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Influence of lead in micro drilling of copper alloys with diameter of 1 mm

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Acronyms

Rm – Tensile strength
$R_{P0,2}$ – Yield strength
A – Elongation
HB – Hardness Brinell
D – Diameter
t – Drilling depth
F – Feed rate
v_C – Cutting speed
F_f – Feed force
fcc – face centered cubic
bcc – base centered cubic
α – Alpha-phase (copper rich phase with a fcc structure)
ß – Beta-phase (Zinc rich phase with a bcc structure)
VB – Width of flank wear land

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1. EXECUTIVE SUMMARY

This investigation aimed at assessing alternative alloys to free cutting brasses e.g. CuZn39Pb3 with respect to their behaviour when micro-drilled. It should be mentioned that this was not a full study encompassing all parameters. Nevertheless important tendencies as basis for further research on that topic were seen as follow:

I. **Machinability** of lead-free brass alloys CuZn38As and CuZn42 as well as silicon alloyed special brass CuZn21Si3P was worse during micro drilling (D = 1 mm, t = 10 mm) compared to leaded brass CuZn39Pb3.

II. **Cutting strategy**: Tool breakage occurred during drilling of CuZn42 and CuZn21Si3P after a few holes for most of the applied strategies. The process was only stable when dividing the cutting process in 10 steps (1 mm each) and moving the tool completely out of the hole after every cut. In general, using this strategy leads to an increase of process time due to increased tool travel path.

III. **Chip formation:** Overall, chip breakage of CuZn42 and CuZn21Si3P was comparable to CuZn39Pb3. When drilling CuZn38As, slightly longer chips were formed on average.

IV. **Feed forces:** Particularly for CuZn38As, mean of feed forces was much higher compared to CuZn39Pb3. Moreover, huge increase of forces was observed during drilling the bottom part of the hole. The latter also applied to CuZn42. The mean of feed forces of CuZn21Si3P was higher compared to CuZn42 due to high hardness. However, no increase during drilling process was observed.

V. **Surface roughness** was the same or even lower when drilling CuZn38As, CuZn42 and CuZn21Si3P. It is assumed that the measurement method did not work as expected as no clear tendency could be seen.

VI. **Tool wear:** High abrasive wear when drilling CuZn21Si3P led to huge increase of feed forces and early tool breakage after 205 holes. In a second trial the tool broke after 180 holes. Abrasive wear caused by CuZn38As and CuZn42 was similar to CuZn39Pb3. It is assumed that in a long term test (e.g. 10,000 holes and more) differences between the abrasive wear of the different materials might occur. Adhesive wear when cutting CuZn38As was significantly increased. When drilling CuZn42, the tool broke after 880 holes. The reason could not be completely identified.

2. Problem and objective

The use of lead as alloying element has been restricted since 2002 through the EU-Directive "End of Life Vehicles" (ELV). The so-called lead-free (max content of lead in materials like copper is 0.1 by weight) solution is promoted. Some copper alloy groups (e.g. CuSn, CuZn, etc.) contains lead as alloying element for many reason. One of them is the machinability. It is well known that lead copper e.g. CuZn39Pb3 has an excellent machinability.

The objective of this preliminary investigation is to evaluate the machinability of lead free brass qualities with regards to their chip formation, cutting forces, surface quality and tool wear. This evaluation shall provide a basis for assessing the future of lead in automotive components made from copper alloys.

3. Experimental setup and test program

1. Machine

The cutting experiments were carried out on a machining center of Excello type XHC 241 (Fig. 1)

A bar was clamped in a vise which was fixed onto a 3-component force measurement platform of Kistler. Before conducting the cutting experiments, the bars were face milled in order to produce a plain entering surface of the drill holes. The lubricoolant (emulsion) was supplied externally via conventional flood cooling.

Figure 1: Experiment setup on Excello type XHC 241

2. Test program

For machinability investigations, twist drills from company Gühring made of uncoated High Speed Steel (HSS) were used (d = 1 mm). As workpiece materials CuZn38As, CuZn42, CuZn21Si3P and CuZn39Pb3 as reference were chosen. The drilling depth was t = 10 mm as decided by the ELV working group. For analyzing chip formation, cutting forces and surface quality, the cutting speed as well as feed was varied in three steps, respectively, leading to 9 different cutting parameter combinations. In consultation with Gühring, cutting speed was chosen to V_C = 20, 40 and 60 m/min, while feed was set to f = 0.01, 0.02 and 0.03 mm (Fig. 2).

For investigating tool wear, the cutting parameters was kept constant (V_C = 40 m/min, f =0.02 mm) in order to reduce experimental effort. Altogether, 1000 holes were drilled into each workpiece material, while tool wear and also cutting forces were measured and documented every 100 holes.

Assessment criteria	Chip formation, cutting forces, surface quality	Tool wear, cutting forces
Machine	Excello XHC 241	
Process	Drilling	
Drill geometry	DIN 338 R-N, diameter d = 1 mm, Gühring 	
Tool material	High Speed Steel (HSS), uncoated	
Workpiece materials	CuZn38As, CuZn42, CuZn21Si3P, CuZn39Pb3	
Lubricoolant	Emulsion, 7 % (Fuchs Ecocool TN 2525 HP)	
Cutting speed v_c / (m/min)	20; 40; 60	40
Drilling depth t / mm	10	10
Feed f / mm	0.01; 0.02; 0.03	0.02

Figure 2: Summary of the test program

3. Materials

The machinability of lead-free brass alloys CuZn38As and CuZn42 as well as silicon alloyed special brass CuZn21Si3P were investigated and compared to the machinability of leaded brass CuZn39Pb3. Primarily decisive for microstructure and hence, machinability, is the percentage of copper and zinc, respectively. In general, brass alloys having a zinc content of up to 37.5 % consist almost solely of α-phases. Lattice structure of these α-phases is face-centered cubic (fcc) and therefore, brasses with high amount of α-phase possess a low hardness and high ductility. This applies to the alloy CuZn38As with α-phase content of 98 %. Increasing the content of zinc over 38% leads to an increased percentage of β-phase. The material CuZn42 consists of 42 % zinc and hence, the content of α- and β-phase is nearly balanced. The β-phase possesses a body-centered cubic (bcc) lattice and is much harder and less formable at room temperature than α-phase. Therefore, hardness and tensile strength of CuZn42 is higher compared to CuZn38As. The used leaded brass CuZn39Pb3 possessed 39 % zinc and 3.32 % lead, resulting in a microstructure of 70 % α-phase and 30% β-phase. Lead is almost not soluble in brass and segregates mainly at the grain boundaries. Hence, shear strength is significantly reduced, whereas elongation to break is similar to leadfree brass alloys. CuZn21Si3P is a special brass that is alloyed with 3.4 % of silicon. Due to low zinc content of 21 % the material possesses a high percentage of α-phase of approx. 60 %. Besides, a silicon-rich, brittle and highly abrasive phase exits in the microstructure, leading to a high hardness and tensile strength of the material (Fig. 3). Moreover, intermetallic compounds (-phases) segregated at the grain boundaries. According to the manufacturer of the material (Wieland), these intermetallic phases do not have any influence on the machinability of the material.

Material	R_m / (N/mm²)	$R_{p0.2}$ / (N/mm²)	A / %	Hardness * / HB
CuZn38As (Wieland)	392	313	22	126 (116-136)
CuZn42 (Aurubis)	478	310	25	134 (122-145)
CuZn21Si3P (Wieland)	654	400	21	210 (199-225)
CuZn39Pb3 (Wieland)	456	324	26	154 (140-167)

* Hardness measured at WZL

Microstructure

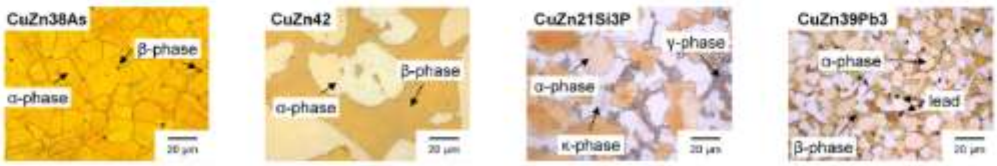

Figure 3: Properties and microstructure of tested alloys

4. Results

1. Drilling strategy

Before main investigations on machinability were carried out, it had to be analyzed first which drilling strategy was most reasonable (Fig. 4). In these investigations, the cutting speed and feed were kept constant to V_C = 40 m/min and f = 0.02 mm. Drilling of the hole in only one step was not tested due to recommendation of the tool manufacturer (Gühring). Furthermore no comparison would have been possible including all 4 materials due to tool breaking. Therefore, the following drilling strategies were investigated to ensure a comparison:

<u>1st strategy:</u>

First 5 mm of the hole were drilled in one step, followed by a second step machining the last 5 mm. With this strategy the tool broke directly at the first hole when drilling CuZn42 and CuZn21Si3P. No tool breakage occurred after 10 holes during drilling of CuZn39Pb3 and CuZn38As.

<u>2nd strategy:</u>

The entire hole was drilled in 2 mm steps. After every 2 mm, the tool was moved back 1 mm towards the entering surface. Using this strategy, the tool broke directly at the first hole when drilling CuZn21Si3P and after the second hole when drilling CuZn42. No tool breakage occurred after 10 holes during drilling of CuZn39Pb3 and CuZn38As.

<u>3rd strategy:</u>

Based on the 2nd strategy, the entire hole was drilled in only 1 mm steps. After every 1 mm, the tool was moved back 1 mm towards the entering surface. However, with this strategy, the tool also broke directly at the first hole when drilling CuZn21Si3P and after the third hole when drilling CuZn42. No tool breakage occurred after 10 holes during drilling of CuZn39Pb3 and CuZn38As.

<u>4th strategy:</u>

Based on the 3rd strategy, the entire hole was again drilled in only 1 mm steps. In difference to the 3rd strategy, the tool was moved back completely out of the hole until it was positioned 1 mm above the entering surface. Applying this strategy, no tool breakage occurred after 10 holes during drilling of all materials. Therefore, this drilling strategy was used for all cutting experiments. It is assumed that better chip evacuation was crucial for improved results with 4th strategy. The reasons for the different behavior of the workpiece materials will be discussed later in this presentation. At this stage, the higher hardness and tensile strength of CuZn21Si3P and CuZn42 compared to CuZn38As seemed to be decisive for tool breakage.

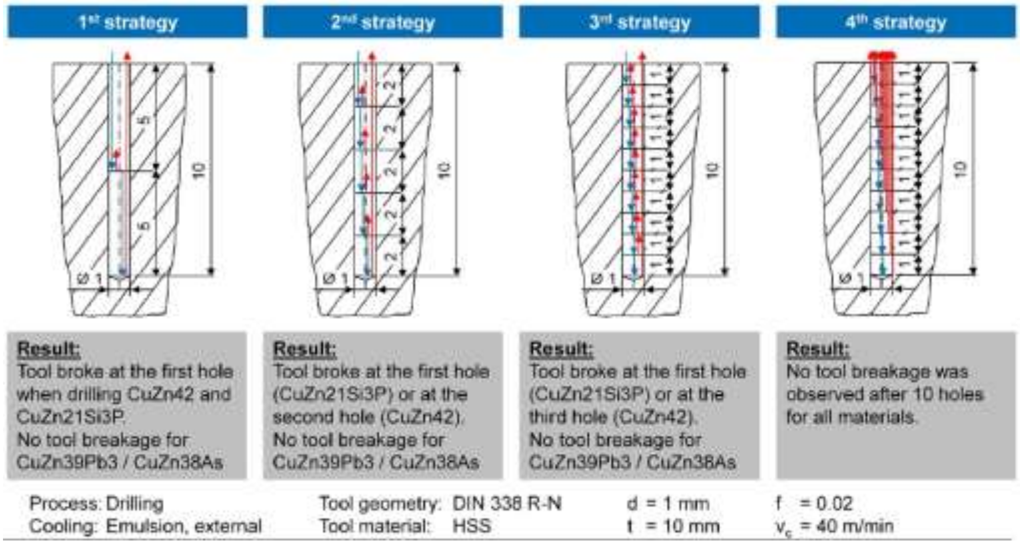

Figure 4: Investigation on the optimal drilling strategy

It is obvious that the strategy 4 will require several time the duration of strategy 1. Even if this was not the perspective of this investigation, it is likely that a longer production time can lead to a higher cost and therefore to less competitiveness on the market.

In order to better understand the differences between the drilling strategies, the following **figure 5** shows the feed force progression for drilling CuZn38As depending on drilling strategy. The cutting speed and feed were kept constant to V_C = 40 m/min and f = 0.02 mm. On this figure, a huge increase of feed force can be observed at the last cut when applying 1st and 2nd strategy. For example, when using the 1st strategy, the feed force increased from F_f = 40 N to almost 100 N at the end. It is therefore assumed that chip evacuation was hindered at the very bottom of the hole. In addition, squeezing of the material was intensified, particularly in the area of the drill's chisel edge. However, in contrast to CuZn42 and CuZn21Si3P, the increase of feed force did not lead to tool breakage in case of CuZn38As.

Applying the 3rd strategy, a similar increase of feed force can be observed at the last cut. In contrast, due to better chip evacuation, only a very slight increase of feed force was measured using the 4th strategy.

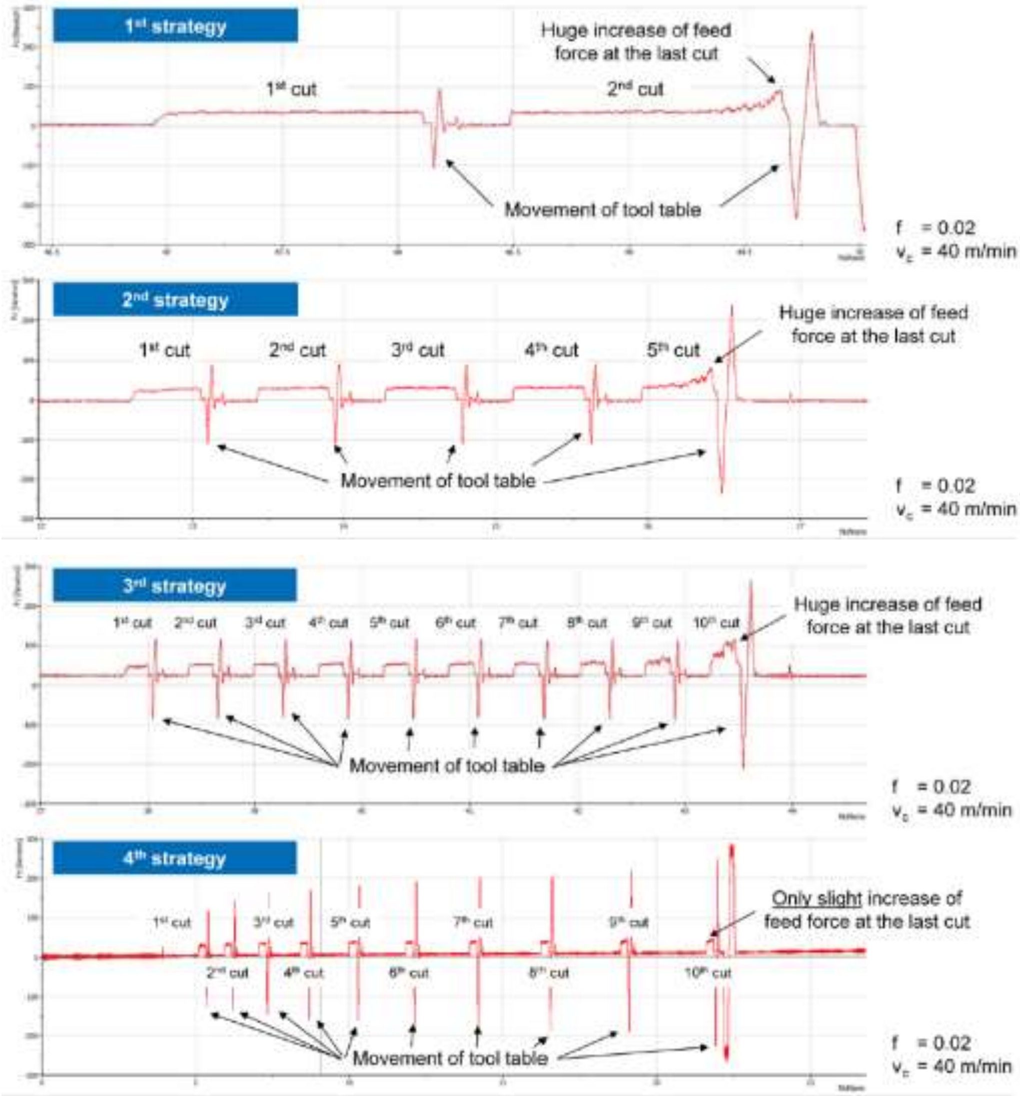

Fig. 5: Comparison of drilling strategies with respect to feed forces when drilling CuZn38As

2. Chip formation

The chip formation behaviour testing materials are shown as followed.

CuZn39Pb3

Due to the chosen drilling strategy, the risk of tool breakage based on the formation of long chips was reduced. Overall, chip breakage was good when drilling CuZn39Pb3 as mainly short arc and conical spiral chips were formed. However, occasionally longer conical helical chips were formed, specially at f

= 0.02 and 0.03 mm (see figure 6). A significant influence of the cutting speed and feed was not observed.

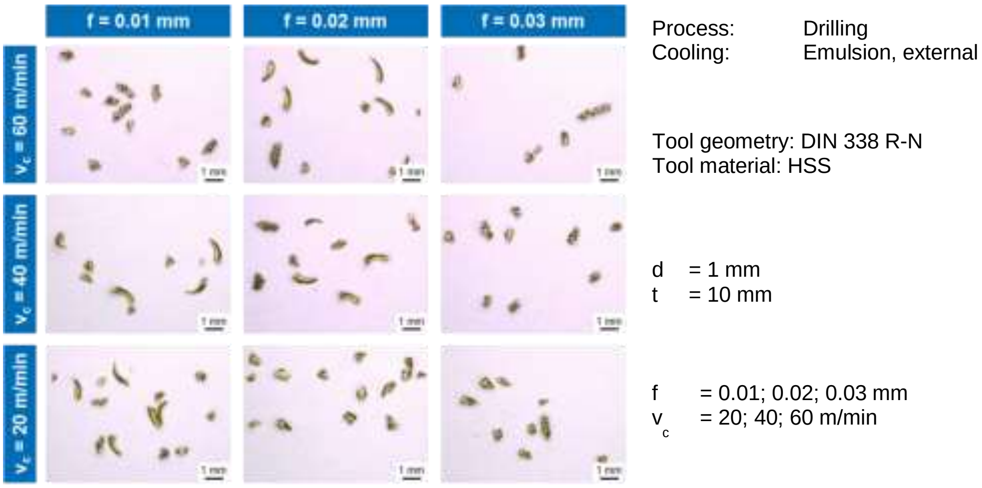

Fig. 6: Chip formation of CuZn39Pb3

CuZn21Si3P

Due to the chosen drilling strategy, the risk of tool breakage based on the formation of long chips was reduced. Overall, chip breakage was good when drilling CuZn21Si3P as mainly short arc and spiral chips were formed. However, occasionally longer conical helical chips were formed, independently on the cutting parameters (see figure 7). A significant influence of the cutting speed and feed was not observed.

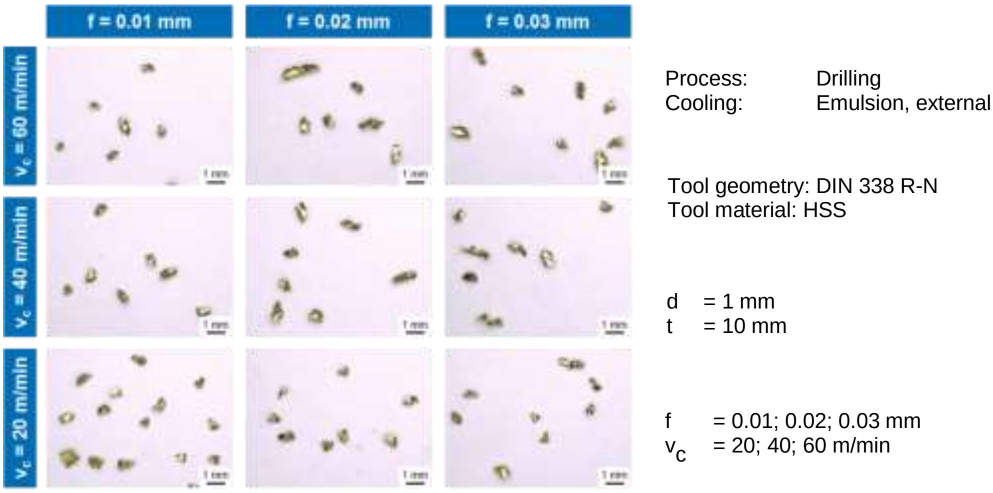

Fig. 7: Chip formation of CuZn21Si3P

CuZn38As

Due to the chosen drilling strategy, the risk of tool breakage based on the formation of long chips was reduced. Overall, chip breakage was good when drilling CuZn38As as mainly short arc and spiral chips were formed. However, occasionally longer chips were formed, specially at f = 0.03 mm (see figure 8). Chip breakage slightly deteriorated with increasing cutting speed. An influence of the feed was not observed.

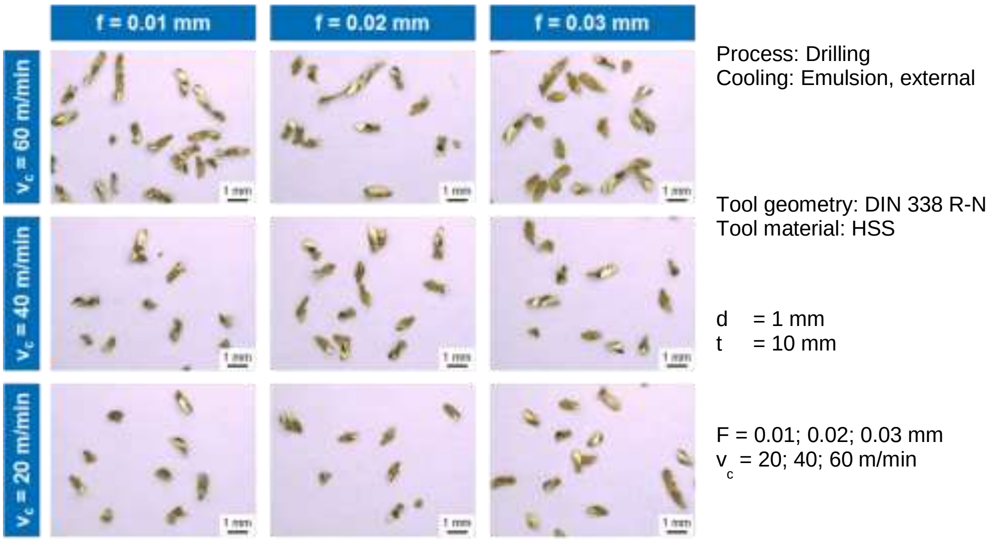

Fig. 8: Chip formation of CuZn38As

CuZn42

Due to the chosen drilling strategy, the risk of tool breakage based on the formation of long chips was reduced. Overall, chip breakage was good when drilling CuZn42 as mainly short arc and spiral chips were formed. However, occasionally longer chips were formed, independently on the cutting parameters (see figure 9). A significant influence of the cutting speed and feed was not observed.

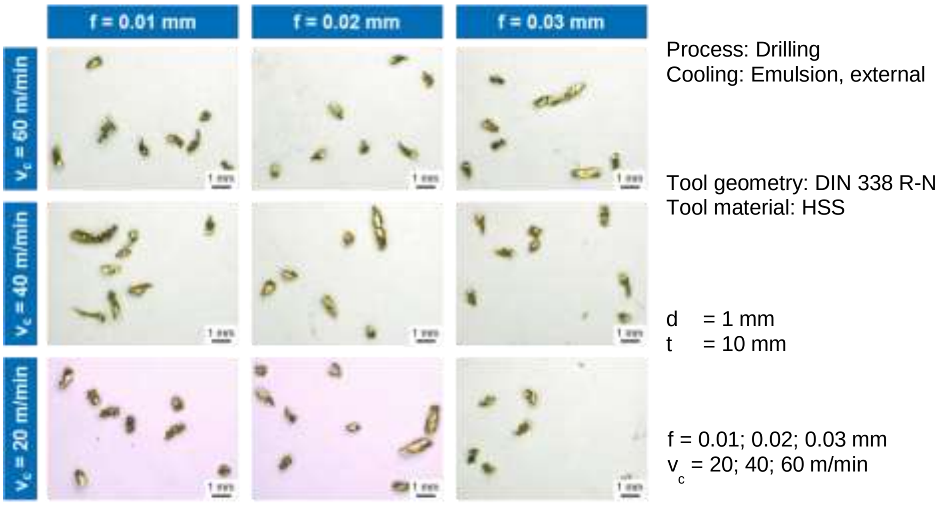

Fig. 9: Chip formation of CuZn42

Independent from the material one or two long chips (**figure 10**) occasionally formed during drilling of one hole. It is assumed these chips were generated when starting to cut. This phenomenon is well known for drilling operations. Due to the chosen drilling strategy, the risk of tool breakage caused by the formation of these long chips was reduced.

Fig. 10: Examples of long chips observed

3. Cutting force

As the force component in feed direction is highest during drilling operations, the following results exclusively refer to the feed forces. Before the feed forces will be compared for all 9 cutting parameters on **figure 11**, the force progression is shown on the next two slides applying V_C = 40 m/min and f = 0.03 mm, in order to analyze the differences in material behavior during drilling. When drilling leaded CuZn39Pb3 the level of feed forces is very low due to the formation of a thin lead film in the cutting zone. Moreover, the forces are constant during drilling process as chip compression and material squeezing are low. Only at the last cut, a slight increase of feed force was observed. Due to higher hardness and material strength of CuZn21Si3P, the level of feed forces is higher compared to CuZn39Pb3. However, the feed forces are also quite constant during the cutting process, as due to silicon-rich, brittle κ-phases chip compression and material hardening as well as material squeezing is low compared to the lead-free brasses CuZn38As and CuZn42. Only a slight increase of feed force can be therefore observed after the 7th cut.

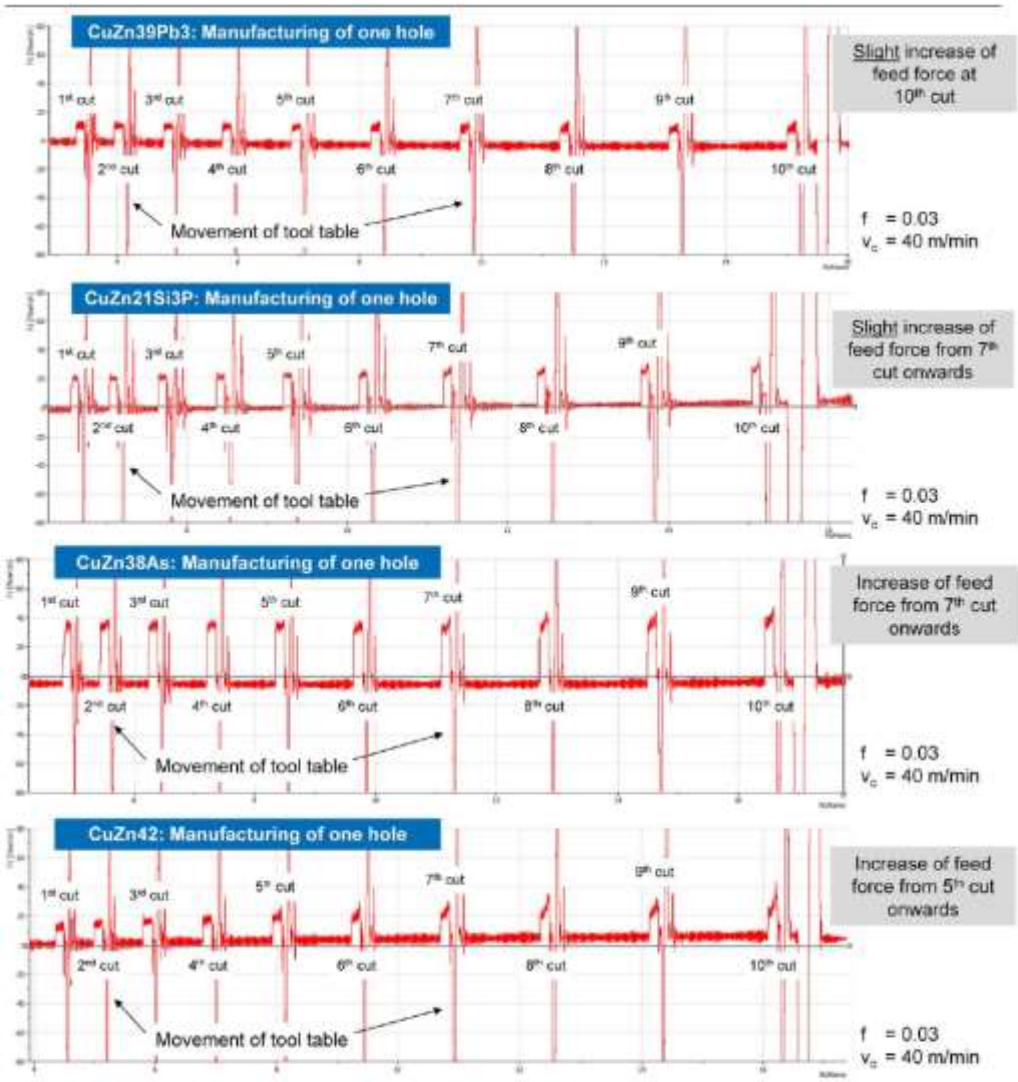

Fig. 11: Comparison at feed forces – v_C = 40 m/min, f = 0.03 mm

When drilling CuZn38As the level of feed force was much higher compared to all other investigated workpiece materials, even though hardness and tensile strength of the material is comparatively low. It is assumed that high feed forces can be explained by high friction in the contact zone and high chip compression as well as material hardening due to high percentage of ductile fcc α-phase (see figure 3). Due to the ductile material behavior and increased rubbing and squeezing of the material, also a higher increase of feed forces during the cutting process was determined when drilling CuZn38As compared to CuZn39Pb3 and CuZn21Si3P. Even though hardness and tensile strength of CuZn42 are higher compared to CuZn38As, the average value of feed force is lower. This can be probably explained by the fact that friction and chip compression is reduced due to much higher percentage of brittle bcc β-phase (see figure 3). Nevertheless, the increase of feed force during the drilling process was extremely high. For example, the feed force increased during the last cut from F_f = 22 N to more than 40 N (**figure 12**). This effect was maybe decisive that the tool broke after a few holes when applying 1st, 2nd and 3rd drilling strategy (see figure 4).

On **figure 12**, the feed forces are compared for all materials when using a cutting speed of V_C = 20 m/min and varying feeds of f = 0.01, 0.02 and 0.03 mm. For every experiment, the feed forces were illustrated at a drilling depth of t = 1 mm as well as 10 mm. Referring to the explanations before, feed forces were lowest when drilling leaded CuZn39Pb3. Also, feed forces were low during cutting of CuZn42, however, huge increase of forces was determined at the last cut, respectively (t = 10 mm). As stated before, feed forces were almost constant during drilling of CuZn21Si3P. Due to high hardness and tensile strength of the material, average value of feed force was higher compared to CuZn42, though. Highest feed forces were measured for drilling CuZn38As (compare slide 20). Similar to CuZn42, extreme increase of forces was observed at the last cut (t = 10 mm). For all materials, an increase of feed force with rising feed was determined. The increase of the cutting speed up to 40 m/min (**figure 13**) and 60 m/min (**figure 14**) did not change the behaviour of the tested materials with respect to the feed forces development.

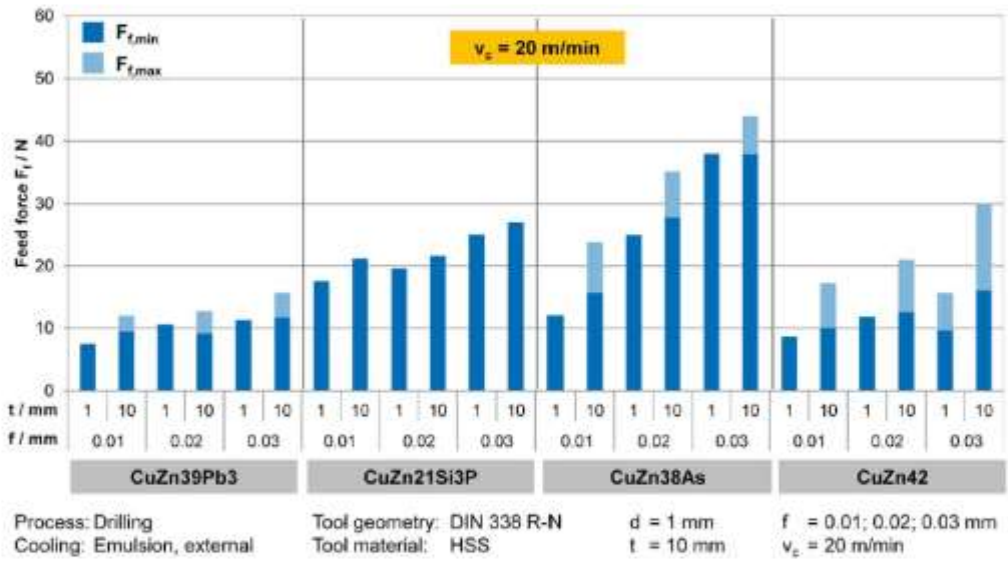

Fig. 12: Comparison of feed force at a cutting speed V_C of 20 m/min

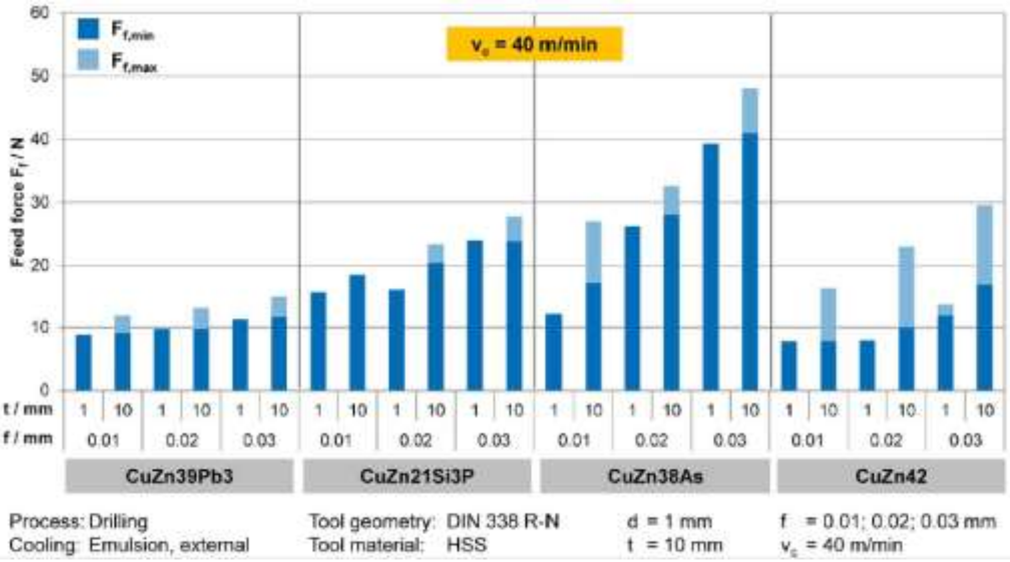

Fig. 13: Comparison of feed force at cutting speed of 40 m/min

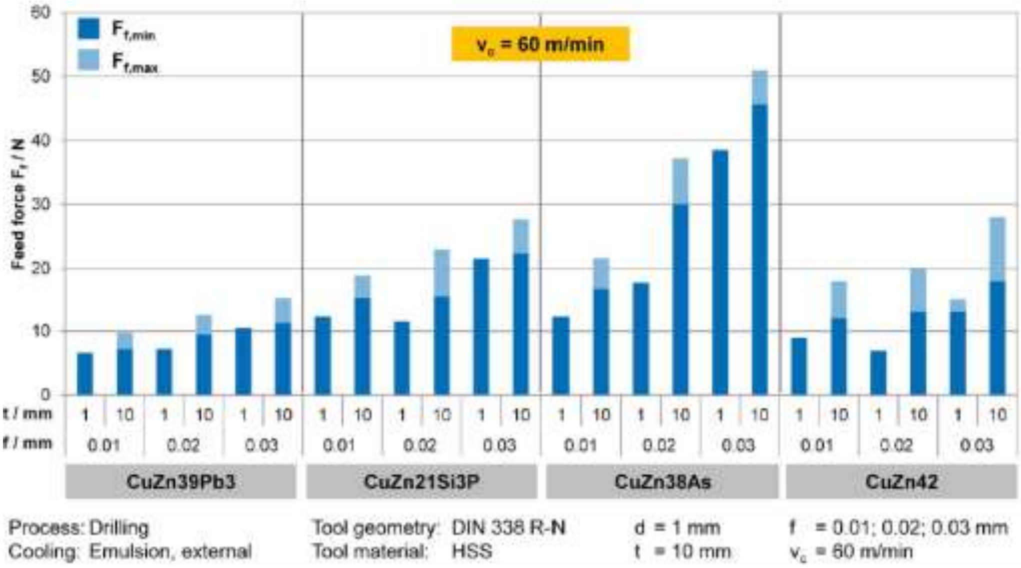

Fig. 14 Comparison of feed force at a cutting speed of V_C 60 m/min

4. Surface quality

The surface roughness was measured at a drilling depth of approximately t = 5 mm. For this purpose, a tactile measuring system Perthometer PGK 120 was used. At every hole, the surface roughness was measured twice and the average value was then calculated. Nevertheless, huge deviations can be observed in some cases which are hard to explain. It has to be stated in advance, that a more detailed investigation is recommendable in order to better analyze the effect of the different workpiece materials on surface quality. For example, SEM photographs of the drilled surface would give detailed in-formation on surface generation. Regarding measured Ra and Rz values (**figure 15**), the surface roughness was higher after drilling of CuZn39Pb3 for almost all applied cutting parameters. In contrast, the values after cutting CuZn38As and CuZn42 were half as much or even less. When drilling CuZn21Si3P, surface roughness was comparable to CuZn39Pb3 when using a cutting speed of V_C = 20 and 40 m/min. For a higher cutting of V_C = 60 m/min, Ra and Rz values were similar to those measured after drilling of CuZn38As and CuZn42. On average, a lower surface roughness was measured with rising cutting speed for all materials, while a rising feed led to increasing surface roughness for most of the experiments. However, as stated above, huge deviations were observed in some cases. A more detailed analysis of the generated surface is recommendable.

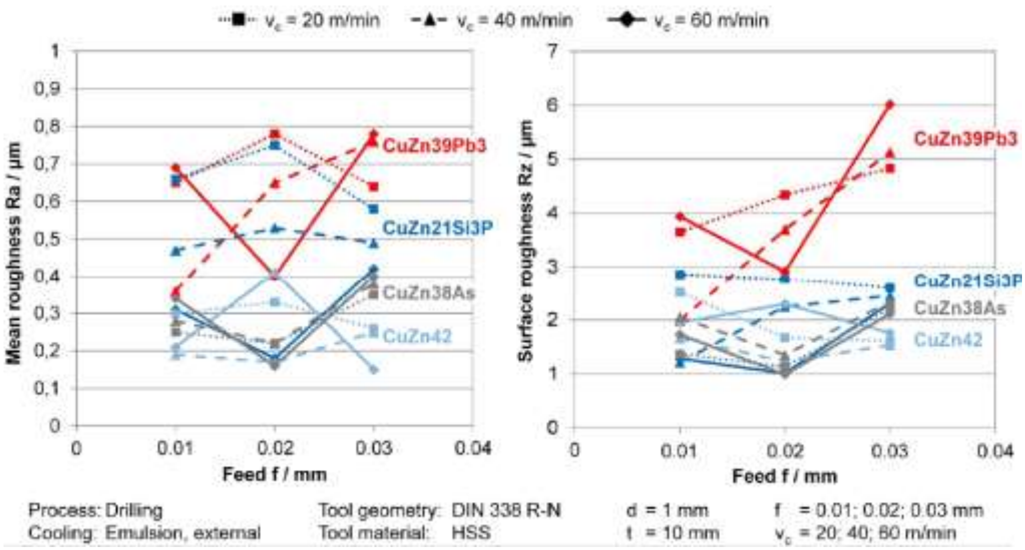

Fig. 15: Comparison of surface roughness

5. Tool wear

After investigating chip formation, cutting forces and surface roughness at varying cutting parameters, tool life tests were carried out at a constant cutting speed of V_C = 40 m/min and a feed of f = 0.02 mm. The end of experiments was achieved after manufacturing 1000 holes or after tool breakage. When drilling CuZn39Pb3 and CuZn38As no tool breakage occurred after 1000 holes. In contrast, the tool broke after 880 holes when drilling CuZn42 and after 205 holes in terms of CuZn21Si3P. In a second test run, the tool even broke after 190 holes when cutting CuZn21Si3P. Besides tool wear, which is analyzed on **figure 16**, feed forces were measured after every 100 holes. On the right side of the slide, the maximum feed force at a drilling depth of t = 10 mm is illustrated. When cutting CuZn39Pb3, maximum feed force was almost constant after a slight increase in the beginning which can be probably explained by initial tool wear. The same applied to drilling of CuZn38As and CuZn42, even though the average level of maximum feed force was more than doubled. A huge increase of maximum feed force was observed during drilling of CuZn21Si3P. After 200 holes, maximum feed force increased from F_{fmax} = 23 N in the beginning to 58 N. It is assumed that the strong increase was caused by higher abrasive tool wear compared to the other workpiece materials which finally led to breakage of the tool. The tool wear is analyzed on the next slide.

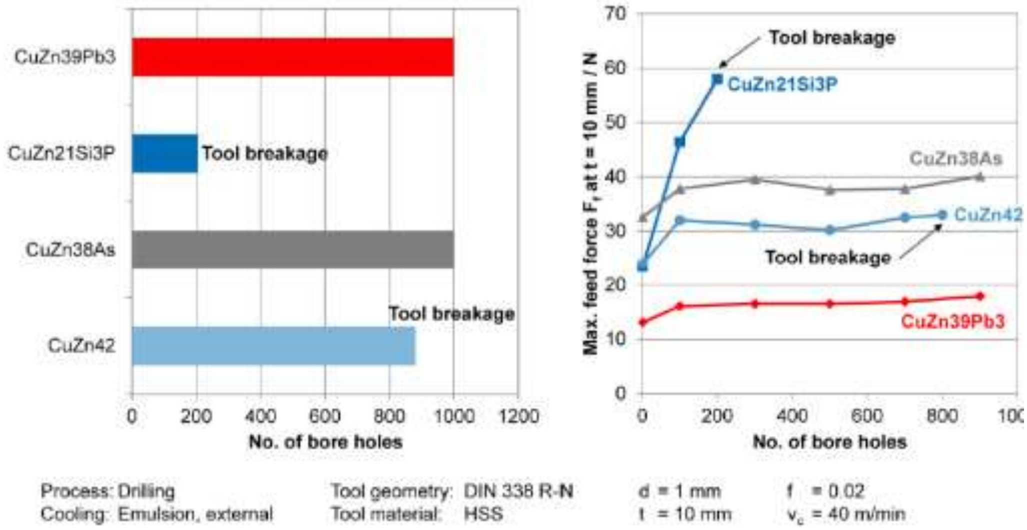

Fig. 16: Comparison of tool wear and maximum feed force

When drilling leaded CuZn39Pb3, tool wear was very low after 1000 holes (**figure 17**). Width of flank wear land was measured to only VB = VBmax = 15 µm. Moreover, only slight material adhesions can be observed at the chisel edge. In contrast, much higher flank wear of VB = VBmax = 35 µm was determined after only 200 holes due to the presence of highly abrasive silicon-rich κ-phases in the microstructure. The increased tool wear probably caused high increase of feed force (see figure 16) and consequently, caused tool breakage. When drilling CuZn38As, average width of flank wear land was similar to CuZn39Pb3 (VB = 15 µm after 1000 holes). However, strong material adhesions were observed at the chisel edge and also along the major cutting edges. The higher amount of adhered material can be explained by high percentage of ductile fcc α-phase in the microstructure. The observed adhesions are a hint to increased rubbing and squeezing of the material which led to high feed forces (see figures 11 to 14). Apart from high adhesive tool wear, abrasive tool wear was increased at the corners of the major cutting edges. After 1000 holes, a maximum width of flank wear land was measured to VBmax = 28 µm. The increased tool wear at the corners might be explained by increased friction and rubbing between the tool and the workpiece. Adhesive tool wear was reduced when drilling CuZn42 compared to CuZn38As due to much higher percentage of brittle bcc β-phase. The average width of flank wear was similar to CuZn39Pb3 and CuZn38As. In contrast to CuZn38As, no increase of abrasive wear was observed at the corners of the major cutting edges. Based on all achieved results, it is not clear why the tool broke after 880 holes when drilling CuZn42, whereas no tool breakage occurred within 1000 holes during drilling of CuZn38As. It has to be considered that the experiments were only conducted once. In order to get a more detailed and statistically reliable statement on machinability of the different workpiece materials during micro drilling, the tool life tests had to be repeated at least two or three times.

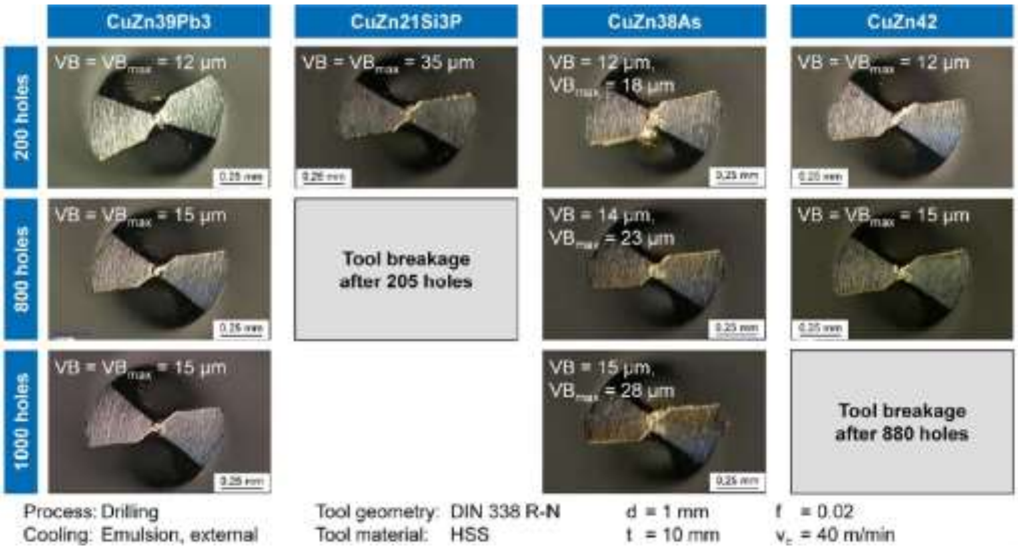

Fig. 17: Comparison of tool wear

5. Conclusion

Copper-Zinc alloys have been micro drilled and compared to each other. Micro-drilling is a delicate machining operation as tool breakage can occur easily. With an adequate drilling strategy a comparative study could be done even if apart from CuZn39Pb3 for some other alloys more than 1000 holes could not be drilled without tool breaking.

Independently from the strategy the presence of lead (e.g. CuZn39Pb3) was beneficial for the machining as feed forces and tool wear were lower compared to tested lead free alternatives (e.g. CuZn21Si3P, CuZn42, CuZn38As).

The measurement of the surface quality did not deliver satisfactory results as no clear tendencies were observed. It is assumed that the measurement method did not work as expected.

As the drilling of fine holes is influenced by a huge number of factors, it should be mentioned that the study could not deal with all details of that topic.

In 2014 WZL of RWTH Aachen University lunched a project with a much broader scope, which will investigate more in details the drilling of fine holes.