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Built-Up Edge Effect on Tool Wear When Turning Steels at Low Cutting Speed

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In any machining process, it is very important to control the cutting variables used during the process because these will affect, for example, tool life and workpiece surface roughness. Since the built-up edge (BUE) increases the wear of the tool and affects the surface roughness of the workpiece, the study of this phenomenon is very important in predicting and minimizing the wear of a cutting tool. This research studies the influence of the BUE formation for coated carbide tools when turning medium- and high-strength steels. Different mathematical expressions were obtained to quantify this effect. Mathematical expressions for uncoated carbide tools were not possible to obtain, due to the fact that for these tools an increase in the wear and their premature fracture was observed.

Keywords built-up edge, machine tools, materials, metallurgic, process

1. Introduction

In a turning process, the surface roughness is related to the quality of the surface obtained after the cutting process and also to the cutting edge of the tool. At low cutting speed (V) values, the built-up edge (BUE) phenomenon appears, producing wear on the cutting tool as well contributing to the rough surface on the workpiece.

The BUE effect is hard to study since it is a dynamic process and microscopic in nature. Researchers have studied how the workpiece surface characteristics and chemical composition influence BUE removal.[1] Recent research on tool wear has concentrated on determining the different mechanisms and types of wear for different materials and cutting tools.[2] Many of these investigations have studied the influence of selected variables (e.g., cutting parameters, tool geometry, and vibration present during the machining process) on the surface roughness of the workpiece.[3,4]

This project was undertaken to study the BUE phenomenon on the tool wear rate and also because no mathematical expression exists that allows users to estimate the wear of the cutting tool during a turning process for different carbon steels as a function of the cutting variables and its relationship to the BUE phenomenon.

2. Experimental Procedures

AISI 1020, AISI 1045, and AISI 4140 steel bars were used as workpiece materials. The chemical compositions and mechanical properties are shown in Tables 1 and 2, respectively.

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WIDIA-coated carbide tools DNMG 150604, DNMG 150608, and DNMG 150612, and WIDIA uncoated carbide tools DNMG 150404 and DNMG 150408 were used for all machining/turning experiments.

Table 1 Chemical composition of the different steel bars used in the experiments

Material	%C ± 0.001	%Mn ± 0.001	%Cr ± 0.001	%Mo ± 0.001
AISI 1020	0.214	0.492	…	…
AISI 1045	0.473	0.837	…	…
AISI 4140	0.419	0.864	0.827	0.172

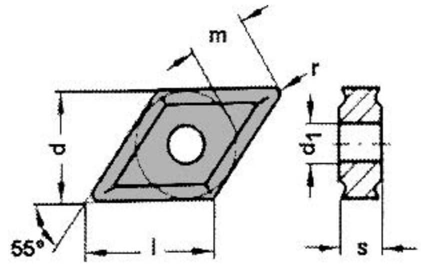
Table 2 Mechanical properties of the different steel bars used in the experiments

Material	HBN(a)	S_{ys}, MPa	S_u, MPa
AISI 1020	131	441	598
AISI 1045	174	490	814
AISI 4140	262	588	1030

(a) Ø = 10 mm; load = 3000 kg
S_{ys}, tensile yield strength; S_u, ultimate tensile strength

Nomenclature

BUE	Built-up edge
C	Carbon (%)
Cr	Chrome (%)
d	Depth of cut
f	Feed rate (mm/rev)
HBN	Brinell hardness number
Mn	Manganese (%)
Mo	Molybdenum (%)
r	Tool nose radius (mm)
V	Cutting speed (m/min)
VB	Tool flank wear (mm)



Code	l	s	r	d	d_1	m
DNMG 150604	15.5	6.35	0.4	12.7	5.16	6.939
DNMG 150608	15.5	6.35	0.8	12.7	5.16	6.478
DNMG 150612	15.5	6.35	1.2	12.7	5.16	6.015
DNMG 150404	15.5	4.76	0.4	12.7	5.16	6.939
DNMG 150408	15.5	4.76	0.8	12.7	5.16	6.478

Dimensions in mm

Fig. 1 Schematic of the tools used for the experiments

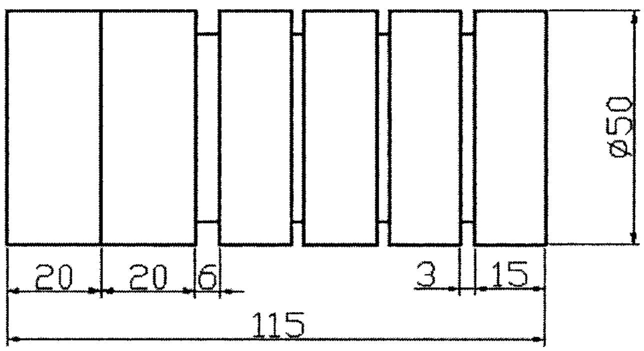


Fig. 2 Schematic of the bars used for the experiments (in millimeters)

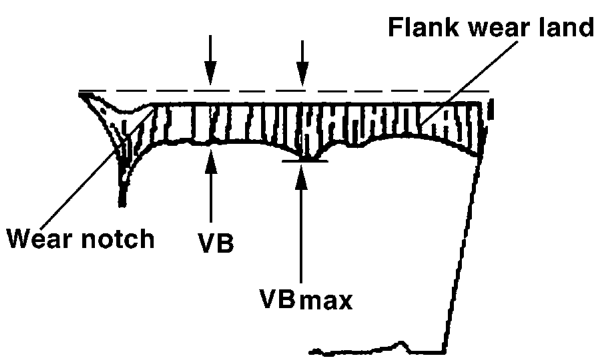


Fig. 3 Schematic of *VB*

The cutting variables used for the experiments in this study are shown in Table 3. To ensure BUE formation, a dry cut with a small depth of cut (*d*) was used for the experiments,[2] and the *V* values were selected based on previous research.[4] Tests were conducted to the specifications shown in Fig. 2.

Combining all the variables for uncoated carbide tools, 72 experiments were conducted. Each experiment was repeated five times, thereby increasing the length of cut to study tool wear increase. This gave a total of 360 experiments. The ISO 3685 NORM establishes a value of 0.3 mm for tool flank wear (*VB*), but in this research a value of 0.2 mm for *VB* was used to reduce the overall experimental time. (See Fig. 3 for details.)

For coated carbide tools, when all variables are considered, a total of 108 experiments were run. These experiences also were repeated to study *VB* as a function of the cutting time (i.e., a constant *V* of 10 m/min was used). Also, for these experiments, a value of 0.2 mm for *VB* was the limiting dimension, giving a total of 378 experiments.

Table 3 Cutting variables used for the experiment

V, m/min	4, 6, 8, 10
f, mm/rev	0.1, 0.2, 0.3
d, mm	0.4
r, mm	0.4, 0.8, 1.2

3. Results and Discussion

Once all the experiments were completed, the following results were obtained: Fig. 4 shows the influence of the *V* on the *VB* for the three experimental conditions. In Fig. 4(a), it was observed that *V* had a small influence on the *VB* for the uncoated tool. Also, it was observed that the range of tool wear was higher for the uncoated tools compared with the coated ones.

Figure 4(b) shows that for the coated tools a slight decrease in tool wear occurs when *V* is increased. This is probably due to BUE formation, since it is well known that the BUE phenomenon increases the tool wear rate. BUE formation also has the tendency to minimize it when the *V* is increased.

Figure 5 shows the influence of feed rate (*f*) on *VB* for both types of tools (coated and uncoated). It was observed that as the *f* increased, the tool wear also increased. This behavior is due to the fact that as the *f* is increased a larger chip is formed, and, as a consequence of this, the cutting force is also increased.

Figure 6 shows representative behavior of *VB* as a function of the tool nose radius (*r*), where the highest values of wear were obtained when using tools with larger *r* values. This behavior does not agree for high values of *V*, and this is probably due to the fact that as the *r* increases, the radial component of the cutting force increases as well, affecting the stability of the cutting process (i.e., an increase in the amount of vibration). Also, if the chip produced during the cutting process is very thin (as it is in this case), an intermittent cut is produced. This leads to a rough surface, increasing the *VB* due to the friction between the tool flank and the workpiece.[5]

Figure 7(a) shows the influence of workpiece hardness on *VB* for uncoated tools. In general terms, it was observed that as the workpiece hardness increases, *VB* increases. This agrees

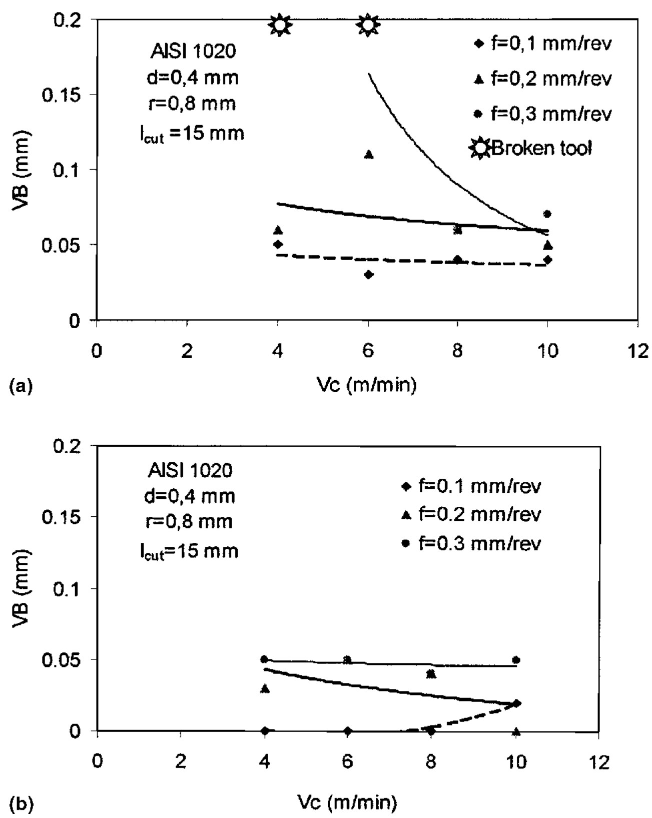


Fig. 4 Influence of the *V* on the *VB*: **(a)** uncoated and **(b)** coated

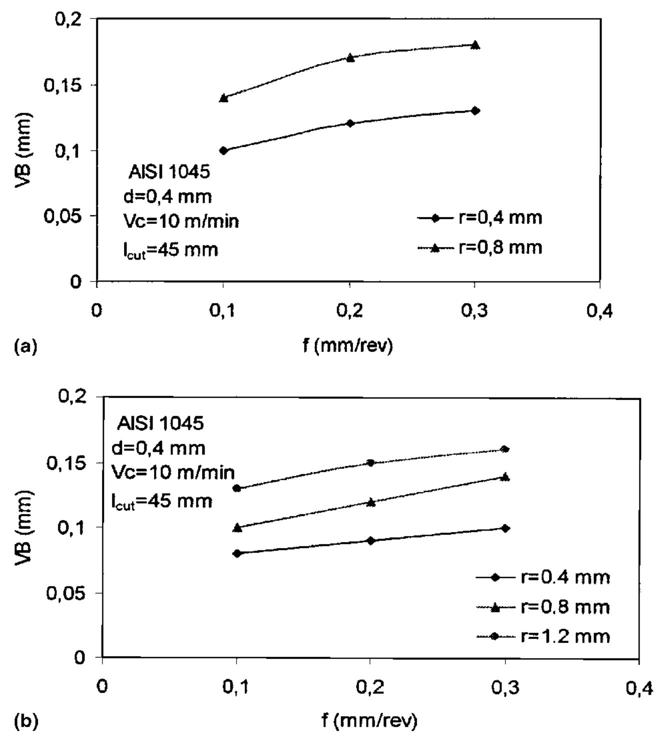


Fig. 5 Influence of the *f* on *VB*: **(a)** uncoated and **(b)** coated

with theory.[6,7] Also, it was observed that the tool used to cut the AISI 4140, under extreme cutting conditions, fractured prematurely.

Figure 7(b) shows the influence of the workpiece hardness on the *VB* for the coated tool. In this case, it was observed that even though AISI 4140 had the highest hardness of all the tested steels, the tool used in this experiment showed very little wear. This result is probably due to the fact that the BUE does not form so easily when using this kind of tool to cut this type of steel. This fact was corroborated later, when the frequency of BUE formation was studied and the tool condition was evaluated after cutting the 4140 steel.

When comparing *VB* values obtained when considering the cutting time spent to reach a wear value of 0.2 mm (as was mentioned before for both types of tools, coated and uncoated), higher values of wear occurred when using uncoated tools. This result is shown in Fig. 8. Evaluating the tool superior face for the uncoated tools, it was noted that for certain cutting conditions, BUE formation occurred. This fact supports the supposition that BUE formation is the responsible for *VB* and the atypical behavior noted for these tools.

A total of 13 of 72 experiments showed BUE formation (18%) for uncoated tools, but since this is a dynamic process this does not mean that the other tools did not undergo BUE formation during cutting. On the other hand, 30% of the tools fractured prematurely, and in these cases they did not show BUE formation. Also, it was observed that BUE appeared more often on tools that were used to cut AISI 1045 steel (Fig. 9), even though greater BUE formation occurred on tools that were used to cut AISI 1020 steel, due in large part to its characteristic ductility. BUEs that occurred on cutting tools for each cutting condition were analyzed using scanning electron microscopy (SEM). BUE was characterized by its porous nature, as indicated in the micrograph shown in Fig. 10. Figure 11 shows the superior face of an uncoated tool that fractured earlier than expected during the cutting process. Most fractures of this type were associated with the cutting of AISI 4140 steel. A tool life of 2.6 min (which is very low) indicates that many factors are involved in tool wear, including, for example, BUE formation and vibrations.

The remainder of the uncoated tools that did not fracture or show BUE formation during the cutting process showed characteristics of adhesion or abrasion wear. Figure 12 (left panels) shows, for a particular case, a surface worn as a result of the continuous flow of the chip during the machining process. This result suggests that an abrasion mechanism is responsible for the surface wear of the tool. This behavior was constant for all conditions.

Figure 12 (right panels) shows a zone where the tool has lost part of its material (superior-left zone), most probably due to BUE formation and removal. It was noticed that an adhesive-type wear mechanism was present in this case.

The coated tool (superior face) did not show any signs of BUE formation on the nose of the tool. All tools showed some signs of wear of the coating, and, in some cases, a partial loss of this coating was observed. Figure 13 shows the details of the different worn zones that have been evaluated.

Different mathematical expressions, describing coated *VB* behavior as a function of the cutting time, *f*, and *r*, were obtained for a *V* of 10 m/min. The expressions were obtained using linear multiples. A mathematical expression for uncoated

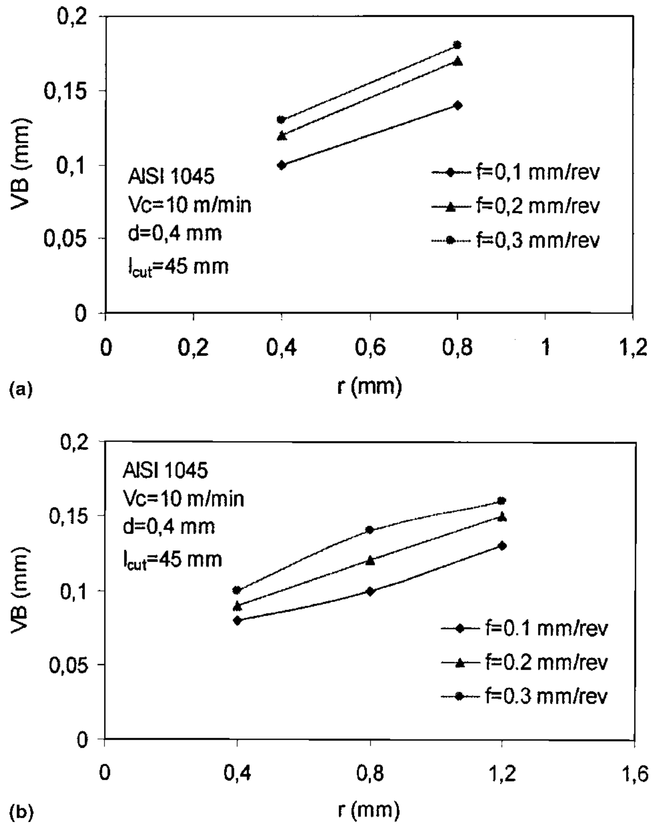


Fig. 6 Influence of the *r* on *VB*: **(a)** uncoated and **(b)** coated

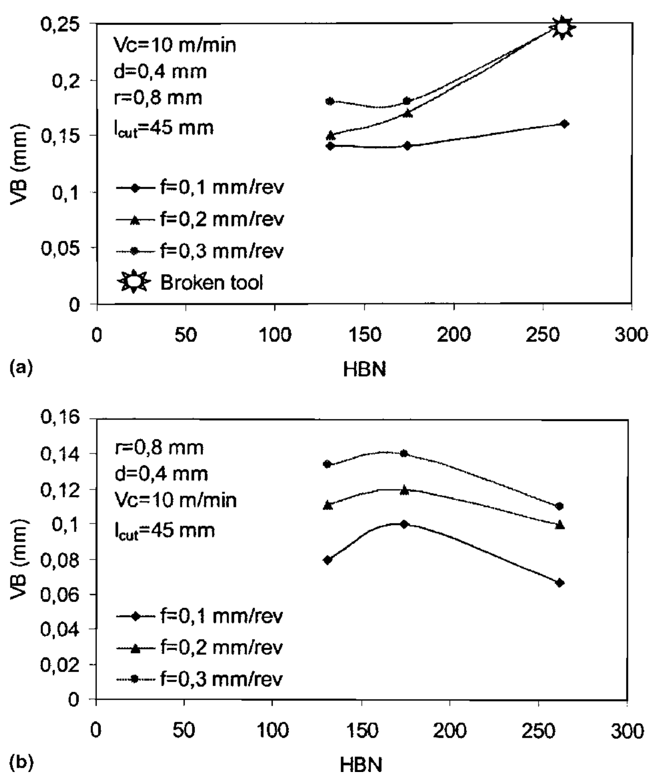


Fig. 7 Influence of the workpiece hardness on *VB*: **(a)** uncoated and **(b)** coated. HBN, Brinell hardness number

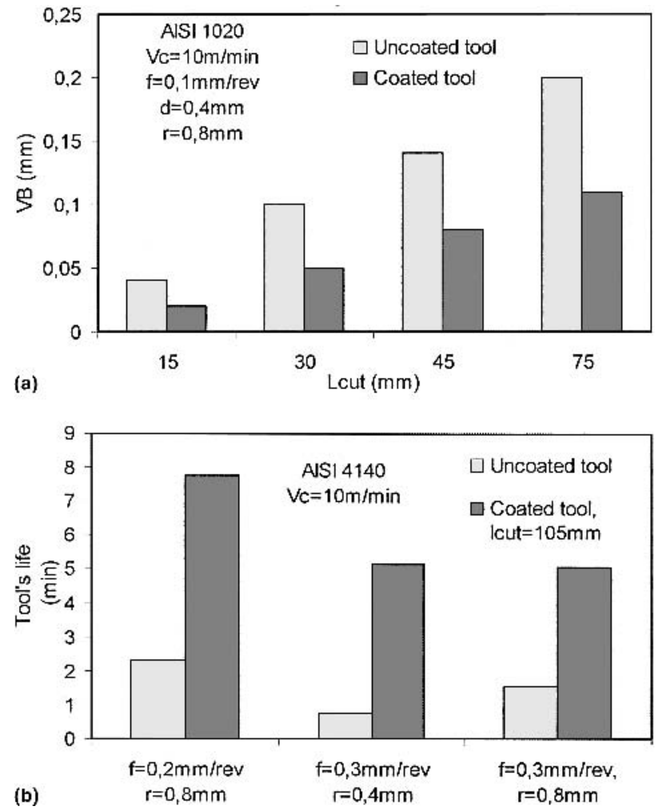


Fig. 8 Comparative diagrams of **(a)** tool wear and **(b)** tool life for uncoated and coated tools

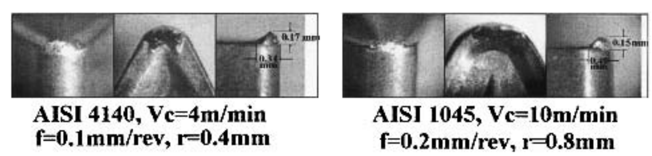


Fig. 9 Superior and lateral views of uncoated tools with the presence of BUE after cutting AISI 1045 and AISI 4140 steels using different *r* values

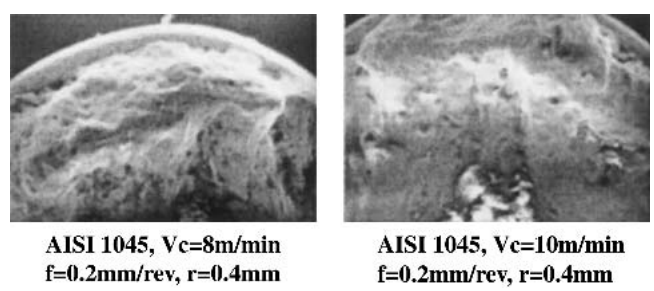


Fig. 10 SEM micrograph of BUEs formed on two uncoated tools that were used to cut an AISI 1045 steel using different *V* values (200×)

tools was not obtained due to the amount of premature fracture exhibited by these tools during the cutting process.

The mathematical expressions for coated *VB* as a function of the different cutting variables and for the different steels studied are listed below:

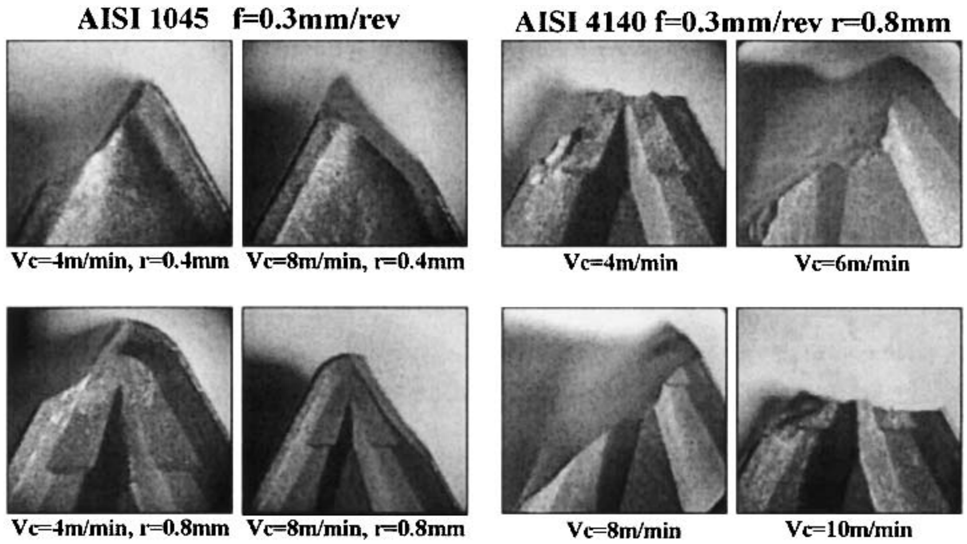


Fig. 11 The superior face of uncovered tools that broke during the machining of AISI 1045 and 4140 steels

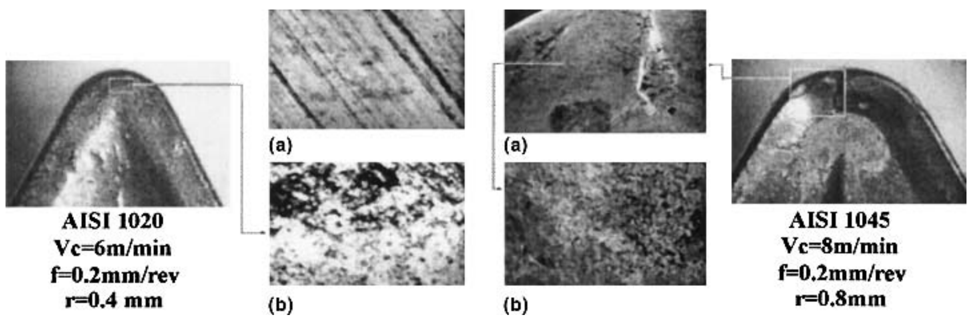


Fig. 12 **Left panels:** SEM micrograph of the zone worn due to an abrasion mechanism: **(a)** unworn surface (1000×) and **(b)** worn surface (1000×). **Right panels:** SEM micrograph of the zone worn due to an adhesion mechanism: **(a)** detachment area (1000×) and **(b)** exposed surface (1000×)

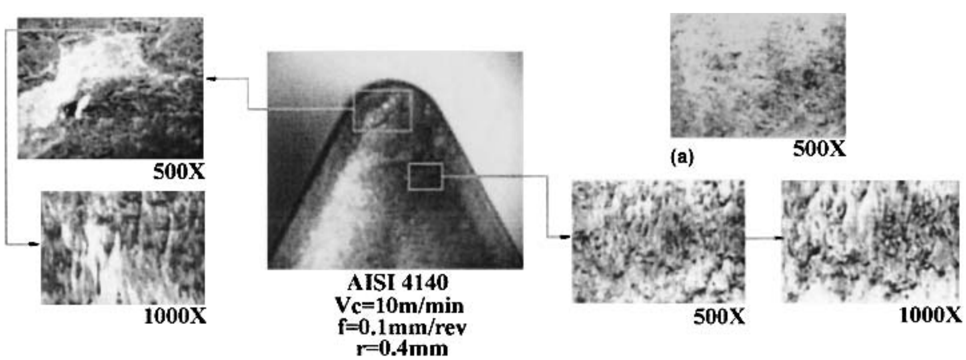


Fig. 13 Different wear zones of a coated tool that was used to machine an AISI 4140 steel

AISI 1020 $VB = 0.133\ (t^{0.437})\ (f^{0.406})\ (r^{0.067})$ (1)

AISI 1045 $VB = 0.115\ (t^{0.425})\ (f^{0.283})\ (r^{0.189})$ (2)

AISI 4140 $VB = 0.111\ (t^{0.458})\ (f^{0.406})\ (r^{0.038})$ (3)

where t is the cutting time (in minutes).

These mathematical expressions were validated with new cutting parameters, showing a very good correlation between the values obtained from them and the experimental values (error is less than 6%).

4. Conclusions

For all the steels tested in this research that were turned at low V and were within the range of the variables used, it can be concluded that:

- When using an uncoated tool, abrasion and adhesion mechanisms are responsible for *VB*.
- When using a coated tool, abrasion is responsible for the *VB*.
- Tool wear is influenced by BUE formation, especially when using uncoated tools during the turning process.
- In the range of cutting variables used in this study, *V* had a small influence on *VB*.
- The tool wear of coated and uncoated carbide tools increased when a larger *r* was used.
- *VB* increased for coated and uncoated tools when the *f* was increased.
- Tool wear rate was higher when using an uncoated tool in a turning process.
- BUE formation was more prevalent when machining AISI 1020 and AISI 1045 steels when using uncoated tools.
- Workpiece *f* has more influence on *VB* when using low *V* values.
- Mathematical expressions were determined using a constant speed of 10 m/min and $d = 0.4$ mm, which described the *VB* for coated tools.

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