Tool life and tool wear in the semi-finish milling of inclined surfaces

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Abstract

Functional die and mold components have complex geometries and are made of high hardness materials, which make them difficult to machine. This work contributes to a better understanding of this type of process and of the wear mechanisms of tools used in semi-finishing operations of hardened steels for dies and molds. Several milling experiments were carried out to cut AISI H13 steel with 50 HRc of hardness using the high-speed milling technique. The main goal was to verify the influence of workpiece surface inclination and cutting conditions on tool life and tool wear mechanisms. The main conclusions were the inclination of the machined surface strongly influences tool life and tool wear involves different mechanisms. At the beginning of tool life, the wear was caused mainly by abrasion on the flank face plus diffusion and attrition on the rake face. At the end of tool life, the mechanisms were adhesions and microchipping at the cutting edge.

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1. Introduction

The manufacturing of numerous industrial parts depends on the construction of molds and dies for plastic injection, forging processes, powder metallurgy, casting, etc. Functional mold and die components are usually made of parts with complex geometries and with materials of high hardness, which makes machining processes difficult. Although the construction of dies and molds represent a minor investment compared with total production costs, their design and manufacturing comprise a significant portion of the total time of development. Another important issue is that, in the production of some parts, the quality of dies and molds directly affects the quality of the final product (Altan et al., 2001, 1993).

Rough milling, particularly for medium and large molds, is done before heat treatments, while semi-finishing and finishing operations take place after heat-treating the workpiece. These final operations normally use tools with small diameters, small feed per tooth, radial and axial depth of cut and higher tool rotation and feed velocity than in conventional processes. This type of process is known as high-speed machining (HSM). HSM includes advantages such as low cutting forces, minimum distortion of machined surfaces and, hence, the possibility of machining thin walls with excellent surface finish, low thermal damage to the workpiece, and reduction of total mold construction time (compared with electric discharge machining). On the other hand, several problems have been identified in the use of HSM, i.e., the need for expensive tool materials and for specific tool-holding systems, short machine life and the use of expensive machine tools with costly control systems (Dewes and Aspinwall, 1997).

Tools for semi-finishing and finishing operations must generate complex forms, which is why they have curved edges, like the toroidal and ball nose end mills. These tools may be either solid (mainly for small diameters) or with inserts (Sandvik Coromant, 2007). There are several options of tool materials for milling dies and molds using HSM, including cemented carbide, cermet, ceramic and cubic boron nitride (CBN). These materials are usually coated to increase their surface hardness, minimize the friction coefficient between chip and tool, and to improve their chemical stability (Schulz and Moriwaki, 1992). The most widely used tool material is coated micrograin cemented carbide (Sandvik Coromant, 2007).

With small radial and axial depths of cut, the angle of the tool engagement in each revolution is very small. Due to this small engagement, the cutting speed can be higher than the speeds used in high angles of engagement while still providing a long tool life. This, allied to the fact that the tool diameter for these operations is small, requires very high tool rotational speeds. Feed per tooth is also higher than that used for regular milling in order to compensate a little the low angle of engagement and to obtain an average chip thickness not very small. Therefore, with high tool revolution and high feed per tooth, the feed velocity is very high. With this set of cutting conditions (small radial and axial depth of cut, small chip thickness, high cutting speed and feed velocity) it is possible to obtain a very good surface roughness with a much higher removal...
rate than that achieved in electric discharge machining processes (Schulz, 1995).

If a surface perpendicular to the tool axis is machined with a ball nose mill, the cutting speed in the center of the tool is zero and the chip thickness is very small. This may cause chipping at the cutting edge, thereby impairing the quality of the machined surface. However, in most cutting operations with this type of tool, the surfaces generated are not perpendicular to the tool axis. With inclined surfaces, the problem of cutting speed is absent since the effective tool diameter is increased (Schulz, 1995; Kang et al., 2001). The angle between the tool axis and the surface (α) exerts a strong influence on the components of the cutting force. When the tool axis is parallel to the surface (α = 90°), only tangential and radial components of force are present (the axial component is close to zero). As this angle decreases, the value of the radial component decreases and the value of the axial component increases, as indicated in Fig. 1 (Diniz et al., 2006). In an end mill, the tool's radial direction is not very rigid, since only the body of the tool resists the tool's deflection. On the other hand, the axial direction is very rigid since, in this direction, the tool fixation and the machine head resist the compression caused by the force component. One of the goals of this work is to evaluate the importance of this variable (angle of surface inclination) on tool life and tool wear mechanisms.

Due to these factors in the HSM conditions, the tool is subjected to high stresses, high temperatures and thermal and mechanical fatigue (Byrne et al., 2003). Moreover, depending on the size of the mold, the end of tool life may occur in the machining of a single part. The literature contains few studies on tool life, and especially on the progression of tool wear mechanisms in HSM conditions. Ning et al. (2008) studied tool wear patterns in a cemented carbide ball end mill with different coatings while milling AISI H13 steel with 55–57 HRC. They report that, after the exposure of tool substrate caused by the initial wear, two zones are formed at the cutting edge: a zone resulting from rubbing and sliding by chips and a crater zone. However, they gave no information about the inclination of the machined surface. Moreover, a high depth of cut (5 mm) was used in the experiments of finishing HSM operations.

This work aims to evaluate the influence of the inclination of machined surfaces (since the surfaces of molds and dies usually have different inclinations), feed per tooth and radial depth of cut (at a constant average chip thickness) on tool life and tool wear mechanisms. Another goal is to understand the tool wear mechanisms in the high-speed milling of hardened AISI H13 steel in order to support the development of tool material grades and tool geometries for this type of operation.

2. Material, equipment and experimental procedures

The experiments were carried out in a 3-axis CNC vertical machining center with 22 kW of power in the spindle motor and a maximum tool rotation of 12,000 rpm.

The workpiece material was AISI H13 steel with 50 HRC of hardness. Fig. 2 shows the geometry of the workpieces. The machined surfaces were designed in such a way that the tool could be accelerated and decelerated while it was outside the workpiece, thereby maintaining a constant feed velocity while the tool was engaged in cutting. The tool's feed movement began 30 mm before entering the cut and ended 30 mm after leaving the cut in each pass.

The tool used in the experiments had two circular inserts with a 7 mm diameter (code R300-0720E-PM) set in a 12 mm steel tool holder (code R300-012A16L-07L), both manufactured by Sandvik Coromant. The tool was assembled on a hydraulic chuck with an overhang of 70 mm. The inserts were made of carbide (H15 grade – Sandvik code GC1025) and coated with multiple layers of TiCN and TiN deposited by the PVD process.

Flank wear was inspected several times during tool life, using an optical microscope. Tool life was considered ended when flank wear reached VB8 = 0.20 mm. After the end of tool life, the worn inserts were examined under a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDS) system in an attempt to understand the wear mechanisms. In one of the experiments, the inserts were examined by SEM at 10-min intervals during cutting in order make a step-by-step evaluation of the wear growth.

One experiment consisted of successive milling passes on two inclined surfaces of 215 mm length (see Fig. 2), interrupting the process at regular intervals to measure tool flank wear. The experiments continued up to the moment when the tool reached the end of its life. Each experiment was carried out in triplicate.

The cutting conditions were varied in order to evaluate the influence of the surface inclination (angle α in Fig. 2) and the radial depth of cut (ar) and feed per tooth (fr) on the tool wear and tool life. The values of radial depth of cut were set to maintain a constant average chip thickness despite variations in feed per tooth and surface inclination. The milling of an inclined surface with a toroidal end mill like the one used here generates a chip curved in both rotational and frontal directions. With this chip geometry, the calculation to obtain the same average chip thickness under different cutting con-
conditions is a complex task. Therefore, a CAD system was required to determine this thickness.

As illustrated in Fig. 3, the average chip thickness \( h_m \) was determined based on the following procedure: (a) determination of the volume of material removed by a cutting edge in each tool rotation based on the cutting parameters \( f_z \) and \( a_p \) recommended by the tool manufacturer; (b) determination of the center of gravity (C.G.) of this volume of material; (c) cutting the volume of material by orthogonal planes converging at the C.G.; (d) determination of the average chip thickness \( h_m \) at the center of gravity of the volume (which resulted in a value of \( h_m = 0.034 \) mm using the cutting parameters \( f_z \) and \( a_p \) recommended by the tool manufacturer); (e) calculation of new pairs of \( f_z \) and \( a_p \), which kept the average calculated chip thickness \( h_m = 0.034 \) mm at \( d \). The used value of average chip thickness \( h_m \) is suitable for semi-finishing in die and mold milling.

Cutting speed \( v_c \) and axial depth of cut \( a_p \) were \( v_c = 300 \) m/min and \( a_p = 0.25 \) mm, respectively. Table 1 shows the cutting conditions used in the experiments. These conditions are also suitable for the semi-finish milling operation of dies and molds.

All the experiments were carried out using down milling and dry cutting.

### 3. Results and discussion

Fig. 4 shows the tool life results of all the experiments. The analysis of variance indicated that the inclination of the machined surface (angle \( \alpha \)) significantly affected tool life (at a confidence interval of 99%). However, neither the cutting parameters (radial depth of cut and feed per tooth) nor their interaction affected tool life. When the angle \( \alpha \) changed from 45° to 75°, tool life dropped sharply, as illustrated in the figure.

The reason why the surface inclination affects tool life so strongly is the variation of the force components. The tool-fixture system was very rigid in the axial direction (in this direction, the tool fixation and the machine head resisted the compression caused by the force), but was less rigid in the radial direction (in which only the body of the tool resisted the deflection caused by the force). When \( \alpha = 45° \) was used, the radial and axial components of the cutting force were balanced, but when this angle changed to 75°, the axial component decreased and the radial component increased. This caused the tool deflection, and hence, the tool vibration to increase, reducing the tool life.

These results are consistent with those reported by Schulz (1995), who also states that a surface inclination of 10–20° produces the best results in terms of tool life. Thus, this is one of the advantages of using a 5-axis machine to cut dies and molds. This type of machine allows the inclination between tool and surface to be kept at a suitable value regardless of the absolute inclination of the surface, thus optimizing tool life.

As can be seen in Fig. 4, the cutting parameters did not influence tool life to any appreciable extent. As mentioned earlier, when feed per tooth increased, the radial depth of cut was reduced to maintain a constant average chip thickness. Increasing the feed per tooth causes the volume of chips removed by the cutting edge in each revolution to increase as well, which tends to decrease tool life. In contrast, decreasing the radial depth of cut causes the contact angle between cutting edge and workpiece in each revolution to decrease, preventing the tool temperature from increasing, and hence, tending to increase tool life. Therefore, the opposing effects of feed per tooth and radial depth of cut caused the tool life to remain constant when the former was increased and the latter decreased. However, the limit for the increase of feed per tooth \( f_z \) is the machine tool’s capacity to reach and maintain the feed velocity \( v_f \). For example, with \( f_z = 0.25 \) mm, \( v_c = 300 \) m/min and \( \alpha = 45° \), \( v_f \) is 5.4 m/min. According to Altan et al. (2001), using an A55 Makino Machining Center, it is necessary for the tool to move 4 mm before achieving a maximum speed of \( v_f \) = 5 m/min. Therefore, depending on the surface complexity, the programmed \( f_z \) is never attained during the cutting operation.

Fig. 5 shows images of the worn tool (taken in a SEM) used in the experiment with \( \alpha = 45° , f_z = 0.25 \) mm and \( a_p = 0.40 \) mm, together with the EDS analysis of several points. These images were recorded at the end of tool life. The other experiments using the same sur-

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Tool Material</th>
<th>Coating</th>
</tr>
</thead>
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<tr>
<td>( v_c ) (m/min)</td>
<td>( f_z ) (mm)</td>
<td>( a_p ) (mm)</td>
<td>( \alpha ) (°)</td>
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<tr>
<td>300</td>
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face inclination showed similar types of wear, so images of the worn tools are not shown here. This figure indicates that the main wear mechanism of this tool was microchipping of the edge (chipping size smaller than the maximum flank wear) and adhesions of workpiece material. In detail “A” of Fig. 5, the EDS analysis revealed iron and silicon adhesion, both from the workpiece material, and tungsten from the tool substrate. Microchipping was visible all along the edge. Ghani et al. (2004) conducted end milling experiments on AISI H13 steel (50 HRc), using P10 carbide inserts with TiN coating. Their cutting conditions were $v_c = 280$ m/min, $f_z = 0.25$ mm, $a_e = 3$ mm and $a_p = 0.3$ mm. Their analysis of the progress of wear was based on images taken in an optical microscope, which does not allow for large magnification or energy dispersive X-ray (EDS) analysis, thus preventing an understanding of the wear phenomenon. Be that as it may, the authors state that the main tool wear mechanisms were chipping and thermal cracking. Their results were partially similar to those obtained in this work. The major difference is that thermal cracking was not detected in the images in Fig. 5 nor in those of other tools used in our experiments. The high amount of workpiece material adhering to the cutting edge prevented the identification

![Fig. 4. Tool lives for all experiments (in cutting time and in machined area).](image)

![Fig. 5. Pictures of the flank wear land in the end of tool life ($f_z = 0.25$ mm, $a_e = 0.40$ mm, $\alpha = 45^\circ$). (a) Flank face. (b) Detail “A”.

![Fig. 6. Pictures of the flank wear land in the end of tool life ($f_z = 0.20$ mm, $a_e = 0.51$ mm, $\alpha = 75^\circ$). (a) Flank face. (b) Flank face.](image)
of possible thermal cracks, but it may have caused the chipping. As we will see later herein, additional experiments were carried out to check if such cracks actually occurred.

Fig. 6 shows two worn cutting edges used in different repetitions of the experiments with \( f_z = 0.20 \text{ mm}, a_e = 0.51 \text{ mm} \) and \( \alpha = 75^\circ \). The experiments with other cutting conditions but with the same surface inclination presented similar types of wear and are therefore not shown here. In both images of this figure, the EDS analysis revealed adhesions of workpiece material (iron and silicon) on the tool flank face with slight microchipping (smaller than that obtained with the tool used to cut the 45\(^\circ\) surface inclination). Therefore, it seems that attrition (cyclical adhesion and removal of workpiece/chip material from the tool, which also causes removal of tool particles – Trent and Wright, 2000) was the tool wear mechanism that caused the end of tool life.

Comparing the wear mechanisms of the tools used to cut the two surfaces (45\(^\circ\) and 75\(^\circ\)), it can be seen that, although tool life was longer for the 45\(^\circ\) surface, the microchipping produced at the cutting edge was greater in these tools. An explanation for this may be the mechanical fatigue of the tool as a result of the frequency and number of tool impacts. Changing the angle from 45\(^\circ\) to 75\(^\circ\) caused an increase in the effective tool diameter. With a larger diameter, it was necessary to lower the tool's rotational speed (rpm) to reach the same effective cutting speed. The reduction of tool rotation meant a decrease of the frequency of the cutting edge entering the workpiece. In this case, the decrease was from 180 to 144 Hz (a 20\% decrease). Moreover, tool life also decreased on average 46.3\% in terms of cutting time. The combination of these two factors significantly reduced the number of impacts of each edge against the workpiece throughout the tool's life. This may have caused the decrease in the extent of microchipping when the surface inclination changed from 45\(^\circ\) to 75\(^\circ\). Whether or not mechanical fatigue was the cause of microchipping of the edge when a 45\(^\circ\) inclined surface was machined is discussed in greater depth below.

To gain a better understanding of the tool wear mechanisms throughout the tool's life, one of the experiments \((f_z = 0.25, a_e = 0.4 \text{ mm} \text{ and } \alpha = 45^\circ)\) was repeated and the tool was examined by SEM at 10-min intervals during the cutting time. Due to the time-consuming nature of this type of experiment (stopping the experiment, removing the insert from the tool holder, cleaning the insert and using the SEM for a long period), it could not be repeated for all experiments, but the results of this experiment should clarify the development of tool wear during the tool's life. Tool life in this experiment was close to 60 min. SEM images of the tool were taken six times during the tool's life \((10, 20, 30, 40, 50 \text{ and } 60 \text{ min})\). To save space, only the images recorded at 10, 30 and 50 min of cutting time are shown. Images taken at 60 min of cutting are already shown in Fig. 5, since this is at the end of tool life.

Fig. 7 shows images taken after 10 min of cutting time. As Fig. 7a indicates, flank wear was 50 \(\mu\text{m}\) at this time. Fig. 7b and c shows magnified views of two regions of the wear land depicted in Fig. 7a. In detail “A”, the wear consists of several abrasive scratches in the cutting direction. An EDS analysis of this wear region showed large amounts of tungsten, iron and silicon. The presence of tungsten indicates that in just 10 min of cutting, the abrasion process had already removed the tool coating, exposing the tool substrate. The presence of iron and silicon indicates adhesion of workpiece material. Detail “B” shows two types of wear: abrasive scratches and cratering in the upper part of the wear land. An EDS analysis of the inside of the crater revealed the presence of tungsten from the tool substrate. The reason for only one type of wear on one side of the wear land (abrasive scratches shown in detail “A”) and two types of wear on the other side (abrasive scratches and cratering in detail “B”) is the chip geometry. Chip thickness changes constantly.
and in every direction with this type of cut. In some regions, chip thickness was much smaller than the cutting edge radius, which was 30 \( \mu m \). High strain rates occurred in these regions, causing the workpiece/chip material to be crushed between the tool flank face and the workpiece. As a result, part of the chip/workpiece, deformed and hardened by this deformation, flowed between the edge and the workpiece, causing abrasive flank wear, which was confirmed by the abrasive scratches shown in the image. This flow of chip/workpiece (called secondary chip flow) also stuck to the flank face, causing the adhesion also shown in the image (detail “A” of Fig. 7). On the other hand, in the areas where chip thickness was larger than the edge radius, the chip was in contact with the tool rake face, causing crater wear (detail “B” of Fig. 7). Cratering is usually related with diffusive wear. According to Trent and Wright (2000), diffusive wear occurs in conditions with high removal rates, where a flow zone appears at the interface between the tool rake face and the chip. Other important factors favoring diffusive wear are chemical affinity between the tool and workpiece and a combination of length of time and high temperatures when the two are in contact. Contact time between these two bodies cannot be short. Moreover, diffusive wear lands look smooth. There is a strong chemical affinity between the H13 steel and the tool substrate material (tungsten carbide and cobalt). The blue color of the chips was evidence of the high cutting temperature. The crater wear depicted in Fig. 7c is smooth. The EDS analysis of this region indicated that the coating, which has less affinity with the workpiece material, had already been removed. Therefore, many clues indicated that this crater wear was caused by diffusion. However, the occurrence of diffusive wear in an operation where the tool/workpiece contact in each tool engagement was so short (the angle of contact between tool and workpiece in each revolution was 22°43’ and the contact time 0.351 ms) was not expected. Another phenomenon that can create cratering is “attrition”. Attrition wear usually occurs at low cutting speeds, when material flow on the tool rake face is irregular and contact with the tool is less continuous. It can be described as a cyclical adhesion and removal of workpiece/chip material from the tool, which also causes removal of tool particles. Under these conditions, microscopic particles of the tool are pulled out and dragged together into the material flow. The irregular material flow necessary for attrition wear to occur is caused by the sliding zone between chip and tool, by interrupted cutting, irregular depth of cut and vibration (Trent and Wright, 2000; Machado and Silva, 2004). Such events also occurred in the experiments reported here. Therefore, it is reasonable to state that diffusion and attrition occurred simultaneously, causing the crater wear shown in Fig. 7.

The images in Fig. 8 were taken at 30 min of cutting time. Fig. 8a shows that flank wear was 85 \( \mu m \) at that moment. Fig. 8b and c is magnified images of the “A” and “B” regions shown in Fig. 8a, respectively. As can be seen in detail “A” of Fig. 8b, the amount of workpiece material adhesions increased greatly when compared with the same detail “A” in Fig. 7b. The adhesions in Fig. 8b have a scab-like appearance, indicating that they occurred at different times during cutting. The adhesions in detail “A” also covered the abrasive scratches shown in Fig. 7b. The detail “B” of Fig. 8c consisted mainly of craters. In addition to the smooth appearance of the craters, an EDS analysis revealed high levels of tungsten inside them. Therefore, the wear mechanism of the crater continued as described earlier, i.e., simultaneous diffusion and attrition leading to crater wear. The abrasive wear visible just below the crater wear in Fig. 7c is no longer as clear in Fig. 8c due to the crater’s increased size.

Fig. 9 shows images taken after 50 min of cutting time, when flank wear was 150 \( \mu m \) (Fig. 9a). Some microchipping is already visible at the cutting edge (Fig. 9a), which increased and had become

![Fig. 8. Flank wear land at 30 min of cutting time (\( f_c = 0.25 \text{ mm}, a_v = 0.40 \text{ mm}, a = 45° \)). (a) Flank face. (b) Detail “A”. (c) Detail “B”.](image-url)
was not so severe in the surface tool was caused by mechanical fatigue of the cutting edge. We explored the possibility that microchipping of the surface was caused by mechanical fatigue or by other mechanisms. If the latter alternative were true, there would be no reason for the 75° surface tool wear to be caused by mechanical fatigue, since this was not detected in the tool used to cut the 45° surface, which impacted the surface much more frequently than the tool used to cut the 75° surface. At this point, it is possible to state that the second possibility is true. The wear mechanisms for the tools that cut the 45° surface were a combination of diffusion, attrition and dislodgment of workpiece material adhesions carrying particles of the tool. The tool was sufficiently resistant to support the cyclical mechanical load of the process without becoming fatigued. Tool lives when milling the 75° inclined surfaces were shorter than when the 45° surfaces were machined, because the higher radial force, tool deflection and tool vibration when machining the 75° inclined surfaces favored mainly attrition and dislodgment of workpiece material adhesions. However, the fact that microchipping was almost absent in the tool which machined the 75° surface must still be explained. As stated earlier herein, due to the larger radial component of the cutting force in this type of process, the tool undergoes stronger vibration than the one machining the 45° surface. The presence of vibration prevents the occurrence of diffusion because the latter depends on the time of contact, as mentioned earlier. Therefore, this tool did not exhibit crater wear (see Fig. 6, where the shape of the edge closely resembles the original shape), so the edge was not weakened and the attrition process did not chip it.

Based on these results, several hypotheses may explain the cause of microchipping: (a) weakening of the cutting edge due to increased crater wear caused by diffusion and attrition; (b) mechanical or thermal fatigue of the cutting edge; and (c) dislodgment of the workpiece material adhesions carrying particles of the substrate. The latter phenomenon differs from attrition due to its scale. While attrition occurs on a microscopic scale, the dislodgment of large adhesions removes particles of hundreds of millimeters. Weakening of the cutting edge resulting from crater wear was already addressed in the discussion of Fig. 7. Mechanical or thermal fatigue would have to be proved by the presence of cracking parallel (mechanical cracks) or perpendicular (thermal cracks) to the cutting edge (Diniz et al., 2006). Such cracks were not visible, either because they did not actually occur or because they were hidden by the adhesion of workpiece material on the wear land. Dislodgment of workpiece material adhesions carrying large particles of tool substrate was very likely due to the strong adhesion between iron and silicon from the workpiece material and tungsten from the tool substrate.

The SEM images allowed for the identification of several wear mechanisms throughout tool life when the 45° inclined surface was machined. At the beginning of tool life, it was found that, on one side of the contact between edge and workpiece, abrasion quickly removed the tool coating, and on the other side, very likely diffusion and attrition caused crater wear. As the wear increased in the region where the tool coating had been removed, workpiece/chip material started to adhere on the flank wear land. When dislodged by the chip and workpiece flow, these adhesions removed large particles of the tool substrate. On the other side of the contact, in the region where crater wear resulted from diffusion and attrition, the increase in crater size weakened the microgeometry of the edge, making the cut more negative and thus causing microchipping at the cutting edge. Since cracking was not visible on the wear land, it cannot be assumed that either mechanical or thermal fatigue caused microchipping.

Earlier in this paper, we discussed the fact that, although tool life lasted longer with the 45° surface than the 75° surface, microchipping of the cutting edge was greater with tools used on the 45° surface. We explored the possibility that microchipping of the 45° surface tool was caused by mechanical fatigue of the cutting edge and was not so severe in the 75° surface tool due to the decrease in both the frequency of the cutting edge entering the workpiece and the number of impacts against the workpiece. At that moment, we could not be sure whether the microchipping of the 45° surface tool was caused by mechanical fatigue or by other mechanisms. If the latter alternative were true, there would be no reason for the 75° surface tool wear to be caused by mechanical fatigue, since this was not detected in the tool used to cut the 45° surface, which impacted the surface much more frequently than the tool used to cut the 75° surface. At this point, it is possible to state that the second possibility is true. The wear mechanisms for the tools that cut the 45° surface were a combination of diffusion, attrition and dislodgment of workpiece material adhesions carrying particles of the tool. The tool was sufficiently resistant to support the cyclical mechanical load of the process without becoming fatigued. Tool lives when milling the 75° inclined surfaces were shorter than when the 45° surfaces were machined, because the higher radial force, tool deflection and tool vibration when machining the 75° inclined surfaces favored mainly attrition and dislodgment of workpiece material adhesions. However, the fact that microchipping was almost absent in the tool which machined the 75° surface must still be explained. As stated earlier herein, due to the larger radial component of the cutting force in this type of process, the tool undergoes stronger vibration than the one machining the 45° surface. The presence of vibration prevents the occurrence of diffusion because the latter depends on the time of contact, as mentioned earlier. Therefore, this tool did not exhibit crater wear (see Fig. 6, where the shape of the edge closely resembles the original shape), so the edge was not weakened and the attrition process did not chip it.

Based on the tool wear mechanisms described above, some changes in the tool can be recommended to improve its performance in the high-speed milling of H13 steel under conditions similar to those reported here. The first change would be a decrease of the cutting edge radius, which was 30 μm in the tool used in this work. As mentioned earlier, the average chip thickness obtained with the cutting parameters employed here was 34 μm, just slightly larger than the edge radius. Therefore, a large portion of the chip was formed at the edge radius where the cut is very negative, causing high strain rates and secondary chip flow, thus favoring abrasive flank wear and adhesions of chip/workpiece material on the flank face. Despite the deleterious effect of decreasing the rigidity of the edge, reducing the cutting edge radius would prevent the occurrence of these mechanisms and would also very likely slow the formation of flank wear. The second change would be the tool coating. According to Paldey and Deevi (2003), although TiCN coating has greater microhardness than TiAlN coating at room temperature, the hardness of TiAIN exceeds that of TiCN when the temperature reaches close to 1000°C. Moreover, TiAIN presents a higher oxidation and diffusion temperature than TiCN. At this high temperature, TiAIN forms a layer of Al2O3 on the tool surface, making it more resistant to diffusion. Therefore, the change of tool coating from TiCN to TiAIN would likely result in higher resistance to both abrasion and diffusion mechanisms.
4. Conclusions

Based on the results for semi-finish milling of AISI H13 steel with coated carbide inserts obtained in this work, it can be concluded that:

1. Tool life decreased with the increase in surface inclination. The other variables tested ($f_z$ and $a_e$ with constant $h_{im}$) did not significantly affect tool life.

2. At the end of tool life, the cutting edge of the tool used to cut the surface with a 45° angle of inclination showed extensive microchipping (chipping size smaller than the maximum flank wear) and adhesions of workpiece material. The tool used to cut the surface with a 75° inclination presented mainly adhesions of the workpiece material on the flank wear land with little microchipping.

3. During the tool life of the tool that cut the 45° surface, the progression of wear involved different mechanisms. At the beginning of tool life, wear was caused mainly by abrasion on the flank face plus diffusion and attrition on the rake face. At the end of tool life, the mechanisms were adhesions and microchipping of the edge.

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