Abstract

Wear determines the productivity of hardmetal cutting tools and thus investigation of its wear behavior is of high interest. Previous studies showed that the cutting edge stability and thus tool life can only be enhanced with the use of specific cutting edge roundings. Therefore, hardmetals with systematically varied hardness and thermal conductivity were produced in this study. As the occurring process temperatures highly influence the hardmetal properties, both hardness and thermal conductivity were studied at elevated temperatures. The cutting process temperatures were measured to identify the relevant temperature window. Finally, the relations between hardmetal properties, tool microgeometry and process parameters and their influence on the measured tool wear are discussed.

1. Introduction

Tool wear in metal cutting is a highly complex topic which is still not completely understood. During metal cutting different wear mechanisms, i.e. abrasive wear, diffusion wear, adhesive wear and oxidation wear, may occur at the same time [1, 2]. Additionally many factors influences tool wear and thus also tool life, for example the workpiece material, cutting conditions such as cutting speed, tool micro- and macrogeometry and tool coating [3–6]. The tool microgeometry can be altered by preparing the cutting edge. Studies showed that tailored cutting edge roundings have the potential to increase tool life and improve performance by influencing the wear behavior, thermal load and cutting process forces [7, 8]. The tool material is also an important aspect, but is often simplified or not included at all due to e.g. the incomplete availability of mechanical and thermophysical properties at elevated temperatures [9, 10]. A widely used material for metal cutting tools are hardmetals or cemented carbides due to the combination of high hardness and good fracture toughness. Mechanical properties of hardmetals at elevated temperature have been studied in general [11, 12], but the interplay between hardmetal properties, cutting parameters and the observed wear has not been studied in depth. This study builds on previous work where hardmetals with systematically varied properties were fabricated and characterized [13]. In this work cutting process temperatures were measured and the hardmetal properties at these temperatures studied. The influence of hardmetal properties, tool microgeometry and cutting conditions are discussed together with the observed flank wear.

2. Experimental

2.1 Fabrication and characterization of hardmetals

Four different hardmetal grades were prepared for this study using a conventional powder metallurgy route. Different combinations of metallic binder (Co) content and WC grain size were chosen to achieve different levels of hardness and thermal conductivity. Grain growth inhibitors, i.e. Cr3C2 and VC, were added where necessary in order to obtain small WC grain sizes. TiC was added to lower the thermal conductivity. The compositions in weight percent are shown in Table 1.

The powders were mixed and ball milled for 12 to 24 hours in n-heptane medium. After vacuum drying and sieve granulation the powder was uniaxially pressed. The samples were debinded in hydrogen atmosphere and sintered in a SinterHIP furnace at 1350 °C for 45 min with 60 bar argon gas pressure. Finally the samples were finish machined to obtain inserts with the geometry SNMN120408. Vickers hardness was measured according to ISO 3878 using 98 N load. Fracture toughness was determined from the indentations using Shetty's formula [14]. Thermal conductivity was calculated by multiplying the room temperature density with thermal diffusivity and specific heat capacity. The density was measured with Archimedes method according to ISO 3369. Thermal diffusivity was measured with laser flash method according to DIN EN 821. The specific heat capacity was calculated with FactSage version.
7.0 using the Scientific Group Thermodata Europe 2014 database. The obtained hardmetal properties at room temperature (RT) were characterized in previous work [15] and are listed in Table 1. The sample designations indicate with the first letter whether the hardness at RT is high (“H”) or low (“L”). The second letter indicates the same for the thermal conductivity at RT.

Table 1: Hardmetal properties at room temperature

<table>
<thead>
<tr>
<th>Designation</th>
<th>Composition (wt%)</th>
<th>Sintered WC grain size / µm</th>
<th>Hardness / HV10</th>
<th>Fracture toughness / MPa·m(^{1/2})</th>
<th>Thermal conductivity / W/(m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL</td>
<td>WC-10Co</td>
<td>0.1 ± 0.01</td>
<td>1,870 ± 20</td>
<td>9.2 ± 0.2</td>
<td>48 ± 4</td>
</tr>
<tr>
<td>HH</td>
<td>WC-5Co</td>
<td>0.3 ± 0.01</td>
<td>1,975 ± 20</td>
<td>8.5 ± 0.2</td>
<td>72 ± 5</td>
</tr>
<tr>
<td>LL</td>
<td>WC-13Co-8TiC</td>
<td>0.8 ± 0.02</td>
<td>1,310 ± 15</td>
<td>11.7 ± 0.2</td>
<td>36 ± 3</td>
</tr>
<tr>
<td>LH</td>
<td>WC-12Co</td>
<td>0.4 ± 0.01</td>
<td>1,460 ± 15</td>
<td>14.3 ± 0.2</td>
<td>77 ± 6</td>
</tr>
</tbody>
</table>

2.2 Cutting edge preparation
Denkena et al. developed the form-factor method to describe cutting edge roundings as shown in Fig. 1 [15]. Cutting edges were prepared with abrasive brushing using a robot-supported system (KUKA KR16) and a diamond brush with 2000 mesh. Two different roundings were applied with \(S_α = S_γ = 30\) µm and \(60\) µm. A 3D scanning device (MikroCAD Compact from GF measurement technology) was used to measure the resulting microgeometry of the inserts. After cutting edge preparation the inserts were coated with a \(2\) µm thick TiAlN layer via physical vapor deposition (PVD).

2.3 Turning tests and measurement of cutting process temperature
For the turning tests the inserts were clamped in a tool holder with clearance angle \(α = 6°\) and resulting rake angle \(γ = -6°\). Orthogonal grooving operations were carried out on a Gildemeister CTX520 linear machine tool. Due to this setup a defined chip thickness and width was available. Continuous cuts with a constant cutting speed \(v_c\) of \(120\) m/min and \(180\) m/min were performed. The workpiece material was AISI 4140 (tensile strength \(R_m = 928\) MPa, yield strength \(R_{p0.2} = 690\) MPa and thermal conductivity \(λ = 42.5\) W/(m·K)).

The temperature measurement was carried out using a two color ‘IGAR12-LO’ ratio pyrometer. Body radiation is guided into the pyrometer with a quartz fibre-optic cable. The fibre was positioned by using grooves on the hardmetal tool. Laser ablation was used to produce these grooves. The closest position to the cutting edge was \(0.2\) mm from the flank and \(0.2\) mm from the rake face. The maximum cutting process temperature occurs at the cutting edge and was extrapolated from the measurement position using a surface function (details are given in [15]).

The maximum width of flank wear \(VB_{max}\) was examined after a cutting length of \(200\) m with a scanning electron microscope.

3. Results and Discussion
3.1 Cutting process temperature
The maximum cutting process temperature was measured in turning tests with different cutting speeds, cutting edge roundings and the four different hardmetal grades. Both cutting speed as well as cutting edge rounding change the maximum cutting process temperature significantly as shown in Fig. 2 with hardmetal grade HH as an example. In this case the measured maximum temperature ranged between \(670\) °C and \(760\) °C. A doubling of the cutting edge rounding from \(S_α = S_γ = 30\) µm to \(60\) µm
resulted in an increase in the maximum cutting temperature by approx. 7%. Larger cutting edge rounding increase the contact length, leading to more friction and thus more heat. An increase in cutting speed from 120 m/min to 180 m/min resulted in an increase in temperature by approx. 7% due to the generation of more frictional heat in the same time period.

The hardmetal hardness did not affect the cutting temperature, but the thermal conductivity clearly influenced the obtained maximum temperature. A decrease in thermal conductivity of the hardmetal tool from 70 W/(m·K) to 40 W/(m·K) resulted in an increase in temperature by 8% as shown in Fig. 3. This is due to the reduced heat flow into the cutting tool. This leads to higher temperatures in the contact area between the workpiece and the cutting tool.

The hardness and thermal conductivity was measured between room temperature and 900 °C and room temperature and 1000 °C, respectively. Using the measured maximum cutting process temperatures, the actual hardmetal properties during cutting can be evaluated.

The thermal conductivity of the different hardmetal grades at room temperature and at maximum cutting temperature using the same cutting speed and cutting edge rounding is shown in Fig. 4.
Fig. 4: Thermal conductivity as a function of the hardmetal grades at room temperature and cutting temperature (cutting edge rounding $S_α = S_γ = 30 \, \mu m$, cutting speed $v_c = 180 \, m/min$)

The hardmetal grades with high thermal conductivity at RT, i.e. LH and HH, show a clear decrease in conductivity at maximum cutting temperature compared to the value at RT. In contrast the hardmetals with low thermal conductivity at RT, i.e. LL and HL, show an increase. However, the difference between the low and high level of thermal conductivity is large enough to lead to significant differences in the cutting process temperature as described above (see Fig. 3).

The hardness values at room temperature and at maximum cutting temperature for all four hardmetal grades using the same cutting edge rounding and cutting speed are shown in Fig. 5.

Fig. 5: Hardness as a function of the hardmetal grades at room temperature and cutting temperature (cutting edge rounding $S_α = S_γ = 30 \, \mu m$, cutting speed $v_c = 180 \, m/min$)

The maximum cutting temperature is higher when hardmetals with low thermal conductivity, i.e. grades LL and HL, are used. This results in lower hardness. About 42-43% hardness relative to the room temperature value are retained at cutting temperature for these hardmetals. The hardmetals with high thermal conductivity, which results in lower cutting temperatures, retain 50 to 55% of the room temperature hardness. The thermal conductivity of the hardmetal therefore has a considerable influence on the resulting hardness under cutting conditions. The grade HL has a high hardness at RT, but low thermal conductivity compared to grade LH, which has low hardness at RT but high thermal conductivity. As a result, the large difference in hardness of 410 HV10 at RT diminishes to just 60 HV10 at maximum cutting temperature.
3.3 Hardmetal tool wear

Different types of wear are observed after a cutting length of 200 m: abrasive wear (flank wear), crater wear and/or cutting edge chipping. In previous work [15] the different types of wear were studied in more detail. In the following only the flank wear is discussed. The maximum width of flank wear or \( VB_{\text{max}} \) is shown in Fig. 6 for all four hardmetal grades and two different cutting edge roundings. The smaller cutting edge rounding leads to less flank wear compared to the larger rounding due to the smaller cutting edge arc length which is in direct contact with the surface of the workpiece [17, 18]. The hardmetal properties significantly influence \( VB_{\text{max}} \) for both cutting edge roundings, but the differences are more pronounced in case of the larger cutting edge rounding of 60 \( \mu m \). The hardmetals with high level of hardness at RT, i.e. grade HL and HH lead to 21 and 24% less flank wear, respectively compared to the grade with low hardness, if a rounding of 60 \( \mu m \) is used. With higher hardness the resistance against abrasion increases. Furthermore, the thermal conductivity also has an impact on flank wear. For example the grades LL and LH have similar hardness at RT, but different thermal conductivities. This results in a higher maximum cutting temperature in case of grade LL, which in turn leads to lower hot hardness. However, the \( VB_{\text{max}} \) is 10% smaller compared to grade LH, although in case of LH the maximum temperature is lower and thus the hot hardness is higher (see Fig. 5). With higher hot hardness a higher resistance to abrasive wear is expected. But the temperature does not only affect the hardmetal, i.e. tool hardness. It also affects the mechanical strength of the workpiece material. The workpiece material softens less when the cutting temperature is lower. According to investigations of Brnic et al. the tensile strength at 600 °C is 30% and at 700 °C 15% of the tensile strength of AISI4140 at RT [19], which could explain why the \( VB_{\text{max}} \) is smaller in case of grade LL and the higher cutting temperature.

![Fig. 6: Maximum flank wear as a function of hardmetal grade for two different cutting edge roundings (30 \( \mu m \) and 60 \( \mu m \)), cutting speed 180 m/min](image)

4. Conclusions

The cutting process temperatures were measured in continuous turning with different cutting speeds, cutting edge roundings and for different hardmetal grades. Higher cutting speed, larger cutting edge roundings and lower thermal conductivity of the hardmetal tool increases the cutting process temperature significantly. When cutting with hardmetal grades with different thermal conductivity, different process temperatures arise. This means that the effective hardness during the cutting process is lower for hardmetal tools with the same room temperature hardness but lower thermal conductivity compared to grades with higher conductivity. The amount of flank wear was influenced by both hardness and thermal conductivity of the hardmetals. Higher hardness leads to less flank wear due to the increased resistance against abrasion if the thermal conductivity of the hardmetals is the same. Comparing grades with the same hardness, higher thermal conductivity resulted in more flank wear due to the lower cutting process temperature resulting in lesser workpiece softening. As a consequence the abrasive wear increases.

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References