap to a crown burr type, by early fracture, near the end of the cutting edges later than in uniform burr formation (when the material does not have moderate ductility, plastic deformation is limited), creating a larger uniform section. With further drill advancement, the strain at the chisel edge exceeds the fracture strain of the material. Continuous cutting occurs up to the final stage of drilling, creating a uniform burr without a drill cap [**Fig.(4)**].

Crown (petal) burr formation

The crown burr has a large and non uniform burr height. Generally, this type of burr in both materials

has a large and irregular height distribution around the hole. A larger thrust force induces plastic deformation earlier in the process. The thicker material layer beneath the drill undergoes plastic deformation, and a larger maximum strain was induced at the center region of the exit surface leading more likely to an initial fracture, at the chisel edge, resulting in a crown burr. Also, because of inefficient cutting due to drill wear at the outer cutting edges, there is a higher possibility of initial fracture to occur at the center region and thus creating a crown burr.

Effect of drill diameter on drilling burr height

The first attempt was carried out to investigate the influence of using different conventional HSS drill diameters on drilling burr size in terms of height only since burr thickness was difficult to measure due to some technical problems. The reason for that is to ensure evidently that burr can be formed during drilling operations and to select the proper drill diameter that provides a reasonable size for suitably measuring purpose.

Figure (5) shows burr height variation with drill size in drilling low carbon steel at cutting speed of 19.6 m/min and feed of 0.03 mm/rev. It is seen that increasing the drill diameter does greatly affect the burr size. This burr size increase is believed due using higher cutting speed and lower feed and thus causing more material deformation owing to thermal effect in cutting moderate ductile material such as low carbon steel [**see Table (1)**].

Therefore it was decided to choose a 12.5 mm drill diameter to use in the whole drilling tests of this paper. Also, the selection of this drill size is to form enough burr size and to be easily measured in conducting the following drilling and milling tests for low carbon and stainless steels. However, Kim and Dornfeld [6] in their analytical model noted that increasing the drill diameter has no great influence on burr size (in terms of burr height and thickness) since they have used a smaller drill size (~ 4 mm in diameter) and lower feed (0.08 mm/rev) in cutting stainless steel AISI 304L.

Regarding the burr shape during drilling tests for low carbon steel used in this work with different drill diameters, a uniform burr with a drill cap was only observed and its size increases with increasing the drill diameter at the higher speed (19.6 m/min) and lower feed rate of 0.03 mm/min.

Effect of cutting speed on drilling burr height

Drilling test were carried out for the stainless (SS) material over a cutting speed range 4.9-13.9 m/min and at a constant feed of 0.32 mm/rev using a HSS twist drill of 12.5 mm in diameter and all results are then depicted in **Fig.(6)** which generally indicates that the increase of exit burr (major burr) height with increasing cutting speed. It can be seen that the corresponding burr heights over this speed range are higher and showed a sharp increase in comparison with those obtained for low carbon steel. The lower speed range was used for drilling stainless steel is to prevent the hardness effect of this material on the twist drill and thus avoiding the tool wear during the drilling operations. The behavior of burr height increase during cutting both materials, is attributed to the effect of cutting temperature rise with increasing cutting speed. This will result in more deformation in the workpiece near the exit surface and then more material extension, creating higher burr size.

It must be pointed that in drilling stainless steel, the steep increase in burr height with cutting speed, is related to drilling burr formation mechanism that resulted in the possibility of forming mainly two shapes of burr, namely: a uniform burr with a drill cap and a uniform burr without a drill cap (transient burr), as shown in **Fig.(3)**. A crown burr was not seen during drilling this material at different cutting speeds. Burr shape is important because the burr size, as a result, the deburring cost is greatly dependent on it. These shapes of burrs are found similar to those observed previously [1,2] in drilling stainless steel AISI 304L at low and high cutting speeds. Kim [1] stated that when feed and the cutting speed are low, the drilling burr tends to have a uniform shape along the hole periphery for most materials. The material property of workpiece makes a big difference when the feed and cutting speed increase. When the material has moderate ductility, the material tends to elongate to some extent during burr formation, resulting in a large burr height and burr volume. However, if the material is quite brittle, catastrophic fracture occurs as the feed and speed increase, resulting in irregular burrs having several large chunks, lobes, or petals as shown in drilling the aluminum alloy Al 6061 [1].

Thus, according to **Fig.(6)**, in drilling stainless steel at lower cutting speeds and in this case at higher feed (0.32 m/rev), uniform, small heights of burrs with separated drill cap first produced due to the initial fracture occurred by plastic deformation at the end of the cutting edges. These burrs have irregular shapes because some of the burr material left with the drill cap by a later fracture took place near the workpiece surface because of the drill cap bending when the drill exiting the surface. Also, another uniform burr with attached drill cap formed at medium speed and high feed owing to plastic deformation at the end of the drill edge. Eventually, a uniform, large, thick, and sharp burr produced at high feed and cutting speed. So, the combined effect of both higher speed and higher feed (higher thrust force) caused the increase of burr height steeply and this behavior is different from that for drilling low carbon steel at various speeds since lower feed of 0.11 mm/rev (lower thrust force) was used, thus creating lower burr height.

It was proposed [14] that burr formation mechanisms for several burr shapes, matched with corresponding pictures observed by a high-speed video while drilling low alloy steel, AISI1018,. The uniform burr has a relatively small, uniform height and thickness around the hole periphery. A drill cap may or may not be formed in the final step of drilling depending on the material ductility, drill geometry, and process condition. The crown burr has large and nonuniform burr height (with irregular height distribution around the hole). Also, the transient burr is a type of burr that forms in the transient stage between the uniform burr with a drill cap and the crown burr and it has a larger burr height than uniform burr but with no cap. Kim [1] has explained the burr formation mechanisms of both uniform burrs with and without a drill cap. As the drill approaches the work exit surface, the material under the chisel edge begins to deform. The distance from the exit surface to the point at which the deformation starts depends mainly on the thrust force during drilling. As the drill advances, the plastic deformation zone expands from the center to the edge of the drill. At the final step, the remaining material is bent and pushed out ahead of the drill to form the uniform burr with a drill cap. If the material does not have moderate ductility, plastic deformation is limited, and fracture occurs early at the center region of the drill. Continuous cutting occurs up to the final stage of drilling, creating a uniform burr but with no cap.

Other tests were also performed for drilling the low carbon steel (LCS) material over a cutting speed range 3.5-27.9 m/min and at a constant feed of 0.11 mm/rev using a new HSS twist drill with 12.5 mm in diameter and all data determined are illustrated in **Fig.(6)** which also shows that the exit burr height increased with cutting speed increase. Burr heights are seen to be lower in comparison to those found for stainless steel. Also, two types of burr shapes as shown in **Fig.(4)** were mainly observed during cutting over this speed range. At lower cutting speeds, a uniform burr with separated drill cap formed while a transient burr (a uniform burr without a drill cap) produced at higher speeds. But, the uniform burr with a drill cap as shown in **Fig.(3)** during cutting stainless steel, was not observed over this speed range. The burr formation mechanisms of these shapes are the same as those described earlier [1,2] in this section and they formed at different cutting speeds except that lower feed (0.11 mm/rev) was used. And, the reason for lower burr sizes obtained in drilling low carbon steel is more likely owing to the less ductility of this material when compared with stainless steel material.

Effect of feed on drilling burr height

Regarding the feed influence on burr height in drilling tests of stainless steel (SS) over a feed range of 0.08-0.22 mm/rev and at a chosen moderate cutting speed 9.8 m/min, the results found are depicted in **Fig.(7)** which indicates clearly that burr height first increased at a feed of 0.11 mm/rev, then decreased to a minimum value at a feed of 0.16 mm/rev, and later increased sharply with increasing feed up to 0.22 mm/rev. The explanation for this variation in burr height is thought to be due to burr shape change since at a feed range of 0.08-0.11 mm/rev, the burr formed is seen to be large and has a uniform shape with no drill cap (transient burr) as shown in and described by Kim [1]. While cutting at moderate feed of 0.18 mm/rev, a uniform burr with separated drill cap produced and it is thin with a very small height since the increase in feed as mentioned earlier [1,2], resulted in expanding the plastic deformation zone from center to the tool edge and thus initial fracture occurs at the end of the cutting edges, creating the drill cap that separated from the workpiece. In addition to that, when the drill approached the workpiece exit surface, this fracture is most probably occurred too near this surface and that is why less material left as a burr adhered to the exit surface and around the hole periphery. In order to ensure that the behavior of height to be very small at this cutting condition, the drilling test using same speed and 0.16 mm/rev, was repeated and a similar result was obtained (burr is very small and has a uniform shape with separated drill cap).

By further increase in feed up to 0.22 mm/rev, burr height raised sharply because of the formation of a large thin transient burr or uniform burr with no drill cap. This trend is attributed to higher thrust force effect induced and thus more material being removed by plastic deformation, causing a fracture in the center region of the drill and thus producing a large burr height. Also, the burr formation mechanisms of these two types of burr shapes are same as for those stated in the last section.

Other drilling tests were achieved for low carbon steel at a cutting speed of 19.6 m/min and over a feed range 0.16-0.45 mm/rev using a new HSS drill with 12.5 mm in diameter. **Fig.(7)** illustrates that burr height is lower at lower feed since the tool is fresh and new with no wear on its cutting edges but then its height increased with feed increase. This trend is believed that at a feed over 0.22 mm/rev, burr height increased owing to more plastic deformation caused by higher thrust force. During the feed range of 0.16-0.22 mm/rev, a small uniform burr with separated drill cap formed whereas a transient burr or a large uniform burr without a drill cap produced during cutting over this feed range as shown in **Fig.(4)**. And, the reason for lower burr size obtained in drilling low carbon steel is more likely due to the effect lower ductility of this material when compared with the stainless steel material.

Concerning the work of this paper, the rolled-back and leaned-back burr types observed by Kim [6], were not seen during drilling low carbon and stainless steels. This is more likely due to the effect of application of coolant which has reduced the thermal effect caused by the friction heat generation when there is no cutting but deformation as in the final stage of burr formation. Also, the higher heat conductivity of steels than titanium alloy enhances slow heat conductive dissipation to the workpiece. Therefore, the temperature rise will be lower in the region near the inner wall of the burr. This will reduce the material expansion and contribute to form a uniform burr with a drill cap instead of rolling or leaning back burr type.

Burr formation and observation in slot-end milling tests

The typical slot-end milling process is depicted in **Fig.(8)[**18]. The surface along the bottom of the slot will be scalloped. As the tool passes through the workpiece, each tooth creates a semi-circular scratch along the bottom of the slot. Thus, the bottom surface will be scalloped. The length of each slot was 50 mm for each milling test.

All slot-end milling tests exhibited clearly formation of burr1 on the top edge of the workpiece surface. It was relatively small, uniform along the test length and their shape looks like protrusion with variable height while, burr3 and burr5 produced when the tool exits the workpiece (in the feed direction). However, burr3 and burr5 were not considered in the present work because of their measuring limitations and since they were too small in sizes when compared to burr1. Therefore, this study concentrated on burr1 formation which is considered the most important for deburring purposes since it is larger in size and presents in large quantities. In each test, a new tool was used to avoid the effect of the tool wear.

Gillespi [10] investigated the effect of cutting parameters on the size of burrs produced in end milling and explained the formation mechanisms for these burrs. He concluded that burr1 (poisson burr) is the result of lateral deformation caused when the tool enters the workpiece. The material tends to bulge at the sides when it is compressed until permanent plastic deformation occurs. Burr3 and burr5 are rollover burrs formed, however their sizes vary noticeably due to the variation of exit angle as the tool leaves the workpiece.

Wright et al [19] reported formation of three different burrs in slot-end milling : exit burr (burr5), side burr (burr3), and top burr (burr1), which occur along (1) the edge between the machined surface and the exit surface, (2) the edge between the transition surface and the exit surface, and (3) the edge between the top surface and the transition surface.

Landers et al [20] stated that, in milling, three major burr types (poisson, rollover, and tear) form due to workpicec plastic deformation. When the cutting tool edge extends over a workpiece edge, material is compressed and may flow laterally forming a poisson burr. Rollover burrs form when the cutting tool exits the workpicec and the chip tends over the edge instead of being cut. If the chip is torn from the workpiece, instead of being sheared off, some material from the chip will be left on the workpice. The material is known as a tear burr. A combination of the poisson and tear burr can end up as a so-called top burr or entrance burr along the edge of top workpiece when a tool cuts a slot or along the periphery of a hole when a tool enters a workpiece [12]. In conventional cutting process, these top or entrance type burrs are substantially smaller than exit burrs so that usually no deburring process is necessary.

In the present work, the slot-end milling test produces the following burr1 (top burr) morphologies at the machined surface: (1) knife burr type or uniform (primary burr), (2) wave-type (primary burr), and (3) secondary burrs as shown in **Fig.(9)**. Knife edge burrs are the largest burrs encountered in this type of milling. They are characterized by uniform height and thickness that is small relative to their height, gives them a laminar appearance. Wave-type burrs are believed to have the same formation mechanism as knife burrs, but are slightly smaller and do not have uniform height [**Fig.(9)].** Secondary burrs are generally not periodic with respect to the feed marks on machined surface, and their size is often one order of magnitude smaller than knife or wave-type burrs (primary burrs)[21].

Hashimura and Dornfeld [22] noted, in face milling process, that uniform burrs are formed due to cumulative leaning of the transition material that is pushed by the tool flank during each successive pass. The cumulative burr (knife burr) formation mechanism under tool exit condition was presented. The exit burr forms as plastically deformed transition material is leaned down towards the machined surface as opposed to rollover of the chip. The ability of the back-up material to carry the cutting forces controls the burr and chip formation processes which are two separate processes. The cumulative deformation of the transition material explains the uniform height of the knife burr, which is approximately equal to the depth of cut.

Effect of cutting speed on slot-end milling burr height

In slot-end milling at cutting speed range of 5.1-12.2 m/min for low carbon steel (LCS) and 3.8-9.3 m/min for stainless steel (SS) at constant feed rate and depth of cut, **Fig.(10),** shows that burr1 (top burr or poisson burr) is formed in all cases, small in size, and uniform along each test length. The burr1 height increased from 0.09 to 0.15 mm for low carbon steel and from 0.08 to 0.10 mm for stainless steel with increasing speed. The burr formation for both materials is more likely a result of lateral plastic deformation due to the thermal effect that increased with increasing cutting speed. This indicates that more generated heat is dissipated and transferred by conductivity to sides of the slot at low feed rate of 14 mm/min, higher cutting speed and depth of cut of 2 mm. Also, the difference in burr1 size between these materials is owing to the difference in their mechanical properties and structures. This means that stainless steel exhibited more resistance to the cutting temperature influence than low carbon steel with speed increase.

Regarding burr1 types, similar observations to those mentioned by Avila and Dornfeld [21], are indicated in the present study. It is noted in that, at any cutting speed for each material, burr1 shape and type depend on its height. A knife edge burr (primary burr) type that only formed at the top of the round edge of the slot, is sharp look like a straight protrusion, thick, and large in size. Whereas a wave burr (primary burr) type that formed along the top edge of both sides of the slot, is curled, thin, and small in size **(see Fig. (9)).** In addition, secondary burr due feed marks at the bottom of the slot surface, is also seen with very small size but this type together with burr3 and burr5 are out of focus of the this work due to the practical difficult problems in measuring their sizes.

Effect of feed rate on slot-end milling burr height

Fig. (11) reveals that at lower feed rates, burr1 sizes are high for both materials. These burrs are only formed by lateral plastic deformation owing to the dominant thermal effect at high cutting speed. At higher feed rate, burr1 height remains unchanged for low carbon steel (LCS) but for stainless steel (SS), it is steadily decreased from 0.13 to .0.05 mm. The stability of burr1 for low carbon steel at higher feed is attributed to more cutting temperature rise at higher speeds and an accompanying increase in thrust force that pushing high amount of material being removed at high feed and depth of cut. Whereas, for stainless steel, the reduction of burr1 is more possibly due to the higher resistance of this material to shearing action than low carbon steel. Therefore, smaller chip is removed and thus creating less burr1 in size.

So, the behavior of burr1 for low carbon steel with varying feed rates is not similar to that observed in Olevra and Barrow work [7] in face milling of medium carbon steel but for stainless steel, it is found identical because they concluded that burr1 height decreased as the tool feed rate increased. This burr is formed by lateral deformation of the material when the cutting tool edge enters the workpiece. They demonstrated this trend in terms of the ploughing effect since at the beginning of the cut, the milling cutter starts with zero cut thickness and therefore no actual shearing of the material occurs. Instead, the material is plastically deformed and pushed underneath the tool. This plastic deformation facilitates the formation of burr1. Thus, at low feed rate, the tool takes longer to start cutting properly due to the small cut thickness and therefore the ploughing effect is increased. While, at high feed rate, the proper cutting action starts earlier (the cut thickness rises more rapidly) and as a consequence the ploughing effect is reduced, hence burr1 is smaller at high feed rate.

In addition, Gillespie [10] in his investigation the influence of machining variables on the size of burrs in end milling,found that feed rate and tool sharpness are the most significant variables affecting the size of burrs produced in this operation. Low feed rates and dull tools resulting in higher and thicker burrs. He also concluded that burr1 is the result of lateral deformation caused by the tool enters the workpiece (poisson burr).

As mentioned in section 3.6, similar shapes of burr1 (knife edge and wave burrs that are noted in previous work [19] at the top of the round edge and sides of the slot, respectively) are also formed over the feed range used in this work for slot-end milling each material.

Effect of depth of cut on slot-end milling burr height

Regarding the influence of depth of cut on slot-end milling burr1 height, slot-end milling tests were also conducted for both materials over a depth of cut range 0.5-2.5 mm at a constant cutting speed of 6.6 m/min and a cutting feed rate of 22 mm/min. **Fig. (12)** illustrates that for low carbon steel (LCS) and stainless steels (SS), burr1 heights are slightly increased almost with increasing the cutting depth. However, at lower cutting speed and feed rate, the depth of cut has little influence on burr1 height because of the temperature and thrust force effects on the plastic deformation of both materials.

These results are identical to ones reported previously by Olevra and Brrow [7] who determined that an increase in the axial depth of cut led to an increase in burr1 height. They interpreted these results according to the observation of Gellespie [10] for the effect of depth of cut on burr1 (poisson burr), Burr1 that forms by lateral deformation of the workpiece material under pressure of the cutting edge, will only form when the cut thickness is sufficiently large so that there is more resistance for the material ahead of the cutting edge to flow in the chip direction (parallel to the cutting edge), i.e. burr1 forms because of the material being displaced by the cutting edge is restricted to the flow mainly in the lateral direction. The foregoing helps to explain the trend shown in **Fig. (12)** for both materials in this work. When the depth of cut increases, the total amount of material being displaced by the cutting edge rises proportionally. Being restricted to flow mostly in a direction parallel to the cutting edge, this will result in larger burr1 size.

Concerning the burr1 shapes, it is found that knife edge and wave burrs, similar to those stated previously [21], are formed at the top of the round edge and sides of the slot with increasing cutting depth for both steels utilized in this experimental study.

Thus, drilling and end-slot milling operations conducted in this work revealed that the burr formation can

cnot be avoided or eliminated but it can be minimized by applying certain cutting conditions at lower and higher levels of cutting speeds, feed rates, and depth of cuts. This is attributed to the additional infuences of cutting forces and temperature during its formation causing material plastic deformation. However, the variations in burr heights obtained in this work are strongly related to its type observed at each cutting conditions. Accordingly, in order to eliminate burr formation during cutting, different strategies have been recently applied [3-5] and focused on the effect of other cutting parameters such as: tool design and angles, work part material property and geometry, tool path and feed direction. Also, much attention has been paid for complete understanding of burr mechanisms [21,22], optimizing and controlling [2,15], and modeling [17] burr formation.

CONCLUSIONS

The following conclusions were gained when conducting this experimental study on burr formation in

drilling and slot-end milling operations:

- It found that a HSS twist drill with a larger diameter provides a higher exit burr height and this is normally due to more material to be removed by plastic deformation owing to higher thermal and cutting forces effects during the drilling operation.

- Drilling tests for low carbon and stainless steels revealed formation of two types of exit burrs changing in shape (uniform burr with a drill cap and transient or uniform burr without a drill cap). Crown or petal burr was not during cutting over different levels of cutting speeds and feeds.

- In drilling tests, it was found that the exit burr height for both materials influenced greatly by the cutting speeds and feeds because relatively uniform small and large burrs with various shapes were formed.

- In slot-end milling tests, burr1 (top burr), burr3, and burr5 are formed during slot-end milling tests for low carbon and stainless steels over cutting at various levels of cutting speeds, feed rates, and depth of cuts.

- It is appeared that the shapes of burr1 were same during cutting at different speeds, feed rates, and depth of cuts and it consisted of: a knife burr type or uniform (primary burr) with a largest size over the round edge of the slot, a wave burr type (primary burr) with smaller and different heights over the whole top straight edges of the slot.

- Slot-end milling tests exhibited that the height of burr1 was generally found to be less than 0.15 mm for low carbon steel and less than 0.10 mm for stainless steel.

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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 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)	**4.9-13.9**	**0.08-0.32**
Low carbon steel (ST37)	**3.5-27.9**	**0.11-0.45**

Table (4): Cutting conditions used for slot-end milling operation.

Material	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
Stainless Steel (AISI316)	3.8-9.3	14-56	0.5-2.5
Low carbon steel (ST37)	5.1-12.2	14-90	0.5-2.5

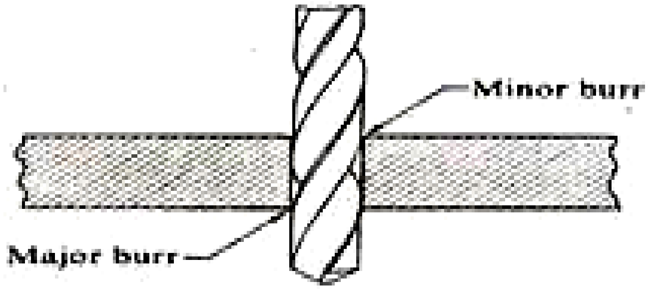

Figure 1 Minor (entrance) and major (exit) burrs positions in a drilling operation [11].

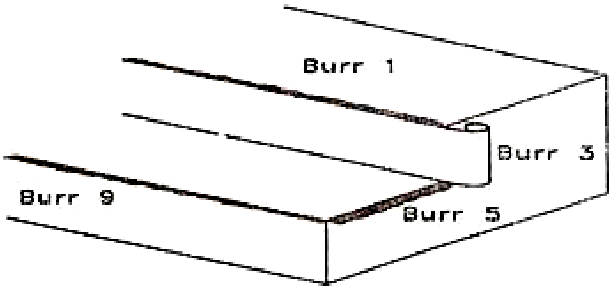

Figure 2 Types of burrs formed in a milling operation [10]
burr1 : top burr, burr3 and burr5 : exit burr
burr9 : rollover burr

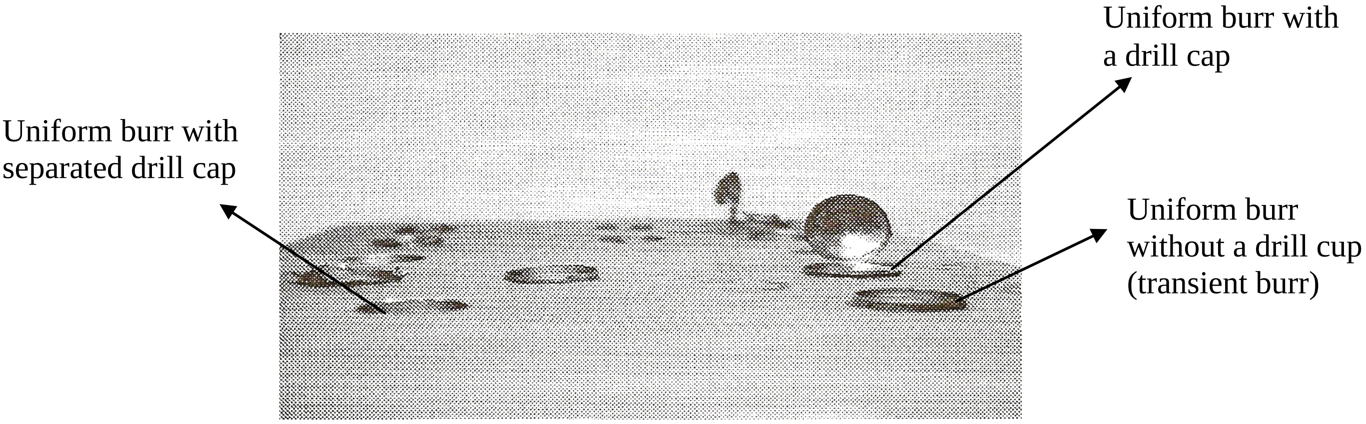

Figure 3 Photograph of the drilling stainless steel plate after machining.

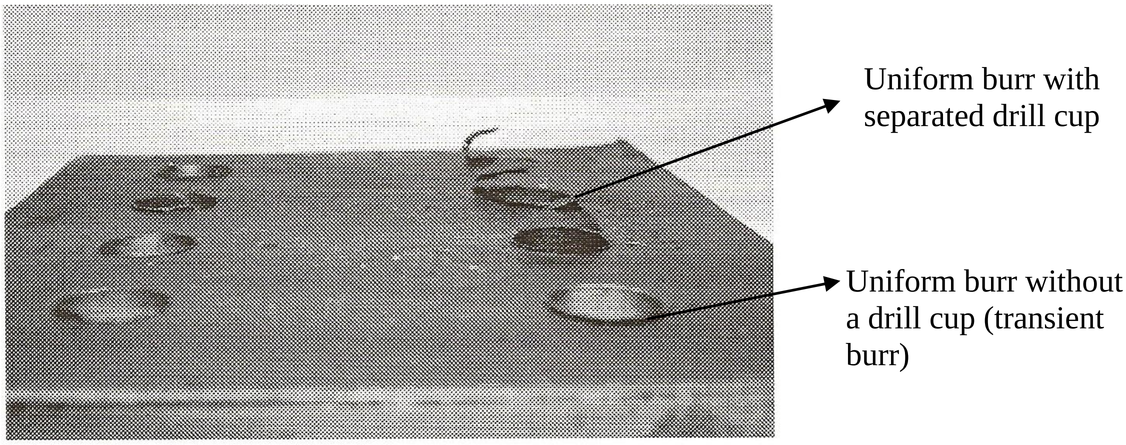

Figure 4 Photograph of drilling low carbon steel plate after machining.

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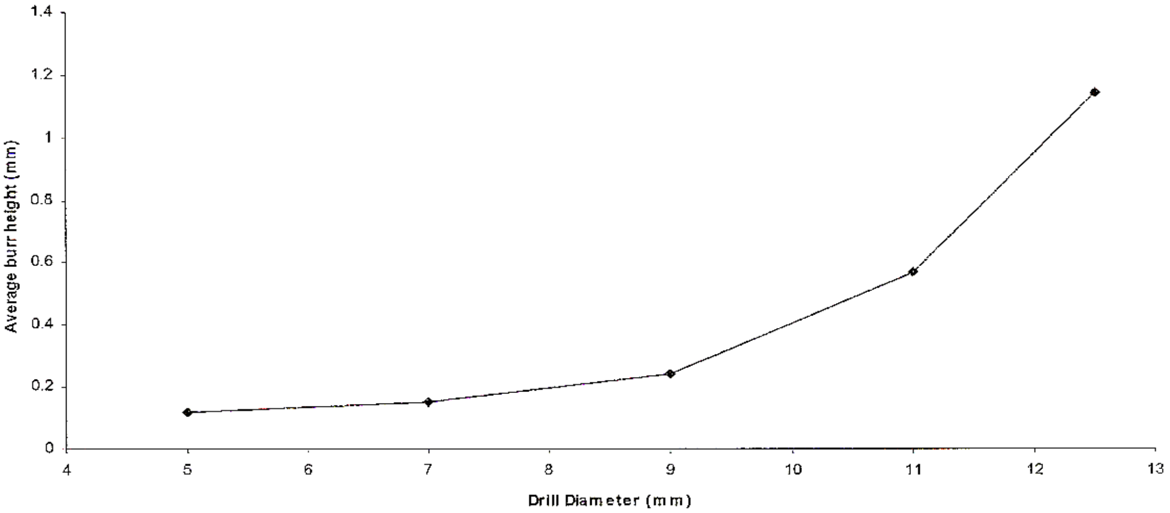

Fig.(5) Effect of using different HSS twist drill diameters on burr height in drilling low carbon steel at a cutting speed of 19.6 m/min and a feed rate of 0.03 mm/rev.

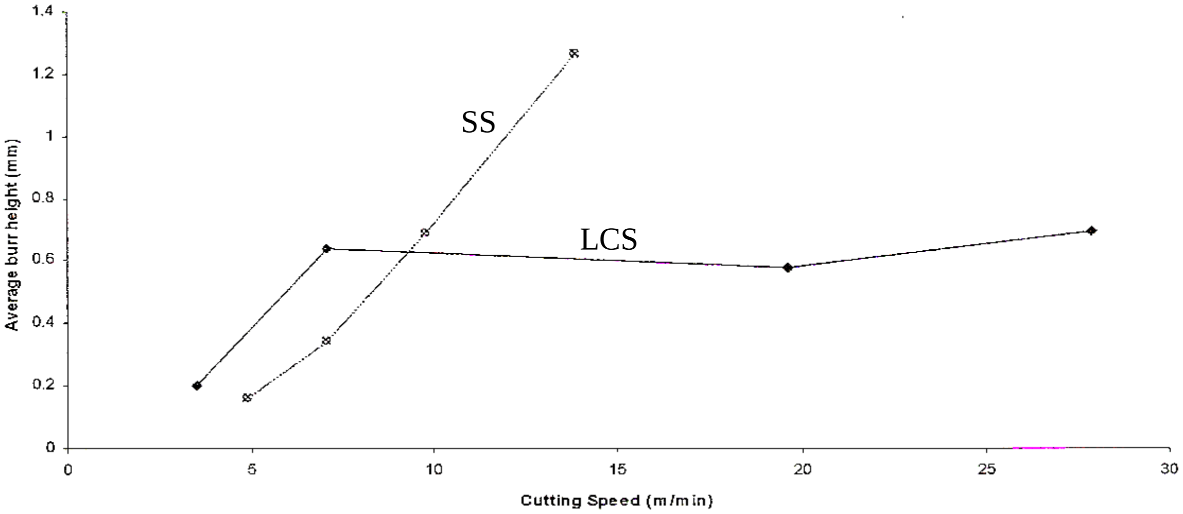

Fig.(6) Effect of cutting speed on burr height in drilling low carbon steel (at a cutting feed of 0.1 mm/rev) and steels (at a cutting feed 0.32mm/rev) with 12.5 mm drill dia.

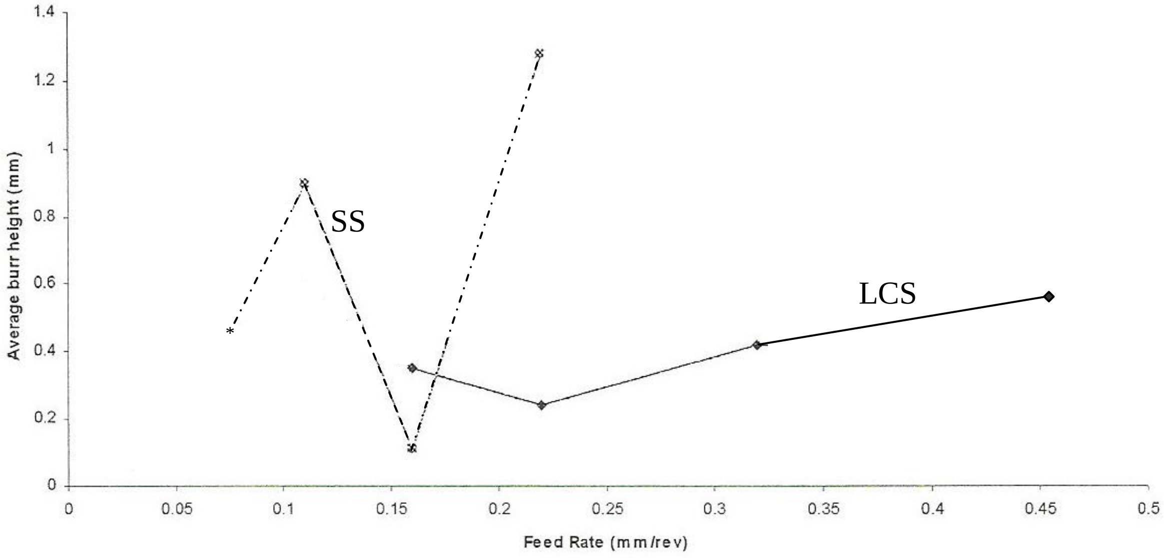

Fig.(7) Effect of cutting feed on burr height in drilling low carbon steel (at a cutting speed of 19.6 m/min) and stainless steel (at a cutting speed of 9.8 m/min) with 12.5 mm drill diameter.

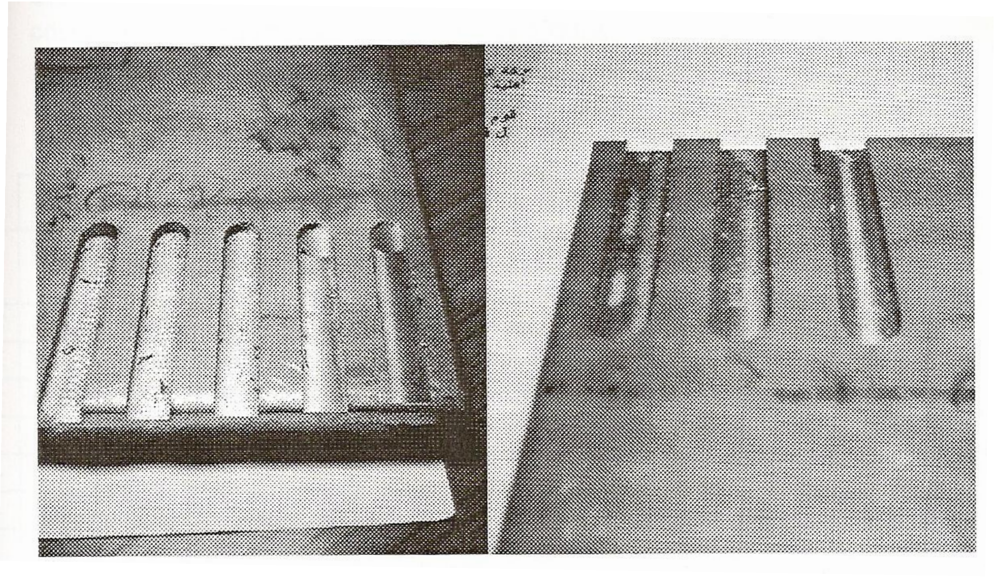

Figure 8 Photograph of milling stainless steel plate after machining.

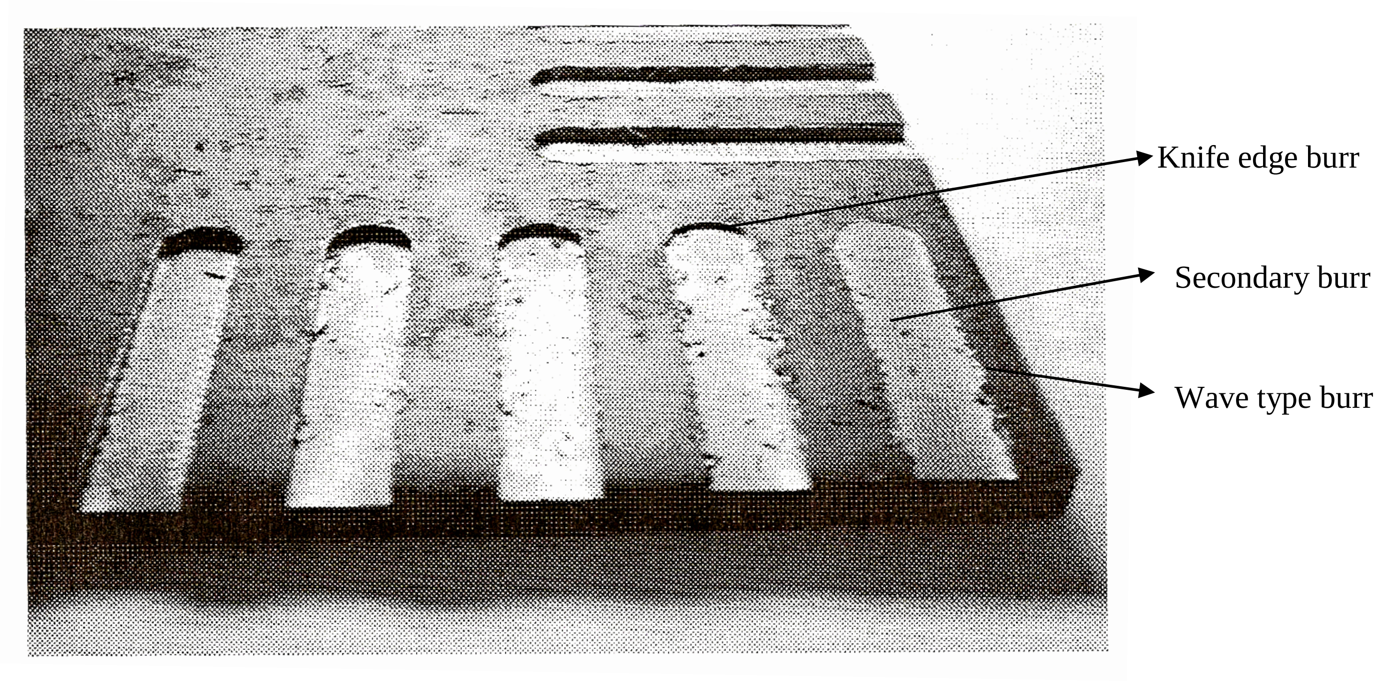

Figure 9 Photograph of milling low carbon steel plate after machining.

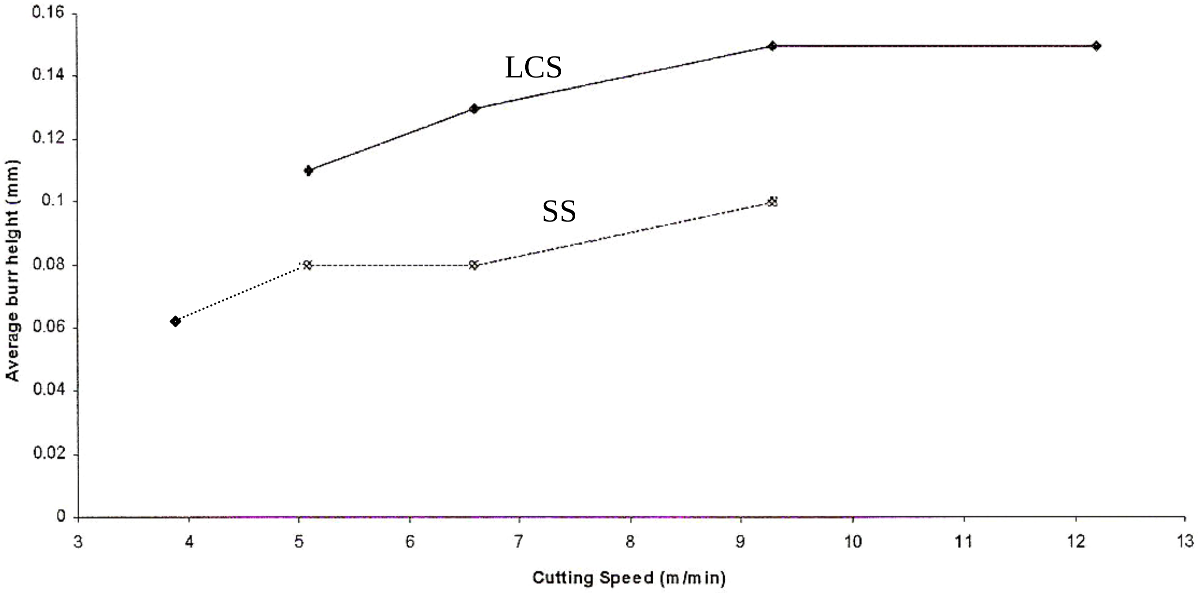

Figure 10 Effect of cutting speed on burr height in slot-end milling of low carbon steel (at a feed rate of 22 mm/min) and stainless steel (at a feed rate of 14 mm/min) with 2 mm cutting depth.

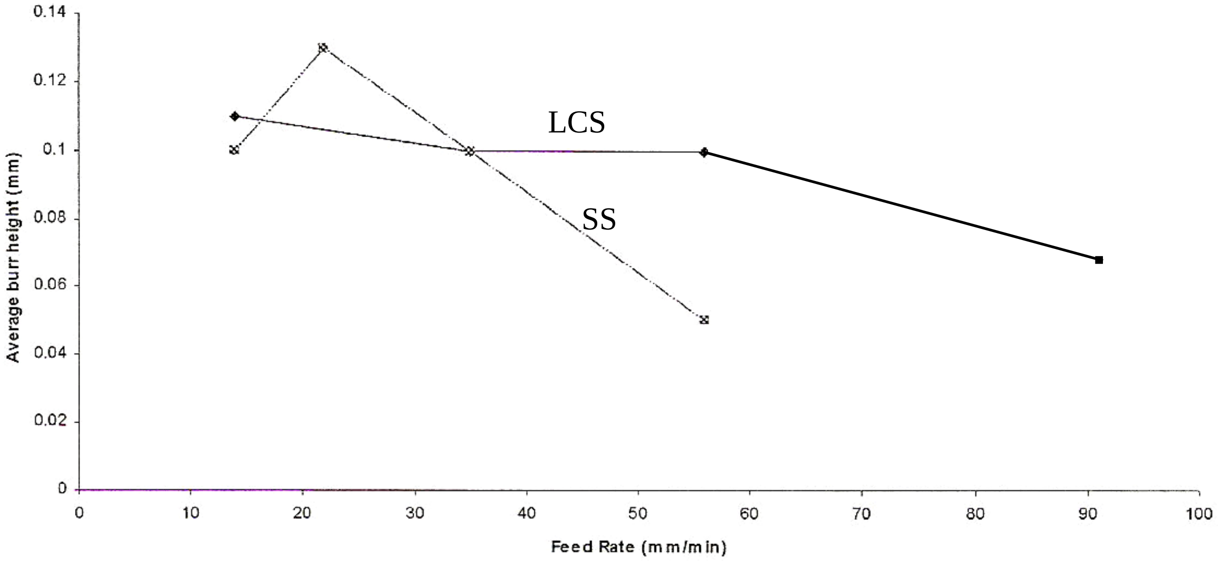

Figure 11 Effect of feed rate on burr height in slot-end milling of low carbon steel (at a cutting speed of 12.2 m/min) and stainless steel (at a cutting speed of 9.3 m/min) with 2 mm cutting depth.

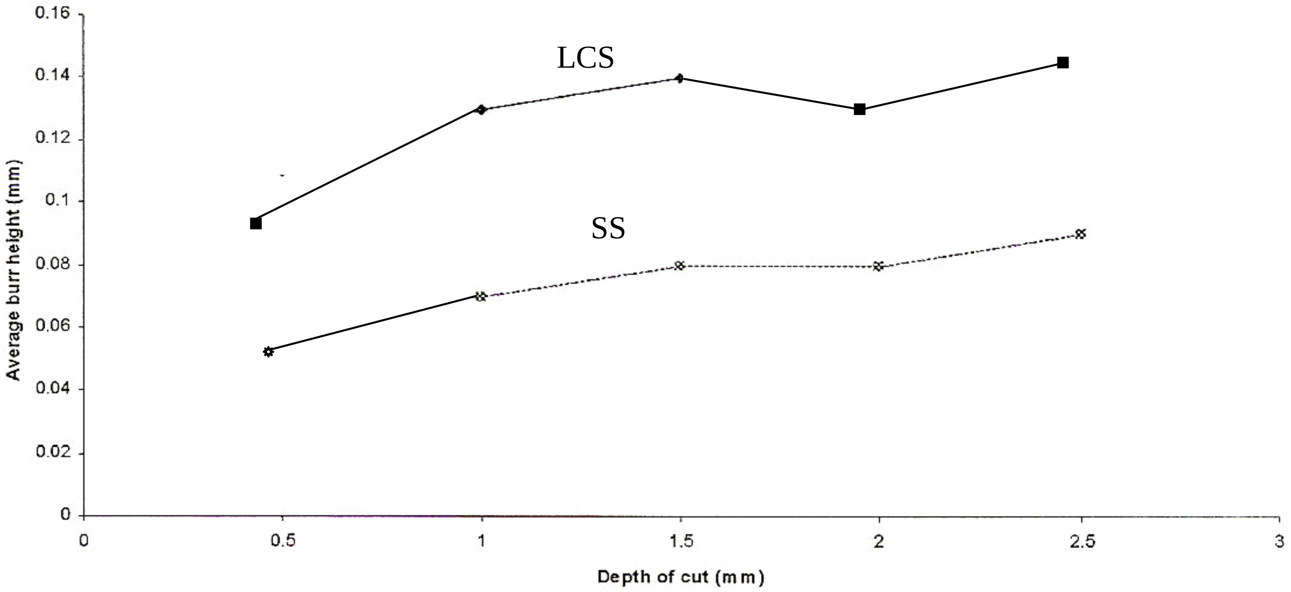

Figure 12 Effect of depth of cut on burr height in slot-end milling low carbon steel and stainless steel at a cutting speed of 6.6 m/min and a feed rate of 22 mm/min.