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Influence of metalworking fluid additives on the thermal conditions in grinding

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ABSTRACT

Extreme pressure (EP)-additives are applied in nearly all metalworking fluids to enable better performance and improved lubrication at high thermomechanical loads. Especially in grinding, lubrication of the contact zone between grinding wheel and workpiece is of high relevance. This paper presents the results of a systematic study to reveal the potential of different additives in surface grinding to reduce the contact zone temperature and to shift the grinding burn limit. It is shown that the performed defined variation of the additive combinations considerably influenced effects regarding the thermal load in the contact zone and the performance of the grinding process.

1. Introduction

Metalworking fluids (MWFs) [1] are applied in a wide range of manufacturing processes to allow for increased productivity and a low number of waste parts. Particularly, the possibility to reduce the amount of energy transferred into heat by lubricating the contact zone between tool and workpiece as well as to dissipate generated heat by cooling liquids make MWFs a highly relevant system component. Consequently, the supply conditions [2], aging effects [3], and the chemical composition [e.g. 4,5] of MWFs are content of several MWF-related publications.

Although the commercially available MWFs are well described to lead to considerable improvements of manufacturing processes in terms of achievable tool life [6], surface integrity [7], and sustainability [8], the working mechanisms of MWFs are still not scientifically understood. Schulz and Holweger [9,10] presented a model for the assumed interactions of MWF-additives with metal surfaces. Based on the results of tribological tests, Huesmann-Cordes et al. strongly indicate that extreme-pressure (EP)-additives interact with steel surfaces based on different types of reversible interactions leading to a characteristic lubrication ability [11]. As a limitation of the presented work, the thermomechanical loads during the tribological tests differ naturally considerably from the conditions during machining processes such as cutting or grinding. Particularly in grinding, a large amount of the specific cutting energy is transferred into heat due to complex combinations of friction, ploughing and micro-chip formation within the contact zone. These effects lead to very high (local) temperatures [12] and mechanical loads [13]. To avoid thermal damage of the workpiece and/or to allow for higher productivity, MWFs and their additives have to work efficiently under these conditions. Until today, it is not clear, how the combination of EP-additives affect the heat generation in grinding processes. Thus, this paper aims at a systematical transfer of the findings from tribological tests to grinding, including a quantification of the thermal conditions (temperatures and grinding burn limit) of the process (Fig. 1). Based on the contact zone temperature, the forces, and the grinding burn limit ($Q'_{w,crit}$), the potential of different sulfur-containing additives are assessed separately and in combination with each other.

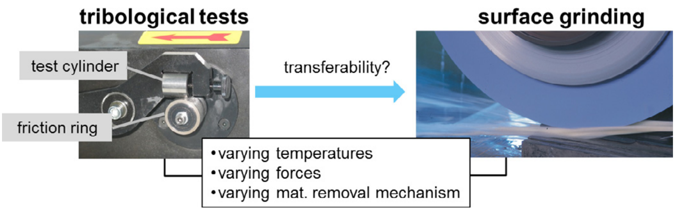

Fig. 1. Approach for the analysis of the effects of MWF-additives.

2. Experimental setup

To allow for reliable conclusions regarding the ability of different sulfur-containing MWF-additives to reduce the thermal load within the contact zone, specifically selected and chemically well-defined variations of the MWF have been used in taper surface grinding experiments.

2.1. MWFs and their supply conditions

As base oil, polyalphaolefin (PAO) from one production batch was used as it is chemically much more defined than e.g. mineral oil, which consists of a combination of a large number of chemical substances. Polysulfide PS40 (PS), overbased sodium sulfonate

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(OBS) and a synthetic saturated ester (E) were investigated being the most relevant EP-additives in industrial practice. Eight different MWF-mixtures were composed by distinct combination of additive-concentration as indicated in Table 1.

Table 1
MWF-compositions.

MWF	Base oil (%)	Poly-sulfide (%)	Overbased sodium sulfonate (%)	Ester (%)	Number of additives
PAO	100	–	–	–	0
PAO + PS	90	10	–	–	1
PAO + OBS	98	–	2	–	
PAO + E	92	–	–	8	
PAO + PS + OBS	88	10	2	–	2
PAO + E + PS	82	10	–	8	
PAO + E + OBS	90	–	2	8	
PAO + E + OBS + PS	80	10	2	8	3

The specific concentration-ratios were derived from [10] but a total maximum of 20 vol.% additives was chosen with reference to values that are transferable to industrial practice. The fluid supply parameters for this study have been chosen based on the approach presented by Heinzel et al. [14] including the identification of the most advantageous combinations of nozzle angle α_{jet}, height h_{jet} of the nozzle based on Rouse and jet-speed/wheel-speed-ratio v_{jet}/v_s. The supply parameters given in Table 2 were kept constant throughout the experiments.

Table 2
MWF-supply conditions.

Parameter	Value
Nozzle angle, α_{jet}	12.5°
Nozzle height, h_{jet}	88.3 mm
Jet-speed, v_{jet}	28 m/s
v_{jet}/v_s	0.8
Flow rate, Q_{MWF}	50 l/min
Distance of the nozzle, x_{nozzle}	420 mm

2.2. Grinding experiments including temperature measurements

Grinding experiments were performed at an ELB surface grinder using a sensor-integrated Tyrolit 97A802J5AV237 grinding wheel. The width of the wheel was identical with the width of cut (a_p = 30 mm). Prismatic workpieces (height × width × depth = 30 mm × 100 mm × 200 mm) made of AISI 52100 (quenched and tempered to a hardness of 58 + 2 HRC) were applied to approximately meet the workpiece conditions in the tribological conditions in [10,11]. The thermal conditions of the grinding process were assessed in taper surface grinding starting with a_e = 0 μm at the wheel entrance to the workpiece and a_e = 600 μm at the end of the workpiece (Fig. 2).

The grinding parameters are summarized in Table 3. To identify outliers, each grinding experiment was performed four times.

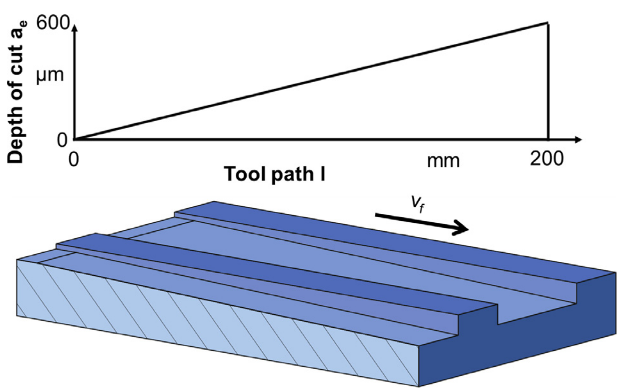

Fig. 2. Approach for continuously increasing depth of cut over the tool path (taper grinding).

Table 3
Grinding parameters.

Parameter	Value
Surface grinding (down grinding)	
Cutting speed, v_c	35 m/s
Depth of cut, a_e	0–600 μm
Feed speed, v_f	600 mm/min
Width of cut, a_p	30 mm
Specific material removal rate, Q'_w	0–6 mm³/mm s
Dressing (single-point dresser)	
Overlapping rate, U_d	4
Depth of cut, a_{ed}	30 μm

2.3. Assessment of grinding burn limits, surface-, and subsurface properties

The temperature T within the contact zone was measured with a calibrated sensor-integrated grinding wheel as described in [14,15]. The grinding wheel was equipped with four optical fibers distributed over the circumferential surface of the tool, which transfer the infrared light from the contact zone to the data processing and telemetry systems.

Barkhausen Noise BN was measured using a Stresstech Rollscan 300 device. The ground workpieces were furthermore etched based on the temper etching method according to ISO14104 to allow for a comparison between the grinding burn limit indicated by the etching and the Barkhausen Noise.

The grinding forces F_n and F_t were measured by a state-of-the-art Kistler dynamometer with a sampling rate of 125 Hz.

3. Results

For each MWF-composition indicated in Table 1, the grinding forces F_n and F_t, the contact temperature T and subsequently the Barkhausen Noise BN were measured and correlated with the specific material removal rate Q'_w after a certain tool path l. Fig. 3 summarizes the results for the grinding experiments using unadditivated base oil (PAO) as a MWF. The lines represent mean values resulting from the repeating experiments. The standard deviations for all experiments were comparable to those given in Fig. 3 for the base oil.

The results clearly show that after a certain run-in phase, the MWFs are able to keep the thermal conditions in a grinding process on an almost constant level although the depth of cut and the forces

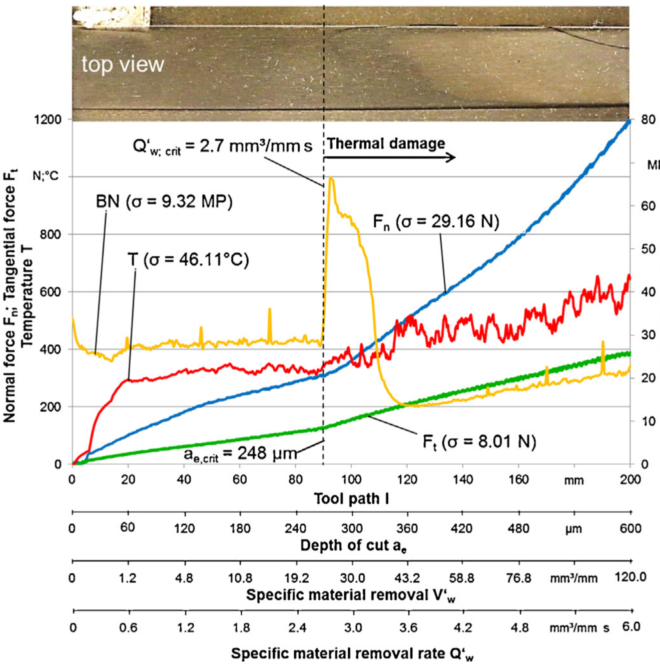

Fig. 3. Force-, temperature-, and Barkhausen Noise-development during the taper grinding using unadditivated base oil as MWF (bottom) and top view picture of the ground surface after temper etching (top).

increase significantly. The Barkhausen Noise indicates the critical specific material removal rate $Q'_{w,crit}$, where the material properties are affected due to the thermomechanical load. Interestingly, the temperatures increase at depths of cut higher than $a_{e,crit}$, but without a sharp change. However, it is noticeable that the temperature signal becomes more unsteady after $Q'_{w,crit}$. Also the force values show an increase of the slope at this specific material removal.

The entirety of the obtained results allows for comparison of characteristic values of the grinding process such as the aforementioned critical specific material removal rate $Q'_{w,crit}$. Fig. 4 summarizes the obtained values for the analyzed MWF-compositions as well as the contact zone temperature at the taper position where the grinding burn limit was achieved. The shown data, represent the mean value of the last 50 measured temperature values before $Q'_{w,crit}$ was exceeded.

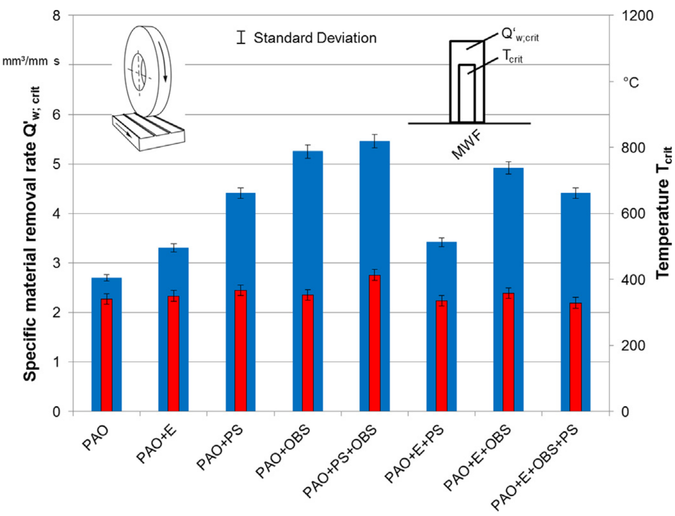

Fig. 4. Influence of the MWF-composition on the critical specific material removal rate in surface grinding deduced from Barkhausen Noise measurements and the critical temperature observed at $Q'_{w,crit}$.

As expected, the unadditivated base oil leads to the lowest grinding burn limit. The separate and individual addition of polysulfide, OBS and ester shows characteristic potential of these substances to improve lubrication and thus an increase of the grinding burn limit. OBS shows the highest increase of $Q'_{w,crit}$ (factor 4 compared to base oil), whereas ester leads to a limited improvement (factor 1.5). Adding OBS and polysulfide to the base oil again leads to a slight improvement of the lubrication ability compared to using solely OBS. This can be explained by the ability of these two types of additives to interact temperature- and pressure dependently with different chemical structures at the metal surface of the workpiece. The demand for the additive molecules to find interaction partners can especially be observed comparing ester and PS to PS as well as OBS and ester to OBS. Here, the application of two additives leads to a drop of the grinding burn limit compared to using only one additive.

The reason for this result is the competitive nature of the chemical interactions of the additives. OBS and polysulfide do not interact with the same chemical structures at the surface. The ester is able to interact with the interacting partners of both, OBS and polysulfide. As ester has a comparably poor lubricating ability, the interacting partners are "blocked" for the additives with higher efficiency. As a consequence, it is the combination PAO + PS + OBS rather than PAO + E + PS + OBS that leads to the highest $Q'_{w,crit}$. Only the combination of additives, which complementary interact with the surfaces of the tribological system results in an improvement of the lubrication ability. The high lubricating ability of OBS compared to PS and especially to ester, as well as the effects of combined additivation show the same relations as the observations in the tribological tests in [11]. This confirms for the first time the transferability of the findings from the tribological tests to grinding processes. Furthermore, the here observed negative effect of giving ester to MWFs with further EP-additives is a considerable example for the risk of decreasing productivity by adding (supposedly beneficial) substances.

The temperature in the contact zone by the taper position where the critical specific material removal rate is exceeded T_{crit} varies from 329 °C to 413 °C. The highest temperature is observed for the MWF leading to the highest grinding burn limit. This indicates, that the best MWF-composition allows for exploiting the full potential of a grinding process by means of shifting the grinding burn limit to higher temperatures. Reasons for these observations might be the higher mechanical loads (c.f. Fig. 6) at higher Q'_w and the resulting thermomechanical conditions but also the increased contact time at higher depths of cut cause by the larger contact length l_g. However, it is noticed that for the given parameters for the majority of the experiments, the critical temperature varies within a range of 329–370 °C.

The comparison of the results from the Barkhausen Noise measurements with the assessment of the beginning of grinding burn based on the temper etching reconfirmed a slightly better sensitivity to the thermal damage by the Barkhausen Noise measurement. Especially the optical evaluation of the etched workpieces was accompanied by a considerable susceptibility to errors. In summary, the grinding burn limit ($Q'_{w,crit}$) indicated by temper etching was increased by 3–15%. Consequently, the more reliable results from the Barkhausen Noise analyses were chosen for the further discussion.

Analysing the temperatures profiles over increasing depth of cut gives a very good impression regarding the potential of MWFs to influence the thermal conditions in grinding. After an increase of the temperature at the beginning of the process, the contribution of MWFs to the productivity of machining processes seems to be the ability to reduce the slope of the temperature profile and thus keeping the temperature under a critical value as long as possible. Fig. 5 summarizes the temperatures for each MWF-composition after a tool path of l = 20, 100, and 180 mm.

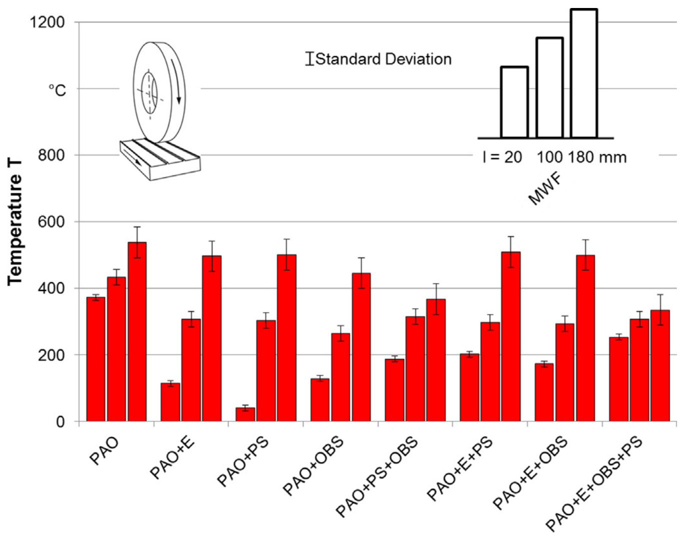

Fig. 5. Contact zone temperatures after 20, 100, and 180 mm tool path for the analyzed MWF-compositions.

The temperatures after 180 mm tool path mirror the observed trend regarding the achievable $Q'_{w,crit}$. The lowest temperatures after l = 180 mm were measured for the MWF-compositions PAO + PS + OBS and PAO + PS + OBS + E whereas the highest temperature was measured for the base oil. Interestingly, this trend is not so obvious after l = 100 mm. Here, the MWF-composition PAO + OBS lead to the lowest temperature. After l = 20 mm, PAO + PS showed the lowest temperature in the contact zone. This strongly indicates that the analyzed additives have different effects on the thermal conditions of a grinding process. PS seems to be able to lead to low temperatures at moderate loads (by means of Q'_w) of the process whereas OBS leads to low temperatures at elevated loads. The combination of the different additives leads to a reduction of the temperatures at low loads and a small slope of the temperature profile at increasing loads. This results in a considerable shift of the grinding burn limit and explains why PAO + PS + OBS is the ideal combination of additives for the given grinding task. Consequently, the Composition of MWFs can be specifically adapted to the demands of the process. Not all additives might be necessary for a certain grinding task.

Taking a deeper look at the grinding forces allows for further conclusions regarding the effects of MWF-additives on the thermal conditions of grinding processes. Generally, MWFs can reduce the risk of thermal damage by avoidance of heat generation (lubrication) or efficient dissipation of the generated heat from the contact zone (cooling). The ratio of the grinding forces μ can give important information on these effects. Fig. 6 summarizes the observed normal and tangential forces and temperatures at the critical specific material removal. The data, represent the mean value of the last 50 measured force values before $Q'_{w,crit}$ was exceeded.

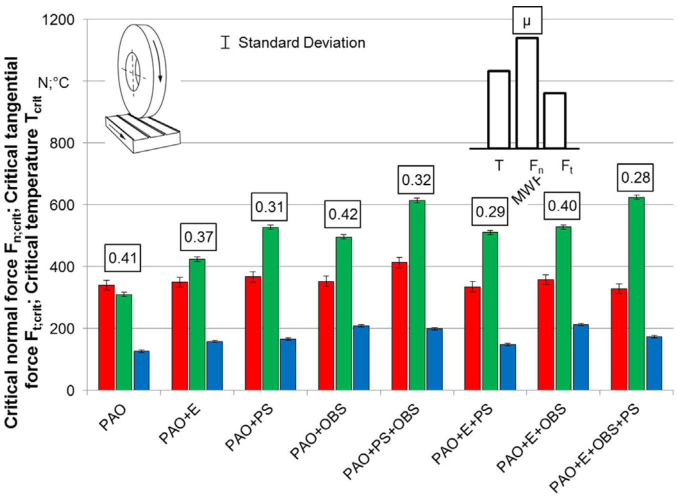

Fig. 6. Temperatures T, forces F, and grinding force ratios μ at the critical specific material removal rate $Q'_{w,crit}$.

The results point out that there is no general correlation between the critical specific material removal rate $Q'_{w,crit}$ and the ratio of the grinding forces μ. Nevertheless, it can be shown that the addition of PS generally reduces the grinding force ratio whereas OBS and ester do not lead to changes compared to the base oil. This means that the application of PS allows for a relative increase of the tangential forces compared to the normal forces. Leading this observation back to the main effects of MWFs, this means that especially PS works based on its high lubrication ability.

4. Conclusions and outlook

The presented work shows for the first time that results gained from tribological tests, which are widely used in the MWF-producing industry, can be transferred to grinding experiments. The observed grinding burn limits show the same relations as the results of wear tests presented in [10,11]. This will make it very efficient to reliably compose high performance MWFs for certain grinding tasks. In combination with the results from tribological tests, the presented work supports the theory on the working mechanisms of MWF-additives discussed in [9,1]. Furthermore, the specific effects of different sulfur-containing EP-additives on the thermal conditions have been revealed and are summarized in Fig. 7. The shift of the grinding burn limit is achieved by a parallel displacement of the temperature profile (PS and E) or by the reduction of the slope (OBS). The critical temperature varies within a small range and in combination with the observed forces, the superior lubrication ability of PS compared to ester and OBS are proven for the given materials of the tribological system. The closer look at the thermal conditions of grinding processes allows for a

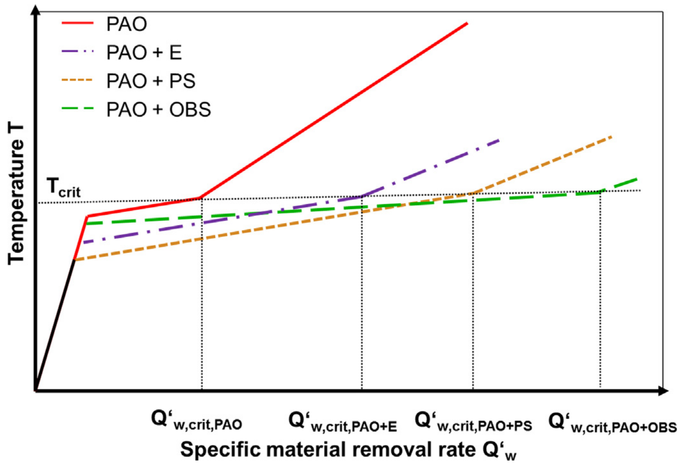

Fig. 7. Effects of different MWF-additives on the thermal conditions in grinding.

demand-oriented choice of the used MWF-additives. Dependent on the loads during the process, some types of additives can and should simply be omitted for the sake of higher productivity. However, this is only possible based on knowledge regarding the relationships between the thermal conditions of grinding processes and the performance of MWF-additives. This paper intends to form a basis for this kind of resource-efficient MWF-compositions for highly productive grinding processes.

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