Machining burrs are considered as unwanted materials projections remaining on the work-piece edge nearly in the whole cutting processes, such as turning, drilling and milling. Burrs form in these operations at the cutting-edge exit beyond completing the cutting process as a result of plastic deformation of metals, incurred by the cutting edge. The development of burr isn’t only degrading the accuracy of the machined component and its quality, but also impedes the manipulating and assembling of the component. So, they usually reduce the quality of the material parts and may cause interference with the subsequent assembling operation. Because of their sharpness, burrs can be hazardous to personnel. There are many solutions and attempts that have been made regarding the burr formation problems, but none of them offers a complete solution. This includes deburring and minimizing burrs by tool design. Thus, several components in the industries of aerospace and automotive need the deburring process, which is a time-consuming, non-producing operation consuming from (15) to (30%) of the entire cost of machining. Therefore, the removal and reduction of burr are taking a raised significance in the current status. The choice of a proper deburring procedure relies upon the burr dimensions and locations. Accordingly, sizes of burr should be governed for the optimal selection of a deburring procedure or cutting variables for the minimization of burr. A single for solving such problem is to perform the analytical models of the formation processes of burr [6-9]. Nevertheless, such approach needs an obvious understanding of the mechanism of formation of burr that can be reached via the practical observations of the evolution process of burr. 

Previous studies on burrs are greatly focused on the final geometry of burr, while the straight observations of the process of formation of burr formation haven’t been intensively studied. Consequently, the process mechanism stays unobvious. It deals with the obtaining of the state of forces leading to formation of burr, the combined effect of the workpiece and the tool geometry, in addition to other cutting circumstances [10]. A thorough understanding of the mechanism of burr formation under high tool engagement is cardinal to the improvement of edge quality in a wide scope of applications [11]. Among the traditional machining processes, the formation of burr in milling is a too intricate mechanism. Thus, investigation and concentrated attention are still required for minimizing and controlling the milling burr formation. This can be done via the influential burr avoidance through the appropriate realization of the essential burr formation mechanisms and a precise suggestion of the optimum parameters of cutting [12].

In cutting a metal, the burr formation is normally considered as a too complicated operation, and its mechanism of formation hasn’t yet been totally depicted. In recent years, some researchers have commenced to...
study the mechanism of burr formation via utilizing the finite element procedure to simulate, analyze, and model the burr formation processes [13,14]. They have made some progress since they provide a numerical analysis procedure for solving the burr formation problem and the physical vision into the burr formation mechanism principle. However, there are few investigations on the mechanism of formation of burr which depended upon the experimental work. Also, only some investigations have been conducted on the burr formation mechanism and the effect of parameters of cutting to aid in the burr minimization and manufacturing components without burrs [15-17]. Improper choice of the parameters of cutting may cause enormous non-preferable costs and poor quality of component. Such case becomes clear in the process of slot milling that possesses an intricate mechanism of burr formation, and it’s associated with the multiple burrs having non-consistent sizes appearing in the edges of the machined component [18]. Accordingly, the aim of present research is to establish the link between the burr formation mechanism and burr characteristics (its shape and size) at different conditions of cutting. So, this paper is devoted to investigate experimentally some characteristics of the process of burr formation in the slot-end milling operations of low carbon and stainless-steel alloys at different cutting parameters (cutting speeds, feed rates, and depth of cuts) for understanding the formation of burr in the simple state and characterizing the mechanism of burr formation.

2. BURR CLASSIFICATION IN MILLING OPERATIONS

In milling, burrs are expected to form along the edges where the cutting tool departures the work-piece, known as “exit burrs”, should be removed via the deburring operations to permit the workpiece to satisfy the limited tolerances. Exit burrs formation in milling process are determined by several parameters, including cutter geometry, work part geometry and material properties, cutting conditions, and selected tool feed direction.

In the milling operation, burrs formed due to plastic deformation have been classified into three major types as shown in Figure (1): (a) Poisson burr (Exit burr) that forms when the work material is squeezed and may move laterally if the edge of cutting tool is extending above the edge of a work-piece, (b) Roll-over burr (Side burr) which forms when the chip is bending above the edge in place of being cut if the tool leaves the work-piece, and (c) Tear burr (Top burr) that forms when the chip is tearing from the work-piece, leaving some of the chip material on it [19].

Figure 1: Basic types of milling burrs identified by Gillespie [26]
3. PREVIOUS REVIEW ON MILLING BURR FORMATION MECHANISM

The milling process produces burrs along the edges of a workpiece, depending on the cutting parameters, tool geometries, and tool path. Milling exit burrs usually form along the edges of a workpiece when the tool leaves the part while removing stock material. Because the milling is a significant cutting process, it's inevitable to possess a deeper awareness of the relation between the formation mechanism of the burr formed in this operation and the cutting parameters. Gillespie [20] identified the following three essential mechanisms that implicated in the burr's formation: lateral deformation, chip bending and chip tearing. He categorized and identified four essential kinds of burrs: Tear burr, Poisson burr, Rollover burr, and less important Cut-off burr (often occurs on saw cuts).

Gillespie investigated also the influence of machining variables on the size of burrs produced in the end-milling operation and explained the formation mechanisms for these types of burrs [19, 20]. He obtained that the rate of feed and the sharpness of tool are the highly important variables influencing the burrs size that produced in such process: the low rates of feed and the dull cutting tools causing thicker and higher burrs. Also, he concluded that the poison burr (burr at top edge) is the consequence of the lateral deformation that resulted if the cutting tool enters the workpiece. The rollover burr (exit burr in the cutting direction) is developed via the ends and side of the milling cutter, when the cutting tool leaves the workpiece above the side edge. Another burr is also a rollover (exit burr in the direction of feed), nevertheless its dimension changes remarkably owing to the exit angle change when the cutting tool departs the workpiece.

A studied the development of rollover burr which induces on the exit edge of cutting tool in the processes of face milling [21]. They defined the terms "Primary" burr and "Secondary" burr for identifying the big and small burrs on the work-piece edge, correspondingly and obtained the cutting circumstances and the geometries of cutting tool which facilitate the secondary burr formation. They inferred that the secondary burrs develop if the quantity of the plastic strain included in the process of cutting is big. Some researchers investigated the rollover burrs formation in the face milling as well as the drilling exit burrs [22]. They deduced that the mechanisms of formation for such burrs are alike.

Avila and Dornfeld investigated the burr formation mechanisms and effect of cutting variables under high radial engagement during face milling tests for different materials [11]. In face milling operations, the largest burrs are formed when radial tool engagement is beyond a critical value. The height of these burrs approach, and may exceed, the depth of cut. Quality in a wide scope high tool engagement condition was observed to produce the largest milling burrs. The mechanisms of burr formation at a high engagement differ from the mechanisms at a low engagement; this resulted via a variation in the size of plastic zone in the transition material in front of the cutting tool. Owing to dissimilar formation mechanisms, it was observed that the effects of tool engagement or exit condition, cutting conditions, and tool geometry are not the same under high and low engagement conditions. They proposed minimization strategies focused on the optimization of the following parameters: depth of cut, insert nose sharpness, lead angle, and axial rake angle, to promote a transition from primary to secondary burr formation.

It was reported that little work conducted on the formation mechanism of knife and wave burrs in previous studies that described the formation mechanism of knife burrs as a cumulative rollover process of the chip upon exit. Hashimura and Dornfeld noted that uniform burrs are formed due to cumulative leaning of the transition material that is pushed by the tool flank during each successive pass [23]. The cumulative burr formation mechanism under tool exit condition was schematically presented. The exit angle at which the wedge of transition material ahead the tool begins to plastically deform depends upon material properties (stiffness and ductility) and cutting forces (affected by rake angles and feed rates, etc.). The cumulative deformation of the transition material explains the uniform height of the knife burrs, which is approximately equal to the depth of cut.

A group researcher suggested a model depending upon the material failure mode to simulate the burr forming processes during milling different materials [24]. Based on the deformation of work-piece materials and the mechanical characteristics from the outcomes of simulation, the mechanism of burrs formation and the principal parameters that influenced the geometrical dimensions of burr were analyzed. Depending upon the contours of stress and strain with the geometry continuous variation at the work-piece edge from the outcomes of simulation, the mechanism of burr formation was divided into three stages: (i) a stage of steady-state cutting (the elastic-plastic deformation of work material occurs chiefly in the primary shear region) (ii) a pivoting or a stage of burr formation (the corner of work-piece and the chip continue to bend around a pivoting point, and the burr raises), and (iii) last stage of burr formation (the strain and stress are going to concentrate in the shear regions, and crack is initiating at the tip of cutting tool in the primary shear region, growing along the line of cutting, and causing the separation of chip along the line of cutting and the remaining a positive burr upon the work-piece).

4. BURR MEASUREMENTS

Burr measurements are considered the principle challenges in the research of burr due to their intricate and uneven size and shape. It’s always too hard to be precisely measured. Accordingly, values of burr are gathered from the work-piece edge surface for thickness burr and height via the surface separation into many parts. Within each part, the distance from the maximum peak to the lowest valley can be measured. After that, the average of each measurements can be taken. This provides a good image of the quality of the performed edge towards the burr thickness and height [25].

Many procedures are existed for measuring the burr geometry, particularly burr thickness and height since these are the most frequently and easily measured burr quantities. Such procedures can be split into non-contact and contact procedures. In general, in a contact procedure, a height gage and stylus utilized for measuring the geometry of burr geometry, while, the non-contact procedure is subdivided into optimal computerized measuring machine (CMM), optical, the laser and the white light procedure, and the technique of image processing [26, 27].

Quantitatively, particular attention has been focused on burr formation mechanism and analysis in previous studies during milling operations of aluminum and its alloys, since they are considered easy-to-machine materials [28, 29]. However, a few researches have been carried out to study the burr formation mechanism during slot-end milling operations of low carbon and stainless-steel alloys [11, 30-33]. Therefore, the aim of the present research paper is to investigate experimentally the mechanism of burr formation in slot-end milling processes of low carbon and stainless-steel alloys and to study the effect of cutting conditions on the mechanism of burr formation.

5. EXPERIMENTAL SETUP AND PROCEDURE

5.1 Work Materials

The work materials investigated in this work are hot rolled low carbon steel (LCS), S337, 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 milling 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 slot-end milling tests for studying the mechanisms of burr formation in slot-end milling operations. The dimensions of each plate are 200 mm length, 140 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.
5.2 Cutting Tools

Slot-end milling tests were conducted using 10 mm in diameter HSS end mills in both milling LCS, and SS plates for burr formation and measuring purposes. Each test consisted of machining of a slot of 50 mm length for different cutting speeds, feed rates, and depth of cuts.

5.3 Machine Tools

All slot-end milling tests were performed on a CNC GARPE-F1 Wagner 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 milling low carbon and stainless steels. This cutting fluid is commonly used as a coolant for lubricating and cooling purposes by reducing the harmful effects of friction and high temperatures during drilling and milling operations.

5.4 Cutting Conditions

The cutting conditions considered in slot-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 for slot-end milling 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, feeds, and depth of cuts used for these tools in milling operations of low carbon and stainless steels [34]. During each test, just one cutting variable (the one its effect on the burr under study) was changed at a time, while the other parameters were kept unchanged.

5.5 Experimental Burr Measurements

For each group of cutting variables, the size of burr that obtained in the slot-end milling tests was highly variable. Then, the average heights of the exit burrs produced were measured. Too many measurements were taken for every individual test for obtaining reliable data. The height of burr was utilized as an indicator of burr size in the current study to take easily too many measurements. At exit of slot, the burr height was measured with a CMM measuring machine (resolution of 0.001 mm). While for exit milling burrs, the height of burr was utilized as an indicator of burr size in the current study to take easily too many measurements. After that, this stylus was swept in a slow way toward the hole periphery till reaching the top of burr. The biggest registered value on the machine stylus deforms the burr and causes small errors, which were neglected in this work. While for exit milling burrs, four points were taken along each side of the slot and one point at the end of the slot. Therefore, the reported results were the average of 9 measurements for the height of the exit burrs formed at different positions for each slot in the slot-end milling tests.

6. RESULTS AND DISCUSSION

6.1 Burr formation mechanism in slot-end milling tests

Similarly, all experimental slot-end milling tests of both steels were conducted using the approach of changing one cutting variable (either speed or feed or cutting depth) at a time. For each plate of steel, 15 slots were made using five values for cutting speed, feed rate and cutting depth according to the layout shown in the Figures 2 and 3. Form these figures, it can be seen that, generally, the largest burr formed only at the top end of the slot for both steels, respectively, and some detached or unbroken chips in form of strings were clearly seen at one side of the slot due to the effect of tool rotation (clockwise). This burr was observed to be larger than the entrance burr. Also, the shape of this burr was irregular with height varying from zero at some positions to reasonably high at the other positions (see Figure 3) due to the influence of detached or broken stringy chips. This behavior was more clearly noted after slot-end milling low carbon steel than stainless steel because of the higher ductility of the first one, especially after milling at various cutting speeds and depth of cuts. While, the feed rate after milling both steels resulted in top burrs without stringy chips remained at the top end of the slot (Figures 4). Therefore, only this top burr was considered and measured in the present work.

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

<table>
<thead>
<tr>
<th>Work material type</th>
<th>%C</th>
<th>%P</th>
<th>%S</th>
<th>%Mn</th>
<th>%Si</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel (ST37)</td>
<td>Max 0.17</td>
<td>Max 0.045</td>
<td>Max 0.045</td>
<td>1.25</td>
<td>Max 0.045</td>
<td>~</td>
<td>~</td>
<td>Max 0.01</td>
</tr>
<tr>
<td>Stainless steel (AISI316)</td>
<td>Max 0.08</td>
<td>Max 0.045</td>
<td>Max 0.030</td>
<td>Max 2.00</td>
<td>Max 0.75</td>
<td>18.00</td>
<td>20.00</td>
<td>8.00 – 12.00</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of the used work materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Yield strength (MPa) min</th>
<th>Tensile strength (02%proof) (MPa) min</th>
<th>strength (% in 50 mm) min</th>
<th>Elongation (% in 50 mm) min</th>
<th>Brinell (HB) hardness max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel (AISI316)</td>
<td>205</td>
<td>515</td>
<td>40</td>
<td>217</td>
<td></td>
</tr>
<tr>
<td>Low Carbon Steel (ST37)</td>
<td>210</td>
<td>380</td>
<td>25</td>
<td>108</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Cutting conditions used for slot-end milling operation

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting speed (m/min)</th>
<th>Feed (mm/rev)</th>
<th>Depth of cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel (AISI316)</td>
<td>2.0 – 6.6</td>
<td>14 – 45</td>
<td>0.5 – 2.5</td>
</tr>
<tr>
<td>Low carbon steel (ST37)</td>
<td>3.8 – 24.2</td>
<td>14 – 90</td>
<td>0.5 – 2.5</td>
</tr>
</tbody>
</table>
Figure 2: Photographic view of the layout of 15 slot-end milling tests conducted on the stainless-steel plate at different cutting speeds, feed rates and depth of cuts

According to Gillespie classification for burr produced by end milling operation due to plastic deformation, both Poisson and Roll-over burrs were not observed in the present work, and only Tear burr (Top burr) formed at both sides of the slot (Figures 4) when the chip was torn from work-piece, resulting in some of chip material left at the top of these sides [19]. Also, some chips in form of strings left at these sides due to the ductility of both steels. The stringy chips were generally found after milling in different sizes and easily detached or broken leaving very small top burrs at various cutting speeds, feed rates and depth of cuts.

Figure 3: Photographic view of 15 slot-end milling tests conducted on the low carbon steel plate at different cutting speeds, feed rates and depth of cuts

Whereas, referring to Avile and Dornfeld classification for the burrs produced in face milling operation with different morphologies at the machined surface, at high radial tool engagement condition, Knife-type or uniform top burrs (as primary burrs) were observed in the present work only at the end of the slot (curved edge of the slot), and they formed with largest size (with a uniform height and small thickness) due to the higher material plastic deformation when the tool leaves the slot [11]. This is most likely because the chip has a big chance to move in the vertical direction instead of moving laterally towards the side of the slot due to tool rotation, particularly at the far end of the slot curve. This Knife-type burr is then changed to Wave-type burr along the top end of both sides of the slot, which is smaller in size than the former burr due to the increasing effect of the tool rotation. So, the wave-type burr was seen at the top end of both sides of slot due to the influence of broken stringy chips. Also, highly small secondary burrs were noticed at the bottom of the machined surface of the slot due to the feed effect, and they were generally not periodic with respect to the feed marks.

6.2 Effect of cutting conditions on slot-end milling burr formation mechanism

Regarding the effects of cutting conditions after slot-end milling of both steels, the whole burrs formed were very small in height (almost less than 0.01 mm) over the whole range of cutting speeds, feed rates and cutting depths in all milling tests (see Figures. 5-10). The value of the measured burr varied in size due to the influence of different milling burr formation mechanisms occurred during the used range of cutting conditions. However, the burr height was slightly higher in case of milling low carbon steel than that for stainless steel due difference in material ductility, and the change in the feed rate resulted slightly lower burr height in comparison with the cutting speed and depth of cut. Therefore, the range of cutting conditions used in the present work is quite suitable for slot-end milling both steels.

Figure 4: Main types of burr formation mechanisms occurred after slot-end milling tests of low carbon and stainless steels

Figure 5: Effect of cutting speed on average burr height in slot-end milling low carbon steel at feed rate = 35 mm/min and depth of cut = 2 mm

Figure 6: Effect of cutting speed on average burr height in slot-end milling stainless steel at feed rate = 14 mm/min and depth of cut = 2 mm
7. CONCLUSIONS

1. Some types of milling burrs mentioned in the previous works occurred during the slot-end milling tests of low carbon and stainless steels.

2. The range of cutting conditions used in the present work is quite suitable for slot-end milling both steels.

3. In slot-end milling of both steels, only top burr (tear burr), knife burr and the secondary burr formation mechanisms mainly occurred were over all the used cutting conditions; however, the change in the feed rate resulted in a slightly lower burr height in comparison with the cutting speed and depth of cut.

4. The type of burr and its formation mechanism depend mainly on the ductility of the material to be machined as well as the used cutting conditions.

REFERENCES


