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ORIGINAL PAPER

Fundamental characterization of lubrication effects through various cooling lubricants in the chip formation zone

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Abstract
Using cooling lubricants in metalworking requires a high consumption of energy and resources. However, cooling lubricants serve to increase the productivity and quality of these processes. Accordingly, it is necessary to expand the efficiency of their application. This requires fundamental understanding of the working mechanisms. Driven by this motivation, this publication compares six cooling lubricants regarding their lubrication effect in orthogonal cutting. Three types of fluid supply, each conducted on a specific special machine tool for chip formation analysis, and two cutting speeds have been used in the tests. In order to analyze the lubricating effect of these different scenarios, force measurements were carried out and the chip formation was recorded with high-speed recordings. It was found that the process improvements due to lubrication is determined by the interaction of fluid properties, supply strategy and cutting speed. Moreover, clear limitations of water-based cooling lubricants (especially oil-water-emulsions) in the ability to lubricate the chip formation zone have been determined and quantified.

Keywords Cutting · Chip formation · Tribology · Friction · Lubrication

1 Introduction

Cutting processes are widely used in the manufacture of industrial metal products. During the machining process, the tool penetrates the workpiece material to be machined, resulting in the formation of a chip. In this process, a superposition of complex material deformation and contact mechanisms occurs, determined by the thermo-mechanical loads in the chip formation zone [1]. High contact pressures [2] and temperatures [3] in the contact zone of the tool and the chip develop, exposing the tool to considerable mechanical, thermal [4] and chemical stresses [5]. These stresses reduce the workpiece quality and tool life. Cooling lubricants can be used to lower these stresses and therefore, enhance surface quality and tool life [6]. The use of cooling lubricants significantly changes the machining process. For example, the cutting forces decrease [7, 8], the natural contact length between chip and tool reduces [9] and the chip form changes [10, 11], which emphasizes the influences of cooling lubricants on the cutting process. High relative speeds, difficult accessibility, and small scales at high mechanical and thermal loads limit the accessibility and usage of different measuring technique. De Chiffre listed three main theories regarding the influence of cooling lubricants on the machining process, which are controversially discussed in the literature [12]. The first theory refers to a thin sliding film that exists between the tool and the chip. The second theory refers to the Rehbinder effect [13]. This effect describes the influence of polar substances on the surface energy of materials through the formation of layers at the interfaces reducing the strength in the plastic region of a material. However, this influence is controversially discussed [14].

Barlow applied a very small amount of cooling lubricant to the advancing workpiece surface just before the shear

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zone [15]. He determined a reduction in forces of some 10% by several tenths percent. He thus supported the existence of the Rehbinder effect. However, Barlow also showed that, paradoxically, this effect did not occur in flood cooling lubrication. Kohn [16] argued for the Rehbinder effect (acceleration of strain-hardening) as the main reason for the reduction of forces in machining. The activity results from the formation of products such as ferric chloride that arise during the formation of newly generated metal surfaces when lubricants are used. They might stabilize the micro-cracks that occur before shear fracture, similar to the way liquid metals act in the embrittlement of aluminum. Because of their low-stress micro-crack stabilization factor, extreme pressure lubricants might therefore reduce the friction, wear, and metal transfer of sliding surfaces by supporting the rapid shear-failure of welded asperities. Kaneeda demonstrates that the Rehbinder effect could not be proven in many areas of machining, especially for high cutting speeds [17]. A third theory refers to a shortening of the chip-tool contact length. This changes the shear angle, cutting forces and chip form etc. De Chiffre recapitulates the investigations with the conclusion that most likely all three theoretical effects take place simultaneously but elaborated that the shortening of the contact length has the largest effect on the resulting cutting forces [12].

Considerable thermo-mechanical stresses exist in the contact zone between the tool and the chip. Zorev [18] described these stresses by increasing normal stresses towards the tool tip. At a certain point, these high normal stresses exceed the shear strength of the workpiece material, resulting in a low material flow in the tangential direction of the chip motion. The area where the effect can be observed is considered to be the real contact zone and sticking is present. As the distance to the tool tip increases, the normal stresses decrease further and there is a transition from the real contact zone to an elastic contact zone in which sliding friction occurs. According to Childs [19], the chip-tool contact is described by the correlation between the normal, frictional and shear stresses, as well as the nominal and real contact zone. To what extent a cooling lubricant penetrates the contact area between tool and chip is one of the oldest questions in cutting research. In 1882, Mallock [20] already reported on the considerable change in chip thickness caused by cooling lubricants. Childs [21] examined the influence of carbon tetrachloride CCl_4 in quick-stop tests at cutting speeds significantly below 1 m/min and found that the chip curled up tighter and the chip thickness decreased when cooling lubricant was used. Applying Merchants law [22, 23], he evaluated the friction coefficients and found them to be significantly lower. However, when the cutting speed was increased up to 100 m/min, Childs reported that the coefficients of friction in wet cutting got closer to those in dry cutting. This indicated that the cooling lubricant did not reach the contact zone at high cutting speeds. In [19] it was assumed that only in the elastic area of the contact zone the cooling lubricant can penetrate through channels between the chip and the rake face into the contact area. This penetration depends on the surface conditions and the roughness of the tool. Investigations with textured tools support this hypothesis [24]. Also, a reduction in cutting force can be seen using a polished rake face compared to a ground surface [7]. Due to special micro geometries, the cooling lubricant flows into the contact zone due to capillary effects and leads to a reduction in forces [25, 26]. In [27], Shaw investigated the effects that lead to the reduction in forces and cutting energy by means of the cooling lubricants. He disproved the previous assumptions that water-based cooling lubricants create a layer with low shear strength. Shaw showed through experiments that chemical reactions between fluid and chip have exactly the opposite effect and necessarily form a layer of high shear strength. He noticed the paradox that the coefficient of friction increases with CCl_4 compared with dry cutting at low cutting speeds. The fluid evaporates during the process, enters the cavities between the tool and the chip as vapor and reacts to form iron chloride. This increases friction, resulting in stronger chip curling, and shorter contact length leading to increased normal stresses near the tool tip.

When the cutting speed increases, the deformation work and strain rates in the material rise, as do the relative speeds between the tribological-partners. This causes an overall increase in the process temperature and the heat flow between the tool and the chip. Therefore, it is generally assumed that as the cutting speed exceeds a certain level, a vapor barrier is formed in the gap between the chip and the rake face, making it difficult for the cooling lubricant to penetrate the contact zone using a conventional external coolant supply [28]. In this case, a suitable concept has to be chosen to adequately fulfill the three main tasks of cooling lubricants: cooling of the chip formation zone, lubrication of the contact areas and transport of the chips. In addition to conventional flood cooling lubrication, process improvements can be achieved by a special internal or external coolant supply in different operations such as turning [29], milling [30], drilling [31] and circular sawing [32]. Investigations also showed that the pressure of the coolant [33] and the volume flow have a considerable influence [34]. For example, reductions in tool wear due to a high-pressure coolant supply were found in different operations [11, 35]. However, special supply systems for delivering the cooling lubricant directly into the gap between the chip and the rake face allow to penetrate the vapor barrier and thus, lead to a better lubrication. The force exerted on the chip by the cooling lubricant at the direct contact with the chip formation zone pushes the chip away from the rake face. This leads to a shortening of the elastic area of the contact zone between the chip and the rake face. For example, the investigations in [36] showed that the chip flow and the elastic area of the contact length can be influenced by a well-directed jet of cooling lubricant under high pressure. Here, the angle of impact and the fluid pressure or volume flow of the cooling lubricant had an influential effect on the chip flow and the elastic area of contact. In [37], the authors postulated that the use of cooling lubricant can also lead to an increase in the coefficient of friction. The authors justified this by an unfavorable cooling lubricant supply, in which the vapor barrier prevented the penetration by cooling lubricant. The cooling led to a faster strengthening of the chip due to less thermal softening compared with dry cutting, resulting in a slight increase in forces. In dry cutting, on the other hand, the self-lubrication effect of the material studied, led to better tribological and thermo-mechanical cutting conditions in terms of the resulting forces.

The mechanisms of lubrication by a cooling lubricant have not been fully clarified yet. However, there have been numerous independent studies on this aspect. The supply strategy [38], the concentration and components of the cooling lubricant [31], the cutting speed [19] and their influence on chemical [39] and thermo-mechanical interactions [12, 27] play an important role here. Even though many influencing factors are known today from the state of the art, the detailed interactions between the machining process and a cooling lubricant are controversially discussed and the actual mechanisms are not fully understood. Moreover, the limits of functionality of different cooling lubricants have not systematically been investigated. Therefore, further investigations are necessary, especially due to the lack of knowledge about the influence of different coolant supply strategies, and for a deeper understanding of the tribological effects of different cooling lubricants regarding the application in the machining process. Within the presented work, the influence of cooling lubricants for various fluid characteristics and of supply strategies at varying different levels of cutting speeds on the mechanical tool loads in the chip forming zone is studied. For this purpose, three different orthogonal cutting experiments were conducted with varying methods of fluid supply. Within these experiments, six different cooling lubricants with diverse characteristics were compared with respect to the individual reduction of cutting and passive forces.

2 Experimental boundary conditions

Three different setups for orthogonal cutting experiments have been used for the study. A number of boundary conditions are of generic character and are presented in Sect. 2.1 ff. AISI 4140 + QT was chosen as a workpiece-material of high relevance for many industrial applications. For the orthogonal cutting experiments, specimens have been used with a length of l_{wp} = 120 mm, a width of undeformed chip of b_{wp} = 2 mm and an initial height of h_{wp} = 40 mm. All specimens were prepared from the same batch of material. Cemented carbide with 99 m.-% tungsten carbide (WC) and 1 m.% cobalt (Co) in form SNMA120408 are used in all investigations. The macrogeometry of the cutting inserts had to be modified via a face plunge grinding process to obtain a sharp corner radius. In addition, a clearance angle $\alpha = 15°$ was applied. The microgeometry of the cutting insert was adjusted to a mean cutting edge rounding of $\overline{S}$ = 35 µm using abrasive brushing. Recent research showed that the surface roughness significantly influences the penetration of the secondary shear zone and the cutting forces. Therefore, the surfaces of all tools are ground in the same way and have a roughness of Sa = 0.202 µm and S10z = 3.809 µm. Subsequently, the cutting inserts were coated with PVD-TiAlN with a thickness of 2 µm.

Six different cooling lubricants were investigated in this study: two emulsions, one solution, and three cutting oils with different levels of viscosity. As the work carried out resulted from joint investigations as part of the priority program “Efficient cooling, lubrication and transportation - coupled mechanical and fluid-dynamical simulation methods for efficient production processes (FLUSIMPRO)”, the selection of the cooling lubricants results from the project activities. The properties of the different media are presented in Table 1. Moreover, this table defines a numeration of the different media which is used for identification throughout the entire publication.

Beside the influence of different cooling lubricants on the chip formation process, the impact of different ways of supply, as well as the cutting speed-influence were investigated. For this purpose, three different settings were used for the experiments. First, the cutting fluids are supplied externally at a cutting speed of v_c = 120 m/min as a reference case. In a second approach, the lubricants are supplied through the rake face of the tool at the same cutting speed. Finally, in order to get fundamental knowledge of the chip formation, fluid-filled slots are used to directly penetrate the contact zone. For the last case, a low cutting speed of v_c = 5 m/min was chosen. The three individual setups are described in the following.

Table 1 Properties of the different cooling lubricants

Sequence number	1	2	3	4	5	6
Product name	Blaser Vascomill MMS HD 1	Blaser Vascomill CSF35	Blaser Blasomill 10 DM	Zeller + Gmelin TTS	Zeller + Gmelin Zuborah 67 H	Blaser VASCO 6000
Type	Oil	Oil	Oil	Solution	Emulsion (10%)	Emulsion (12%)
Density ρ in kg/m³ at T = 40 °C	1,004	900 (20 °C)	884	998	993	994
Kinematic viscosity ν in mm²/s at T = 40 °C	40.0	35	10	1.114	1.05	1.07
Flash point T_f in °C	200	310	208	101	102	129 (concentrate)

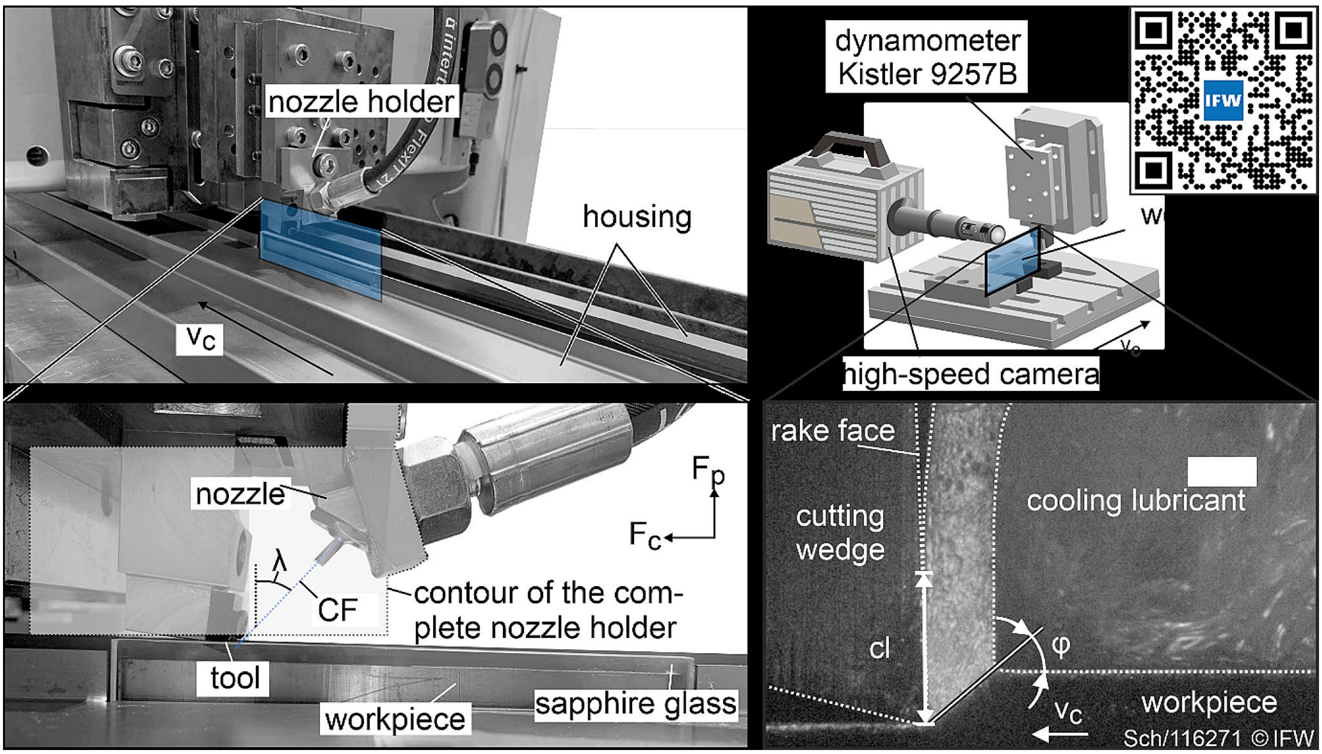

Fig. 1 Orthogonal cutting experiment with external fluid cooling lubricant supply

2.1 First experiment: external supply of media at v_c = 120 m/min

To investigate high cutting speeds and an external coolant supply, a planing test-rig was used which allowed high-speed video recordings and force measurements. Moreover, wet and dry machining at cutting speeds of up to v_c = 500 m/min can be applied. In this setup, the tool was stationary and the workpiece was clamped to the moving machine table. The experimental setup is shown in Fig. 1. The camera provides a view orthogonal to the cutting motion of the workpiece. In order to protect the camera setup from cooling lubricants, a sapphire glass sheet is put behind the workpiece in front of the camera. The high-speed recordings were conducted with a *Fastcam Nova S20* camera by *Photron.* To reach the required lighting, a LED light source of the type *UHP-F5-630* by *Prizmatix* was used. The forces were measured with a *Kistler 9257B* dynamometer. For supplying the cooling lubricant, an external nozzle with a diameter of d = 1 mm was set up at an angle of λ = 40° and with a maximum pressure of up to p = 30 bar which corresponds to a volume flow of Q = 3.8 l/min, applied using a manual pump and accumulator. The distance of the nozzle and the cutting edge has been kept constant for all experiments at 24 mm. The coolant is released via an electronic controlled valve. A detailed description of the setup for the cutting fluid supply can be found in [7].

2.2 Second experiment: fluid supply through the rake face of the tool at v_c = 120 m/min

In a second experiment, the coolant supply was realized through the tool. For the experiments, a machine designed for fundamental investigations into orthogonal and oblique cutting was used [40]. On this machine, the tool was attached to a three-component dynamometer by Kistler (type 9129AA) for measuring the mechanical tool loads (Fig. 2). During the cutting process, the tool was statically fixed, while the cutting motion was performed by the axis of the machine table on which the workpiece was mounted. This axis had a linear direct drive and achieved cutting speeds of up to v_c = 180 m/min. A pressure accumulator is filled to $p = 10$ bar with the respective cooling lubricant by an external manual pump. By means of an inductive sensor, a valve is activated at a defined time, which supplies the cooling lubricant to the cutting process. A tool holder of the type RH100.2020.1.34. IK_02 is used to realize the internal coolant supply through the tool. The high-speed recordings from various experiments can be viewed using the QR code depicted in Fig. 2.

2.3 Third experiment: fluid-filled slots at v_c = 5 m/min

In the last experiment, a special machine tool for chip formation analysis in orthogonal cutting conditions *Berger PFS 5558-1* was used. This kinematic setup is similar to a gantry machine tool, but does not feature a spindle-system. Like in the two test rigs before, the tool is stationary and can be moved by two translational axes, while the workpiece is mounted at a table with a linear direct drive that can reach a maximum relative speed of v = 180 m/min. The machine tool as well as the entire experimental setup (detail 1) is illustrated in Fig. 3. For measuring the mechanical tool loads from the tool-side, a *Kistler* three component dynamometer *9263* was equipped to the machine, which carries the insert holder. In addition, the chip formation process is recorded by a high-speed camera *Keyence VW-9000*. To improve the image brightness of the high-speed recordings, a LED-light source is installed at the machine and directed to the chip formation zone. A rather unconventional way of supplying the cooling lubricant has been used within this experimental series (detail 2): three slots are applied to the workpiece that are filled with the individual lubricant prior to the experiment. During a single cut, the tool passes these slots and the fluid, which is not pushed out of the slots due to the workpiece motion, is supplied with the chip motion directly to the rake face and penetrates the contact zone. Further details of the experimental procedure can be taken from [41].

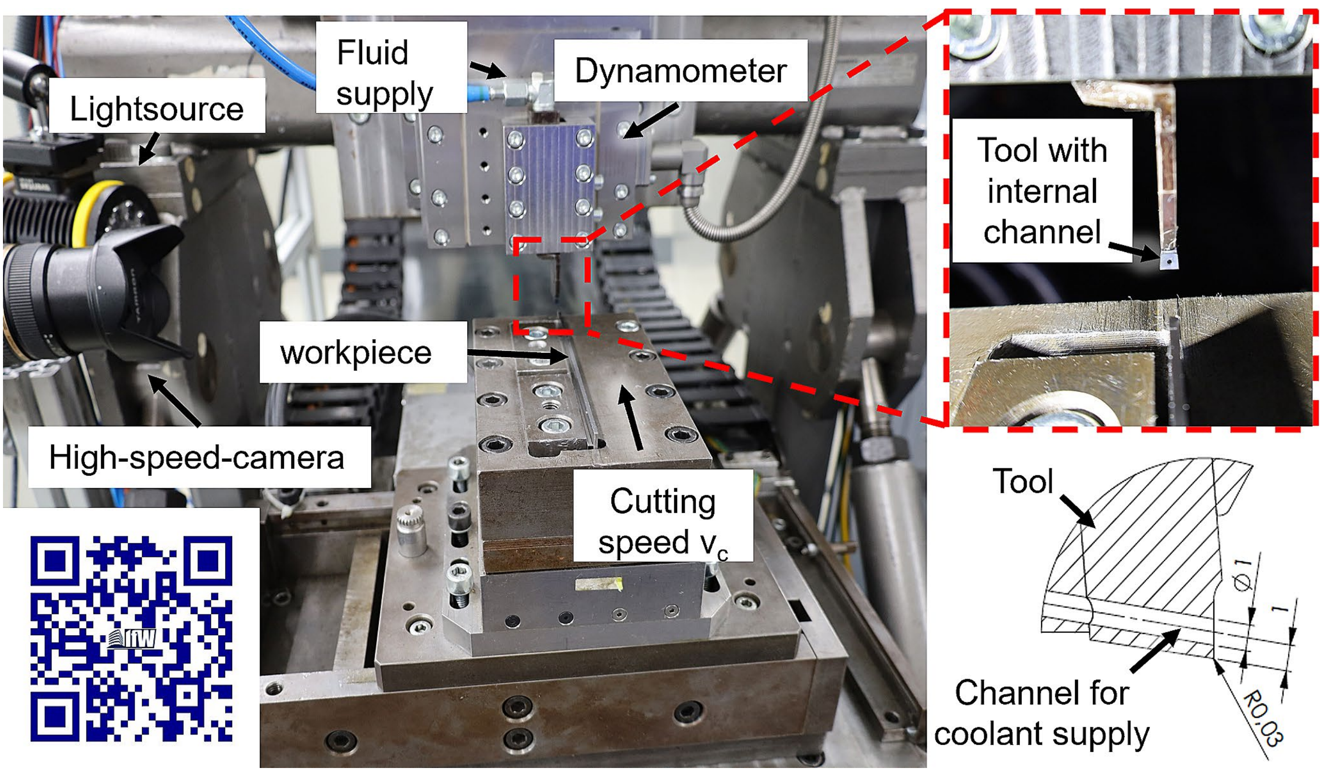

Fig. 2 Orthogonal cutting experiment with setup for supplying cooling lubricants by an internal channel on the rake face

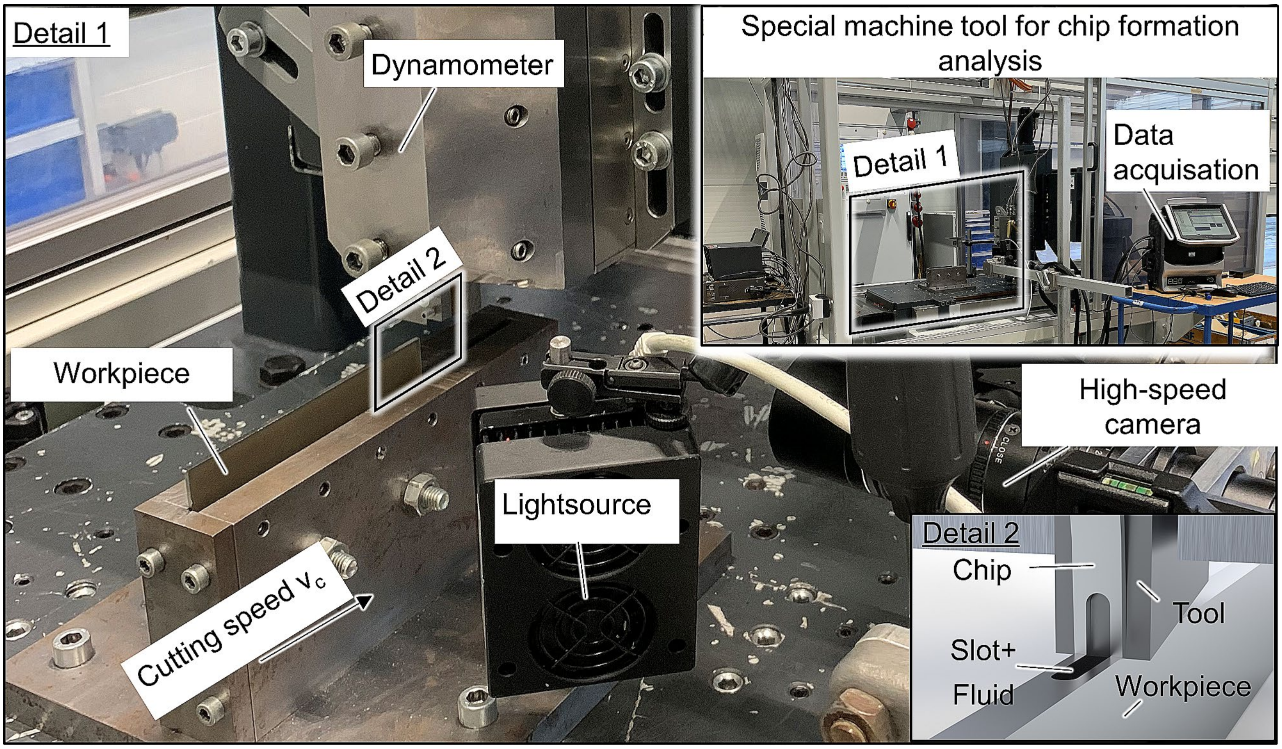

Fig. 3 Orthogonal cutting experiment with setup for supplying cooling lubricants by fluid-filled slots

3 Results and discussion

In the following, the results of the different test series are presented and discussed. First, the individual experimental approaches are considered, and then the results as a whole serve to get insights into the lubrication mechanisms in the chip formation zone. It is worth noting that the analysis in all three test setups focused on the contact between the rake face and the chip surface. This is motivated by the investigated types of supply, which apply the majority of the cooling lubricant in the area of the secondary shear zone. For this situation, preliminary work has shown that the influence of the lubricant on the cutting force is primarily indirect via an increase in the shear angle and the resulting decrease in chip thickness, which is caused by the contact between the chip and the rake face.

3.1 First experiment: external supply of media at v_c = 120 m/min

In comparison to dry cutting, the process forces, which are shown in Fig. 4, are influenced by the type of cooling lubricant at cutting speeds of v_c = 120 m/min. Only cutting oil number 2 shows a tendency to reduce the passive force F_p, whereas emulsions and solutions show slightly higher cutting passive forces except cutting fluid number 6. All fluids show the tendency for higher cutting and passive force compared to dry cutting for external cooling lubricant supply with a pressure of $p = 30$ bar. It can be concluded that the influence of the cutting fluids may not result in a reduction in friction in the secondary shear zone but from different heat dissipation rates and therefore, different levels of thermal softening of the workpiece material. Consequently, the higher cooling capacity of water-based solutions and emulsions possibly is the cause for the increase in the process force. Previous research has shown that the normal stress at the cutting edge increases under the influence of the pressure of the cooling lubricant as a result of a reduced contact length [42]. However, the process forces are not significantly influenced by the supply pressure of the cooling lubricant medium, so that the effects of the process force shown in this work can be attributed to tribological effects of the medium.

3.2 Second experiment: fluid supply through the rake face of the tool at v_c = 120 m/min

In an additional experiment, the influence of the internal coolant supply near the chip forming area was examined. Figure 5 shows the percentage deviations of the cutting and passive forces for the different cooling lubricants. In all experiments, the cutting speed was v_c = 120 m/min, the undeformed chip thickness was h = 0.15 mm and the width of cut was b = 2 mm. The experiments have been repeated

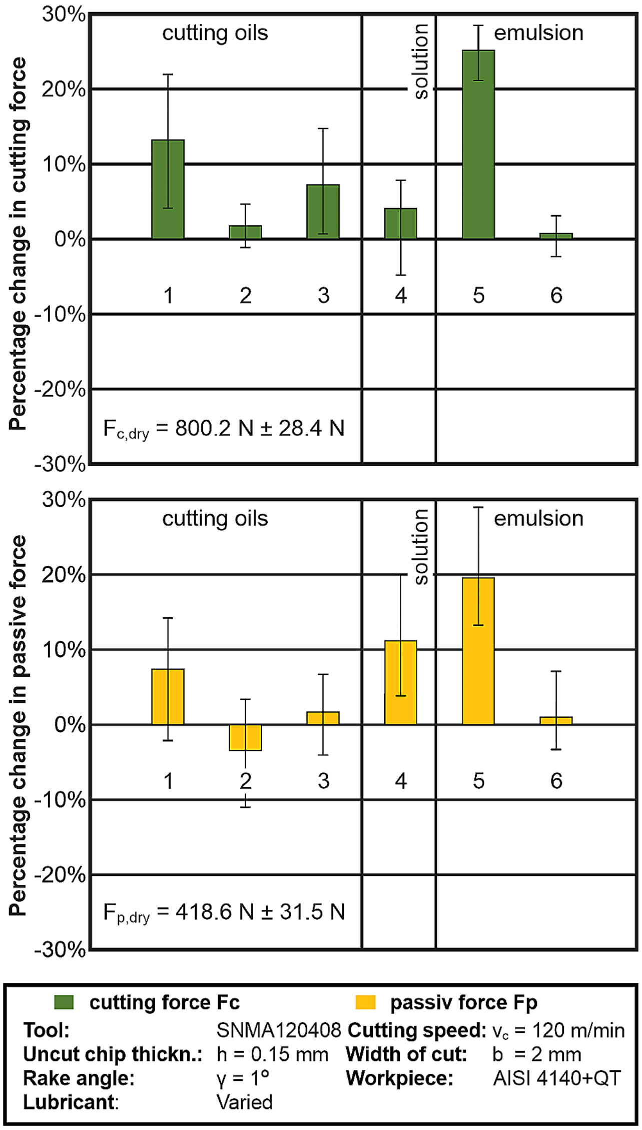

Fig. 4 Influence of the lubrication on the process forces under flood cooling

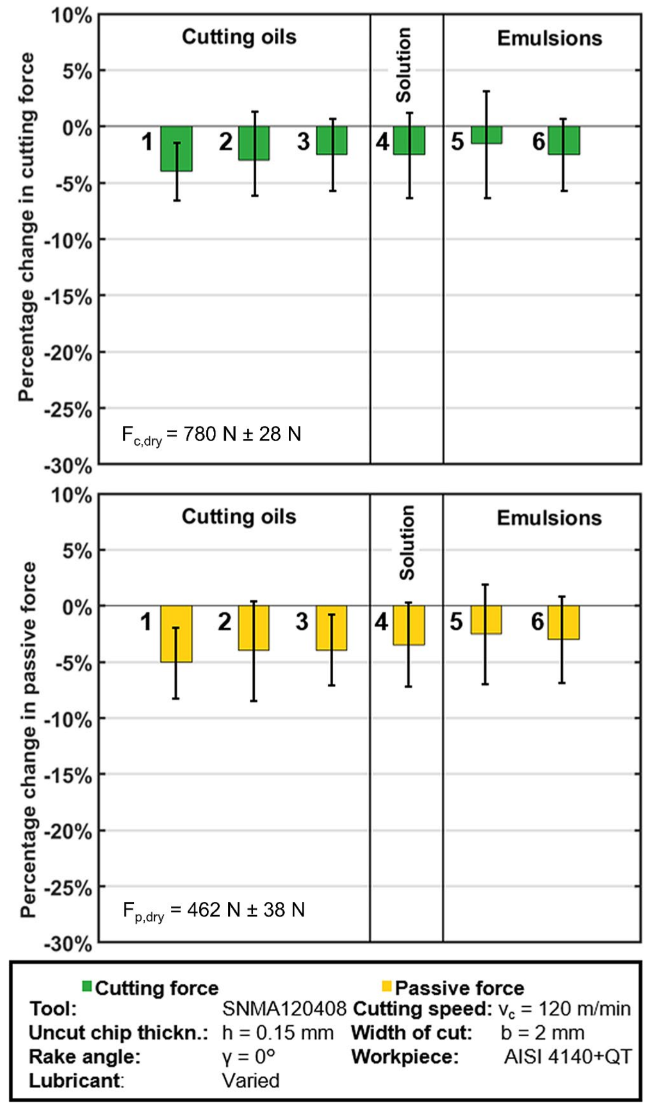

Fig. 5 Comparison of force-reduction for varying lubrication media with internal coolant supply close to the cutting process

five times. The percentage deviation referred to dry cutting. The results showed that the cutting and passive forces decreased almost independently of the cooling lubricant. This could be explained by the special method for the cooling lubricant supply. Because the cooling lubricant was applied onto the rake face, a force acted on the chip sliding over its contact area to the tool. This force pushed the chip away from the rake face, so that it is assumed that the cooling lubricant could flow with an external coolant supply. This led to a lubrication of the contact in the elastic zone. However, the investigations showed that, even with a special supply of cooling lubricant, only small reductions in cutting force were possible at high cutting speeds. This effect was also reported in the literature. Yet only at low cutting speeds, more pronounced lubrication effects and thus force reductions could be achieved by using cooling lubricants [11, 42]. In addition, the tests showed a larger reduction in forces by means of cutting oils compared with the water-based cooling lubricants. Cutting oils have a higher viscosity than water-based emulsions and generally show good lubricating characteristics. Due to the higher viscosity, the cutting oils can better withstand the pressure in the elastic contact zone between chip and tool. When the cutting oils are delivered through the tool directly to the cutting zone, they can lubricate the chip forming process and reduce the passive force better than emulsions.

3.3 Third experiment: fluid-filled slots at $v_c = 5$ m/min

In the last experiment, orthogonal cutting investigations were conducted with fluid-filled slots for supplying the cooling lubricants and at a low cutting speed of $v_c = 5$ m/min. Figure 6 shows two exemplary cutting force-time diagrams, one from a test series using the emulsion Blaser VASCO 6000 (green line) and one from a test series with Blaser Vascomill MMS HD 1 (in the following 'MQL oil', yellow line). The basic course of the graphs is the same for both cases: At the very beginning, the cutting force increases rapidly since the initial tool-workpiece contact occurs. Afterwards, a mostly stationary level over a certain time period is reached at $F_c \approx 1{,}170$ N. This state shows significant fluctuations, which can be explained by the unstable chip formation at very low cutting speeds. As soon as the first fluid-filled slot is reached, the cutting force rapidly decreases because of the reduced uncut chip width, before it returns to a steady state again. This behavior is repeated three times in total, related

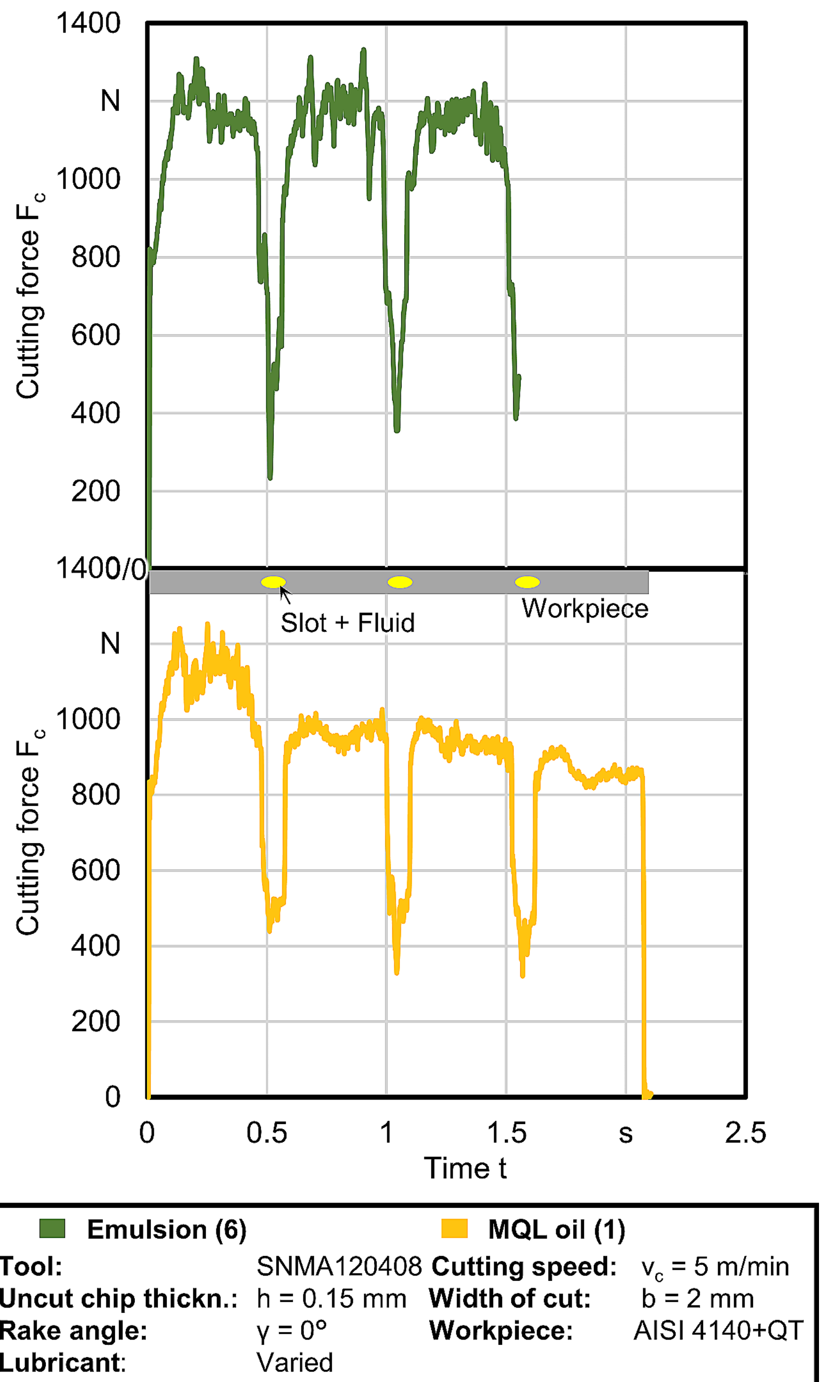

Fig. 6 Exemplary force measurements with low cutting speed for two lubricating media

to the number of fluid-filled slots in the workpiece. The very first steady state represents dry cutting, since the tool has not been in contact with the cooling lubricant. In contrast, the other sections characterize the condition of lubricated cutting with the respective fluid. It turns out that, while the force level in case of the emulsion nearly stays at the same level, showing only a very slight decrease in the last section, where it is significantly decreased due to the oil lubrication ($F_c < 1000$ N).

In order to analyze these phenomena in detail, mean values of the steady state sections were calculated for all conducted experiments, including the repetition tests. The overall result is presented in Fig. 7, divided into a diagram of the cutting force reduction in percent, as well as one for the passive force. Both diagrams contain one bar for each individual cutting lubricant. It turns out that the two high viscosity cutting oils (1, 2) show the largest reduction of both force components, ~15% for the cutting force and ~20% for the passive force. The fact that the reduction in passive force is larger than in cutting force, which applies to almost all fluids (except number 5), can be explained by the larger amount to which the passive force is driven by friction. In the case of the low-viscosity oil Blaser Blasomill 10 DM which is typically used in deep hole drilling applications (especially diameter range of single-lip and twist-drills) [43], the reduction in force was much less (~5% in cutting force and ~7% in passive force). Therefore, the viscosity seemed to play a vital role for the lubrication effect in the chip formation zone when using low cutting speeds, and higher viscosities could lead to a more distinctive effect of force reduction. In terms of the influence on the forces, the solution could be found between the high-viscosity and the low-viscosity oil. In contrast, the lubrication potential of the emulsions was nearly negligible and the force reduction is in the low single-digit percentage range. Using fluid number 5 even led to a necessary increase in passive force, which needs to be analyzed in detail. It could be hypothesized that the mechanical (viscosity) and thermal stability (evaporation temperature/flash temperature) of emulsions consisting primarily of water was not sufficient to withstand the high contact pressures and temperatures in the secondary shear zone. In order to get a deeper understanding of the individual working mechanisms of the different fluids, further investigations had to be conducted. For this purpose, a high-speed-video analysis is presented in the following.

Frames from high-speed recordings are shown in Fig. 8 using the example of three fluids with reference to dry machining. Fluids 1, 3 and 6 were selected here, that is a high-viscosity oil, a low-viscosity oil and an emulsion. It turned out that the high viscosity oil (fluid 1) remained in the contact zone after the penetration and built a lubricating film that significantly reduces the friction between chip and rake face. The characteristic shiny reflections of the fluid in the area between the chip and the rake face can be seen in Fig. 8. As a direct result of this lubrication, the mainly friction-caused passive force decreased, and the chip flow speed increased because of the reduced frictional resistance. Due to the rising chip flow speed, the shear angle increased. Therefore, the chip thickness decreased and became more homogenous. Consequently, the cutting force also decreased compared with the dry state because less deformation work must be performed. As the shear angle increased, the chip thickness became smaller as well. In the case of the emulsion (Blaser VASCO 6000), the fluid with the comparatively low viscosity was not able to withstand the high mechanical pressure in the secondary shear zone and was pushed out of

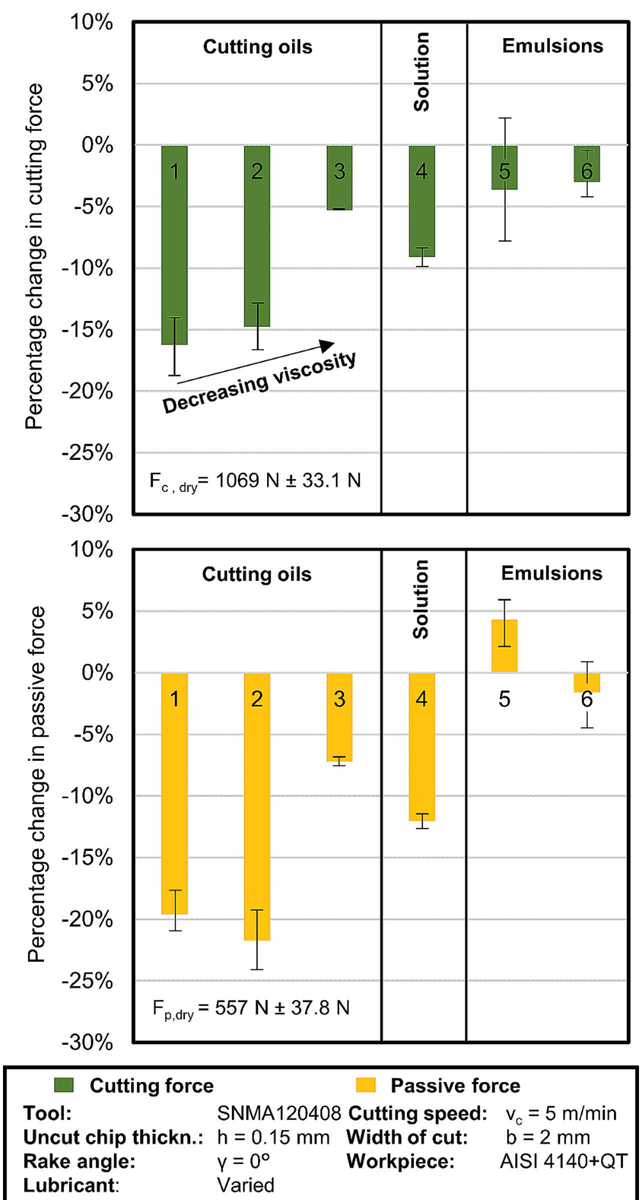

Fig. 7 Comparison of force-reduction for varying lubrication media

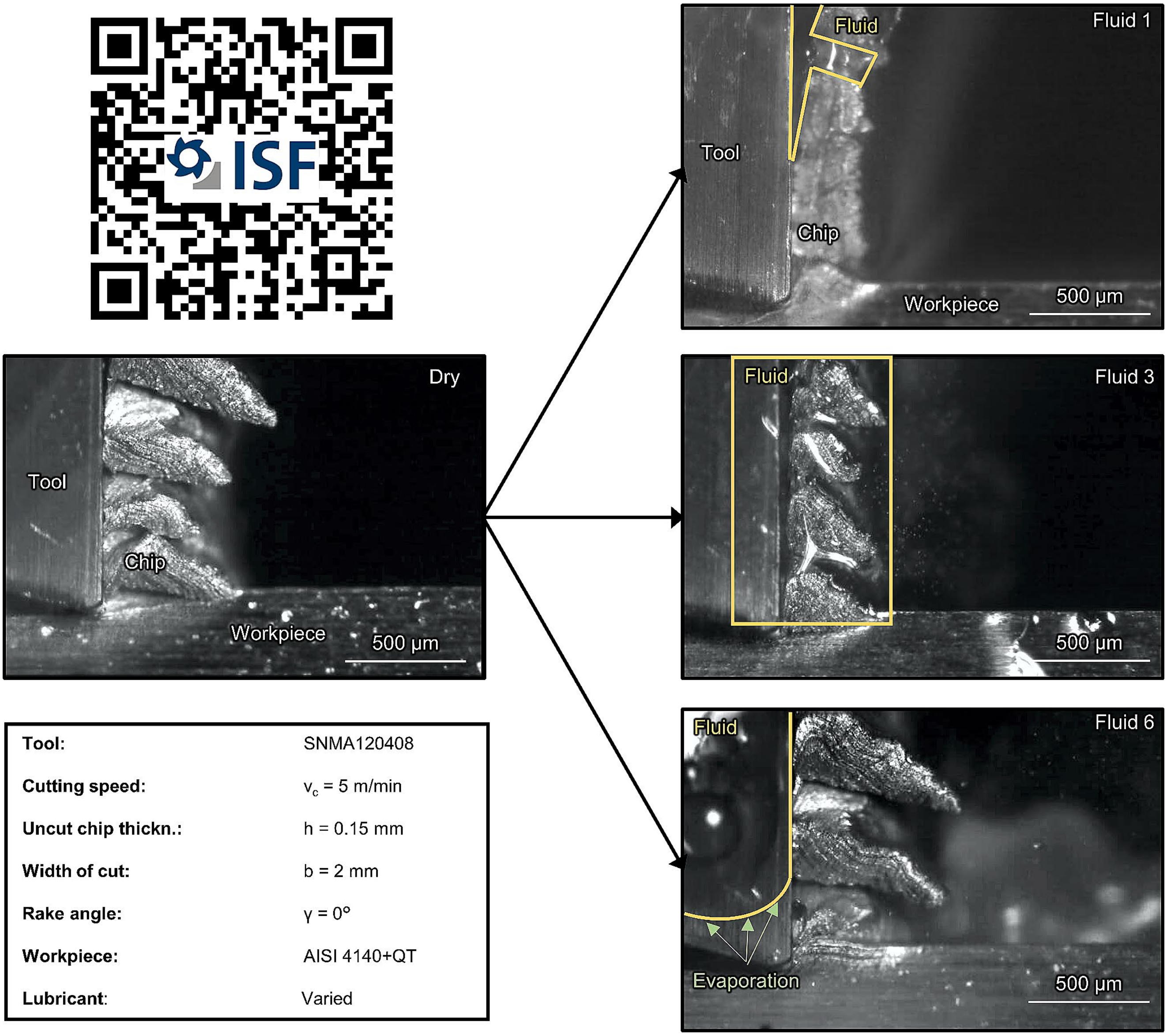

Fig. 8 High-speed recordings of the experiments at low cutting speeds for three different cooling lubricants

the contact area. After, it had accumulated at the side of the increasingly hotter tool in course of cyclic impacts. This can be seen in the corresponding photo with the bubbling liquid at the side of the tool. The fact that no significant lubrication effect showed could therefore be explained by two aspects: The viscosity was too low to withstand the mechanical transport out of the contact and the thermal stability was not high enough to endure the thermal loads in the chip formation zone. It could be concluded that the influence of emulsions is more or less limited to the cooling effects (based on the evaporation). The analysis of the DHD oil (Blaser Blasomill 10 DM) showed that the viscosity again was not high enough to withstand the mechanical loads in the contact zone and the fluid was transported out to some extent as well. Yet the amount of fluid pushed out of the contact zone seemed to be lower than in the case of the emulsion. In addition, it accumulated not only at the side of the tool but also at the side of the chip. It was concluded that, due to the higher thermal and mechanical stability compared with the emulsion, the remaining fluid in the contact-zone with comparatively low normal contact pressures could have some lubrication effect. This result was consistent with the results of the force measurement.

3.4 Comparative discussion of the test series

Apart from demonstrating the influence of different cooling lubricants on the lubrication in the chip formation zone, the results achieved here also showed the effect of the supply and the cutting speed on the achievable force reduction in orthogonal cutting. These two influences could be mainly attributed to the filling of the fluid into the contact zone. At a high cutting speed of v_c = 120 m/min and with an external fluid supply, the immersion seemed to be almost completely restricted. The reason for this was that the fluid, which was supplied from above the chip, could only withstand the mechanical resistance of the chip-rake face contact and the kinetic resistance of the flowing chip to a very limited extent. The fluid amount that could enter the contact zone was exposed to very high thermal loads and evaporated quickly. This supports DeChiffre's [12] assumption that a thin sliding film in the secondary shear zone between chip and rake face can hardly exist under conventional cutting conditions. In addition, the fluid jet exerted an external force on the forming chip and thus changed the contact length at the rake face. This showed a noticeable change in the cutting and passive forces. This underlines the study in [12] that a change in the contact length due to the cutting fluid leads to a change in the cutting and passive forces. The superposition of these effects means that only a minor lubrication effect could be achieved in some cases and for some of the cooling lubricants. Moreover, the cutting and passive forces were even greater than in dry cutting due to the external force of the fluid jet. A slightly better lubrication could be reached with the help of a modified supply method. When the fluids flowed in the opposite direction of the cutting motion through the rake face of the tool, a larger amount of the fluid was able to overcome the mechanical resistance of the chip at the rake face and enter the contact zone. As a result, the reduction of the forces was greater than in the case of the external fluid supply. A further intensification of the lubrication effect could be achieved at lower cutting speeds (v_c = 5 m/min) and with a special solution for the fluid supply by means of the described fluid-filled slots. This way of delivery allowed the fluid to benefit from the chip flow since it was approaching in the same direction. Consequently, it did not have to overcome this resistance and therefore could enter all areas of the contact zone, where it should theoretically withstand the normal contact pressures. It was known from a previous research that these areas are located at a certain distance above the cutting edge since the pressures in the sticking zone are too high and no cavities exist to be entered by the fluid [41]. The influence of the cutting speed can mainly be attributed to thermal effects. When the cutting speed is significantly lower than in the above-discussed experimental series, a lower level of temperatures occurs. Therefore, the thermal discharge of the fluid from the chip formation zone is much slower than at higher cutting speeds.

4 Conclusion

This paper discussed some fundamental working mechanisms of different cutting fluids, concerning the lubrication in the chip formation zone. For this purpose, six different commercial cooling lubricants (water-based as well as oil-based) were compared in three different settings of orthogonal cutting experiments. These settings here mainly differed in the way of supplying the fluids. In one case, an external supply from above the chip formation zone was chosen. In the second, the fluid was pumped through a nozzle in the rake face of the tool (parallel to the cutting direction), and in the last setup, the lubricant directly entered the contact zone with the aid of fluid-filled slots. In addition, different levels of cutting speed were investigated: A speed of v_c = 120 m/min, as usual in industrial practice, and a very low cutting speed of v_c = 5 m/min were used. The latter is suitable to achieve a full immersion of the fluid in the chip formation zone in order to analyze the influence of different cooling lubricants fundamentally. It turned out that the external supply was not very suitable to fill the contact zone and thus the mechanical tool loads stayed nearly at the same level than in dry cutting. The immersion could be improved by supplying the fluid through the tool into the chip-rake-face-contact, leading to a more distinctive force reduction compared to an external supply. By the help of fluid-filled slots and the lower cutting speed level, the immersion could be increased further and the overall force reduction was the greatest in all three experiments. Based on these results, the characteristic behavior of the different fluids could be observed. Emulsions were not able to withstand the high pressures in the secondary shear zone and were pushed out of the contact zone. Therefore, the resulting lubrication effect was limited to a small area of low normal contact pressures, only leading to little force reductions. A low viscosity oil was also unable to create a lubricating film in the entire zone of immersion, but the force reduction was a bit higher compared to the emulsions. Only high-viscosity fluids formed a significant lubricating film, which reduces the forces by up to 20% due to their great mechanical stability. It was inferred that the lubrication in the chip forming zone was not only limited by the thermal discharge of the fluids but also by the high pressures in the secondary shear zone and the fact that the moving chip hinders the fluid from entering the contact area. This mechanism was intensified with increasing cutting speed.

In total, these results illustrate that lubrication in cutting processes with continuous tool-workpiece contact is a complex phenomenon with various superimposed influencing factors and mechanisms. Moreover, it seems that conventional conditions (industry-relevant cutting speeds and emulsions by external supply) are not able to generate any lubrication at all. Consequently, it can be concluded from this study that there is a significant need for development. For example, this concerns the supply systems of cooling lubricants, which should take into account of the high mechanical and kinematical resistance against a delivery of the fluid to the contact zone. To benefit directly from the chip flow direction, like in the case of the fluid-filled slots, is quite challenging for industrial applications, but could be a starting point for future inventions. In general, the fluid supply should be close to the contact zone. Moreover, the cooling lubricants need to be improved concerning their mechanical and thermal stability, as well as their capability to enter the small cavities of the secondary shear zone.

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Declarations

Competing interests The authors declare no competing interests.

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