



Abrasive wear behavior under metal cutting conditions

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ABSTRACT

The tribological system of metal cutting is characterized by severe conditions. High stresses and seizure as well as high temperatures and freshly generated surfaces define a unique tribosystem. Therefore, many tribological tests at low relative speeds and temperatures do not represent metal cutting conditions and the derivation of quantitative relationships for friction and wear is hardly possible. By means of powder metallurgy a ferritic-pearlitic steel with varying content of abrasive Al_2O_3 particles has been manufactured and machined in order to investigate abrasive wear under metal cutting conditions for coated as well as uncoated cutting tools. A sample without any abrasive particles is used as a reference to quantify the effect of the addition of 0.5 wt%, 1 wt% and 2 wt% of Al_2O_3 in the workmaterial. Whereas on the flank face of the cutting tools, the wear rate progressively increases with the content of abrasive particles, the rake face wear does not depend on the added content of Al_2O_3 . The results show that the abrasive wear rate under metal cutting conditions is high in initial stages but decreases considerably over cutting time. This phenomenon is discussed against the background of machining theory.

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1. Introduction

Abrasive wear is one of the most common sources of mechanical damage in engineering industry [1]. The wear mechanism of abrasion has been investigated for a long time. A lot of empirical work was done in the late 50's and early 60's. Based on analogy tests mostly for pure metals, researchers concluded that the abrasive wear rate within a wear regime generally is inversely proportional to the hardness of the abraded body [2–8], proportional to the applied load [6,9,10] and the sliding speed under negligence of thermal effects [6,11]. Khrushov summarized these findings as 'Principles of Abrasive Wear' [12]. Many more influencing factors have been investigated, for example the size [6,7,11], the shape [10,11,13] and the type [6] of abrasive media as well as the humidity [9] and the environmental temperature. Xu et al. recently performed a correlation analysis between abrasion resistance and standard mechanical properties of low alloy steels for a comprehensive data set [14]. They used a standard abrasion test (ASTM G65) and investigated 40 steel samples of which 20 samples were chemically identical and 20 samples were different in terms of chemical composition and microstructure but with comparable mechanical properties. Xu et al. concluded that a strong linear correlation between several mechanical properties and wear resistance exists for chemically identical samples. For the

chemically divergent samples with similar mechanical properties, however, the correlations were found to be much weaker.

Some authors derived analytical models of the abrasion mechanism [14–18]. Torrance developed a model relating the wear rates of materials to their mechanical properties [16]. Halila et al. derived an analytical stochastic model of abrasive wear for metal cutting [17]. Later the same authors extended the model to account for the sticking/sliding contact conditions on the rake face of a cutting tool [18]. Based on their models they performed parameter studies and found a good agreement with experiments.

Although a lot of empirical relationships have been investigated and abrasive wear rates can be predicted quite well on the basis of various mechanical properties during test setups, difficulties arise during the transfer to real applications with non-ideal conditions [16]. This is especially true for metal cutting, since from a tribological point of view, metal cutting is a unique and challenging tribo regime [17]. It is characterized by very high temperatures, high normal pressures and sliding speeds as well as freshly generated surfaces in a plastic contact between tool and workpiece. Furthermore, two tribological interfaces, namely the rake face - chip interface and the flank face - workpiece interface with considerable differences, participate in the metal cutting process [19,20]. The complicated physical, chemical and mechanical phenomena involved in the chip formation process result in a lack of thorough wear theory in metal cutting [21]. Furthermore, the results obtained in tribological analogy tests that do not represent the conditions of metal cutting provide a basis rather for qualitative than quantitative conclusions [21].

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Several wear mechanisms contribute to the overall wear of a cutting tool. Whereas some wear mechanisms like abrasion or adhesion undoubtedly occur in metal cutting, the significance of other wear mechanisms like diffusion is a controversial issue [19–22]. Abrasion in metal cutting is caused by hard particles in the workmaterial which indent the cutting tool and generate wear debris through the applied relative motion. Since metal cutting tool grades are generally considerably harder than the machined workmaterial, this seems to be paradoxical but the explanation can be found in the thermal softening of the cutting tool in operation. While the tool grade is clearly softened through the high temperatures in the contact zone, which may reach the melting point of the workmaterial, the abrasive particles in the workmaterial are solely transiently heated during their pass through the shear zone. [23].

The aim of this work is to contribute to the understanding of the abrasive wear mechanism directly in the tribological regime of machining. An innovative experimental technique is refined and applied to empirically investigate the abrasion process of cutting tools directly in the tribological regime.

2. Abrasion under conditions of metal cutting

In order to investigate the abrasive wear mechanism specifically for metal cutting conditions, an experimental technique based on Powder Metallurgy (PM) has been developed. PM enables researchers to control the microstructure of a workpiece and to systematically investigate the effect of artificially added abrasive materials as well as their size and hardness on tool wear [20]. Byrd and Ferguson were the first researchers to apply that technique as they carried out a feasibility study [24].

By means of sintering and successive forging, they produced Fe-C-Al₂O₃ compacts with two different sizes of 2 vol% abrasive grains (1 and 25 µm) and investigated the effect on tool wear in turning tests. The matrix material consisted of AISI 1020 and AISI 4620 powder mixes. Concerning the experimental technique, Byrd and Ferguson found out that (1) some residual porosity was left in the specimens despite forging and (2) the 1 µm particles tended to agglomerate. The wear tests revealed a clear influence of the added abrasive particles on both flank wear and rake face wear. For the flank face wear Byrd and Ferguson found the highest wear rates in case of 25 µm abrasive particles, whereas the lowest wear rates were observed with the base material without added abrasives. For the rake wear, as measured by maximum crater depth, the content of abrasive particles showed an impact but the crater wear was insensitive to the particle size. The fact that flank wear showed particle size dependence and rake face wear did not was attributed to the embrittlement through the addition of hard particles. Byrd and Ferguson concluded this experimental technique to be a viable one for the quantitative examination of the effect of hard inclusions on machinability [24].

Faulring coincidentally investigated the influence of the addition of SiO₂ particles on tool wear in drilling experiments with HSS-tools [22]. Both volume fraction and the particle size were varied in this study. Faulring was able to confirm the results of Byrd and Ferguson for a different machining process and tool grade as she found an increased flank wear with increasing content of silica. However, the effect of the particle size showed contradicting results to those obtained in turning by Byrd and Ferguson, since Faulring found higher wear for 5 µm particles than for 10 µm particles, both for 0.4 vol% and 0.2 vol% of added SiO₂ [22].

Ramalingam revisited the experimental technique and analyzed the results of both studies with respect to the different tool grades [20]. For HSS tools having a lower thermal strength than

cemented carbides, plastic ploughing was identified as main abrasive mechanism for both rake face and flank face. Ramalingam assumes the same mechanism to be responsible for abrasive wear on the rake face of a carbide tool, due to high temperatures. At the flank face where temperatures are generally 300–400 °C lower, Ramalingam expects the cemented carbide to react in a brittle manner and while plastic ploughing may happen with abrasive particles of any size, the abrasive mechanism at the flank face is particle size dependent [20].

Marinov also used a PM technique to investigate the effect of non-metallic inclusions on tool wear [21]. The used specimens varied with respect to the abrasive particles (Al₂O₃, SiO₂ and SiC), the size of the particles (8, 40 and 90 µm) and the volume fraction (0.0127 vol%, 0.0255 vol%, 0.127 vol% and 0.318 vol%). The base material was a high manganese steel. Marinov's findings support the thesis that the hardness of the abrasive crucially affects the abrasive wear. For Al₂O₃ the highest wear was observed, followed by SiC and SiO₂ according to their hardnesses. Furthermore, the results do not reveal a clear relationship between particle size and abrasive wear. The different volumetric contents enabled Marinov to derive a relationship between the abrasive wear and the abrasive particle concentration. Based on the empirical results Marinov derived a non-linear degressive relationship between abrasive wear w_{abr} and particle concentration n , where C_1 is an empirical constant:

$$w_{abr} \propto C_1 \cdot n^{2/3} \quad (1)$$

3. Experimental procedure

3.1. Preparation of specimens

Four rotationally symmetric specimens have been fabricated using hot isostatic pressing (HIP) varying the content of added Al₂O₃. The commercial water-atomised powder ASC100.29 (Company Hoeganaes) with a grain size of 100 Mesh was mixed with 0.5 wt% of carbon and furthermore with 0 wt%, 0.5 wt%, 1 wt% and 2 wt% of Al₂O₃ respectively. The grain size of the Al₂O₃ abrasive particles was chosen to be 12.8 µm according to the size of secondary deoxidation products that develop during cool down and solidification of a steel melt [25]. The Al₂O₃ was provided by a grinding wheel manufacturer (Company Tyrolit) and is of angular shape. The abrasive grains and the iron powder are depicted in Fig. 1.

The powder mixes have been filled into capsules, compacted and sintered under Ar-Atmosphere for 3 hours under 1100 °C and 100 MPa. Afterwards, the capsule was removed via external longitudinal turning. Before the specimens were used for the machining tests, metallographic sections were prepared in order to check the possible porosity of the specimens and to furthermore ensure that the abrasive particles did not conglomerate. The micrographs are depicted in Fig. 2, showing the etched micrographs on the left side and the unetched state on the right side. The work material shows a pearlitic-ferritic microstructure which was intended by the addition of 0.5% carbon. No considerable porosity is visible, thus the machinability of the material is assumed to be comparable to a conventional steel alloy. The abrasive particles, which can be located as black inclusions, are equally distributed within the sections and no conglomeration can be found.

The hardness of the four specimens was tested. A mean hardness of 134.25 HV30 was measured. Four measurements were conducted for every sample with low scatter, compare Fig. 3. The low differences in obtained hardness justify the comparison of the machining results of the four specimens. The hardness of AISI1045

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