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PRODUCTION PROCESS

Burr formation in short hole drilling with minimum quantity lubrication

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Abstract Machining with minimum quantity lubrication (MQL) is state of the art. Previous investigations were, however, concerned with tool optimisation and the surface quality of workpieces as well as coating technology. By now the same or partly better machining results than in conventional cutting with flood lubrication can be achieved due to adjusted tool geometries, workpiece materials and coatings. Tests about burr formation in short hole drilling exist for dry cutting or the machining with emulsion. This paper expands these results to the burr formation in machining with MQL.

Keywords Production process · Burr formation · Minimum quantity lubrication

1 Introduction

Cutting fluids constitute a threat for soil, water and air, which is caused by leakage and drag-out losses, emissions, washing water and not least their disposal. In this way, about 100,000 t of lubricants get into the environment through vaporisation and atomization every year [1]. Components of cutting fluids, bactericides and fungicides, arising reaction products as well as brought-in contaminants may cause illnesses, especially skin diseases [2]. Furthermore, investigations into health dangers by the arising oil vapours exist, showing that there is less risk of fire but a possible danger to the respiratory tracts [3]. By increasingly stricter laws, the trade associations and the legislator react for protecting the workers and to the environmental threat coming from cutting fluids. For enterprises, these legal guidelines and technical regulations mean not only an enlargement of their responsibility and new duties towards their employees, but also higher financial burdens above all.

An approach to solving the lubrication problem is to move from wet machining to dry machining or rather the cutting with minimum quantity lubrication (MQL) [4]. Regarding MQL, the concentrations of fluid in air is about 50% below those of cutting fluids [5]. This change requires a very careful adaptation of the boundary conditions because the primary cutting fluid functions such as cooling, lubrication and chip removal are no longer necessary. Owing to the constant further development of carbides and coating technologies, a partly higher tool life could be attained with MQL than in flood lubrication [6].

In the machining with MQL, it has to be taken into account that its efficiency depends especially on the kind of supply to the tool [7]. In addition, the flow conditions influence the supply from the production to the cutting region. In the case of internal supply, the flow rate decreases and drops by about 35% for rotational speeds greater than 3,000 min^{-1} [8].

Apart from the costs of cutting fluids, burr formation in the cutting of metallic materials poses a great problem in many branches of industry. The required deburring operations can take up a noticeable portion of the time needed for manufacturing a product and thus of its cost, particularly in the case of components with small material removal but high demands on the freedom from burrs.

In general there are two ways of solving this problem. These are burr removal on the one hand and burr minimisation during machining on the other hand. Based on the

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principle that a burr is removed only as far as necessary and not as far as possible [9], a subsequent machining could be omitted by that in many cases.

2 Test facility

The testing machine is a high-speed machining centre with a maximum rotational speed of 24,000 min^{-1}. The MQL system applied in combination with the machining centre can be used for the external supply of lubricants by means of spray nozzles as well as for the internal supply through internal channels. The system is particularly suitable if the requirement of lubricant is high due to the material to be machined, in the case of high spindle speeds resulting in centrifugal forces, disadvantageous supplies through angular heads and turret heads, or if fast response and reaction times are necessary.

Inside the MQL system a lubricant aerosol is produced, which is delivered through hose lines and channels to the cutting region. Because the drop size of the lubricant drops is low, they have an extremely low settling speed and hence can be delivered through long channels and around corners or edges without losses. Due to the extremely low mass, nearly no centrifugal forces act on the particles within rotating spindles. Consequently, sedimentations and separations of aerosol particles are avoided before the exit from the tool.

The MQL system has 15 function levels, each of which can be selected by the control of the machine tool (Fig. 1). These 15 function levels are subdivided into the machining with pure compressed air and three different pressure levels. Within one pressure level, the proportion of lubricant quantity in the air is varied.

The amount of lubricant cannot be given as absolute value, since it depends on the air quantity flowing through the tool. It is not possible to give general absolute values such as ml/h for the lubricant, due to process influences such as, for example, the supply of compressed air, the diameter and length of the cooling channel.

Serving as MQL agent is a lubricant that was especially developed for minimum quantity machining and is based on special fatty alcohols. Five commercially available standard tools were tested, which have a diameter of $d = 25$ mm and two cooling channels with diameters between $d_K = 2.5$ mm and $d_K = 3.0$ mm. The geometries of the accompanying indexable inserts are presented in Fig. 2.

Variant	Description	
0	MQL system off (machining pause)	
1	Blowing out of pure air	
3	Pressure Level 1	Lubricant quantity 50%
5	Pressure Level 2	Lubricant quantity 55%
12	Pressure Level 3	Lubricant quantity 55%
15		Lubricant quantity 100%

Fig. 1 Examined MQL variants

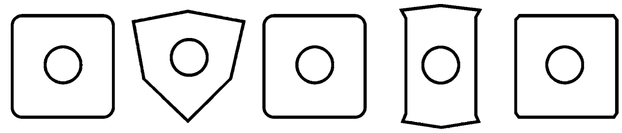

Fig. 2 Tested geometries of indexable inserts

The heat-treatable steel C45E was used as reference material for the basic investigations into the burr formation in short hole drilling with MQL. Comparative tests were carried out with 42 CrMo 4 V, 16 MnCr 5 and AlCuMgPb-F34.

3 Determination of minimum quantity

In the case of internal supply, the cutting fluid is delivered through two cooling channels inside the drill to the machining zone. The following test serves to determine the lubricant amount used per hour. The test facility in Fig. 3 includes a container that holds and stores the cutting fluid.

To measure the amount of lubricant, the drill is brought into the container and simulates a machining operation for a defined rotational speed, given MQL variant and particular machining time [10].

The container, weighed beforehand, was clamped in a defined position into a chuck for determining the lubricant amount. Then the drill traverses up to 1 mm before the baffle plate and turns at a set MQL variant and a rotational speed of $t_S = 10$ min. Finally, the drill is driven out of the container, and the container is weighed again with a special accuracy weighing machine. The supplied amount of

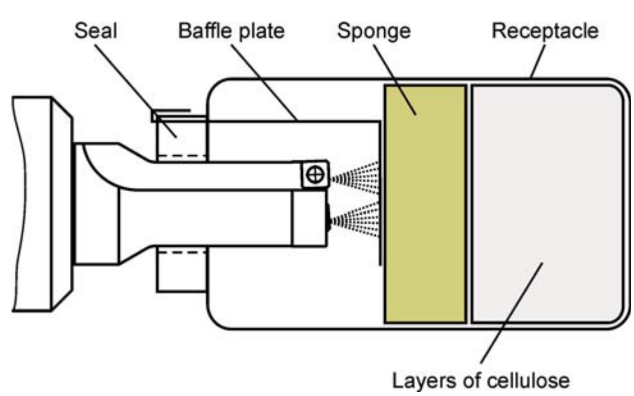

Fig. 3 Measurement of lubricant amount in drilling

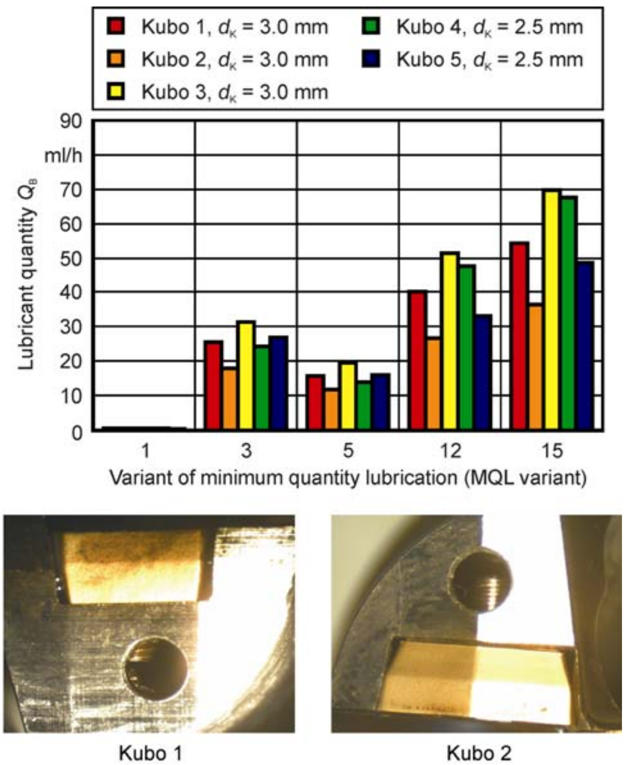

Fig. 4 Lubricant amount in tool comparison for n = 1,910 min^{-1}

lubricant Q_B in millilitre per hour is calculated from the density ρ of the lubricant and the difference in mass m_E–m_S at the end and start of the spray test with the gaging time t_S [10].

As expected, the highest amount of lubricant is measured in the tests with the MQL variant 15 since the saturation of the air with lubricant is 100% in this variant (Fig. 4). As expected, the lowest amount of lubricant arises for variant 1, in which no lubricant is used and only pure air is blown out. The lubricant amount still measured (less than 1 ml/h) results, on the one hand, from remnants of lubricant, which remains in the system despite sufficient inlet phases before the measurement, and, on the other hand, from inaccuracies of measurement in the range of less than 0.1 g.

While the proportion of lubricant amounts is very similar among the MQL variants in all test tools, the absolute amount of cutting fluid exhibits considerable differences among the drills. The highest amount of lubricant is measured for short hole drill 3, the lowest amount for short hole drill 2. This great difference can be explained, on the one hand, by the standard fastening screw of the indexable insert, which extends, in full diameter for short hole drill 2 and in approximately half diameter for short hole drill 1, into the outer cooling channel (Fig. 4). On the other hand, the geometry of the drills and of the cooling channels affects the flow of the air–oil-mixture.

4 Definition of burr and burr parameters

The assessment whether a burr is critical or not is mostly laid down internally in company standards. Many companies even check and deburr all components as a precaution. A small number, however, does without the analysis and evaluation of burrs [11].

To characterise a burr, the burr height or the five burr types defined by CODEF (Consortium on Deburring and Edge Finishing) for drilling are used frequently [12]. The standard ISO 13715 defines the edge of a workpiece as burred if it has an overhang greater than zero. With regard to a burr avoidance or reduction this definition is not very meaningful though, as no measure is given for the machinability of the burr. For this reason, Schäfer [9] defined the so-called burr value (Fig. 5).

By the burr value g the four geometric parameters of burr root thickness b_f, burr root radius r_f, burr thickness b_g, and burr height h_0 are combined to a comparative value. The different weighting factors result from the effect with which the individual burr parameters influence the deburring process. In the following, the burr value will be used to describe burr formation. The burr value or rather the burr parameters were determined with micrographs by means of a microscope (Fig. 5) at least two points. For each parameter combination the tests are repeated twice.

5 Burr formation

5.1 Influence of feed

Basic investigations into short hole drilling showed that feed decisively influences burr formation. The burr value rises with increasing feed [13]. In contrast to that, the table of the test results with a feed of $f = 0.07$ mm (Fig. 6) shows no direct correlation between burr value and the amount of lubricant used.

The highest burr value for all MQL variants results in the tests with the short hole drill Kubo 5 (see Fig. 2) and

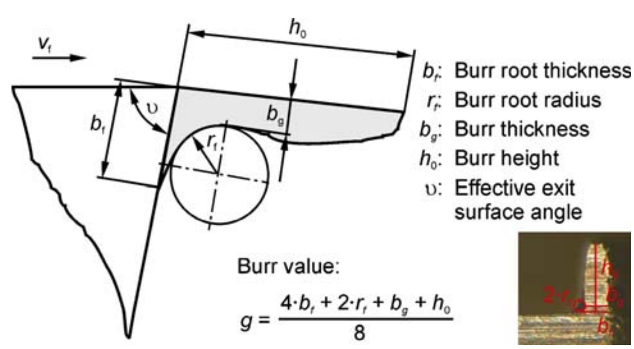

Fig. 5 Measured values of a burr [9]

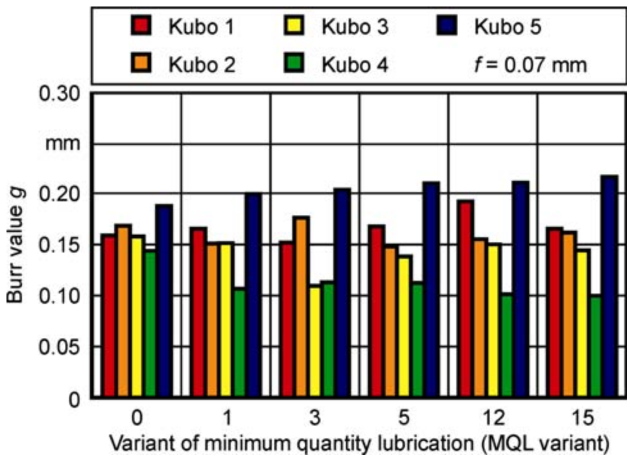

Fig. 6 Burr value comparison $f = 0.07$ mm

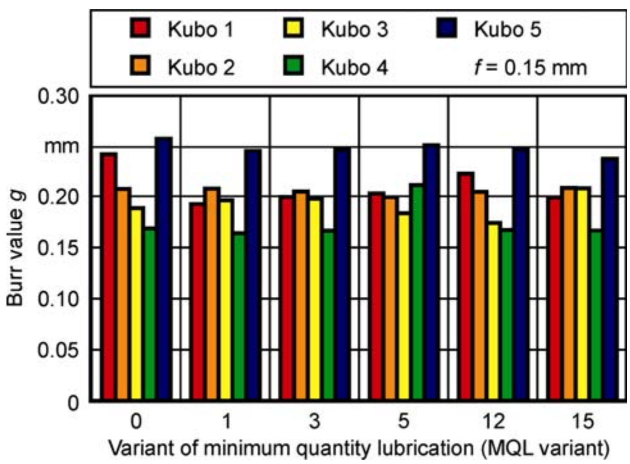

Fig. 7 Burr value comparison $f = 0.15$ mm

takes on values between $g = 0.19$ mm and $g = 0.22$ mm. The burr value increases steadily from variant 0 to variant 15. However, no conclusions can be drawn from this about the lubricant quantity used since it does not rise continuously, as shown in Fig. 4. The fluctuations rather result from variations in measured values of uneven burrs (see Fig. 7).

Compared with $f = 0.07$ mm, burr formation increases at a feed of $f = 0.15$ mm. The highest burr values arise again when using the short hole drill Kubo 5. The second and third highest burr values are produced with the short hole drill Kubo 1 and the short hole drill Kubo 2. The lowest burr values are obtained with the short hole drill Kubo 3 and the short hole drill Kubo 4.

5.2 Influence of cutting speed

Figure 8 presents the results of the variation in cutting speed at a feed of $f = 0.07$ mm. The influence is minimal.

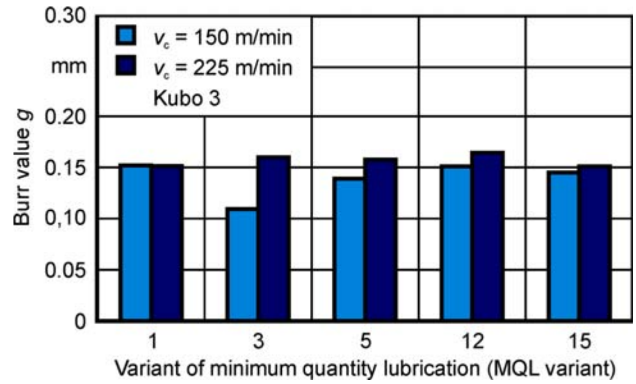

Fig. 8 Influence of cutting speed on burr value (Kubo 3)

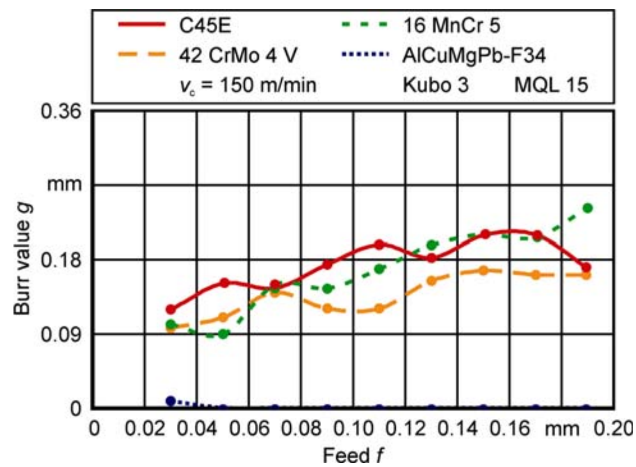

Fig. 9 Influence of workpiece material (Kubo 3)

An outlier can be seen in the case of variant 3 and $v_c = 150$ m/min.

The same holds for the other short hole drills examined. Hence, it is not necessary to present their results here.

5.3 Influence of workpiece material

Whereas in the case of the steel materials the burr value increases with rising feed and hardly differs at all from those in dry machining from previous investigations, the burr value drops to nearly zero for the aluminium wrought alloy AlCuMgPb-F34. This could not be established in the investigations into dry machining [13] (see Fig. 9).

6 Temperature in the burr forming area

6.1 Influence of cutting speed

The cutting speed mainly determines the temperature in the chip forming area via heat conduction and convection. As cutting speed increases, the chip formation rises as well.

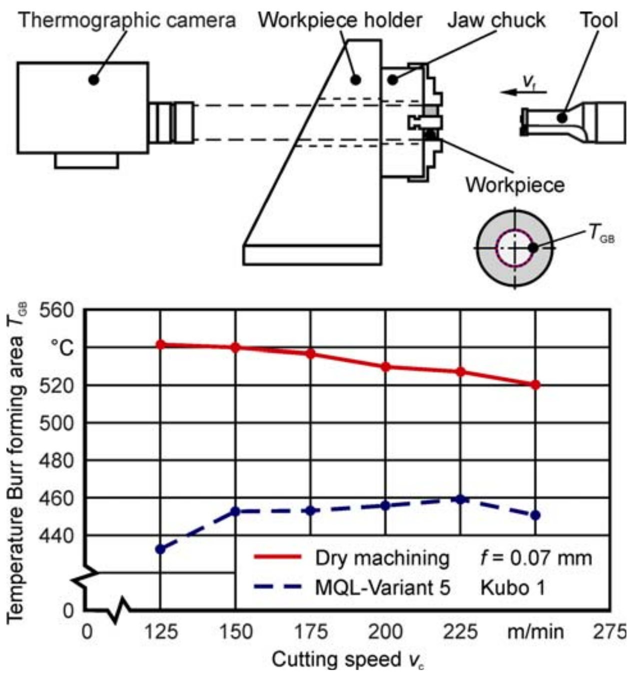

Fig. 10 Temperature in the burr forming area depending on cutting speed

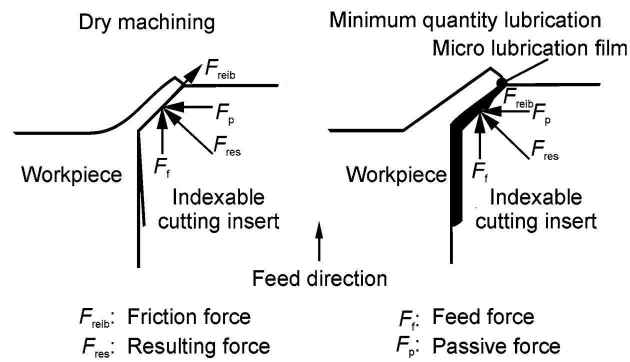

Fig. 11 Lubrication effect of the MQL agent [13]

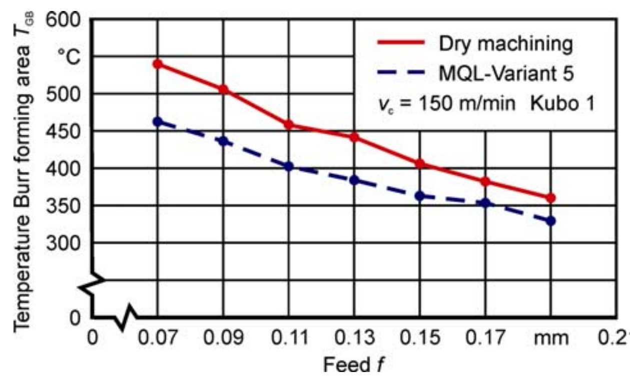

Fig. 12 Temperature in the burr forming area depending on feed

Most steels are more deformable, owing to the temperature increase. In contrast to previous tests, the temperature in dry machining decreases slightly with increasing cutting speed (Fig. 10). In the course of the tests, it could not be settled whether this may be attributed to the conditions of chip removal, the friction conditions during drilling or measurement errors.

In contrast to the temperature curve in dry machining, the curve rises during drilling with the MQL variant 5. This corresponds to previous investigations. However, the temperature falls again between $v_c = 225$ m/min and $v_c = 250$ m/min here as well.

A tendency of the curve can be detected nevertheless. The gradient decreases with rising cutting speed. The influence of lubrication becomes lesser in this case [13]. As the supplied amount of minimum quantity lubricant remains nearly constant and the drill rotates clearly faster, the lubricating film arising is thinner and thus prevents an effective reduction in friction (Fig. 11).

6.2 Influence of feed

In contrast to cutting speed, feed has a great influence on the progression of temperature and hence on chip form. Feed determines the chip compression ratio and thickness, which in turn affects the deformation of the chip. As feed increases, the temperature in the burr forming area decreases [13]. Due to the higher feed, the proportion of heat dissipated by the chip rises. This leaves the conclusion that higher temperatures are caused by the friction arising in the case of lower feed and longer drilling time. Due to the thermal energy, the workpiece material softens and deformability rises. Steel materials have blue brittleness as special feature. This range of short-term embrittlement is passed through owing to the thermal action. This range arises between 300 and 500°C, depending on the workpiece material.

As feed rises from $f = 0.07$ mm to $f = 0.21$ mm, temperature decreases by about 180°C in dry machining (Fig. 12). Hence, the higher the feed is the lower are the temperatures arising.

Temperature has a little less influence on feed in the case of the MQL variant 5, since additional factors such as friction reduction, chip removal and the cooling effect by MQL have an effect over the whole test spectrum (Fig. 12). The sum of heat development is lower and does not only depend any more on the shorter machining time due to the increase in feed.

Like in the case of the influence of cutting speed on the temperature in the burr forming area, the difference decreases with growing feed. Here the MQL quantity is also constant during the course of the test. Consequently, the percentage of supplied MQL amount compared to material removal is higher and hence can have a better effect, if feed is lower.

6.3 Influence of machining variant

The input of heat into component and tool is closely connected with the support of the chip removal by the cutting fluid. According to other measurements for lubricant reduction, ca 70–97% of the conducted work are converted into heat. Shearing and cutting work make a major contribution to this. The development of heat through friction arises at the flank face and rake face of the cutting edges. The lubricant component of MQL can develop its effect at these working surfaces and reduce the heat development by diminishing the coefficient of friction [14].

As can be seen from Fig. 13, the MQL variant itself has nearly no influence on the temperature in the burr forming area. Regarding the supply of pure compressed air, the temperature with $T_{GB} = 450°C$ is only insignificantly higher (10–15°C) than when machining with MQL. A considerable reduction in temperature can, however, be achieved in contrast to dry machining. In dry machining, the temperature in the burr forming area is nearly 100°C higher than in the machining with compressed air and MQL [15].

6.4 Influence of tool

Regarding the use of the different drills, the temperatures vary by up to 100°C at most (Fig. 14). This can possibly be explained by the fact that only a small amount of cutting fluid comes out when using the short hole drills 1 and 2, compared with other drills (see Fig. 4). In the case of these two drills, the standard fastening screws of the indexable inserts extend partly or completely into the cooling channels [10]. The geometry of the indexable insert as well as of the tool orthogonal rake angle have a considerable influence, since the results differ by up to 100°C in dry machining.

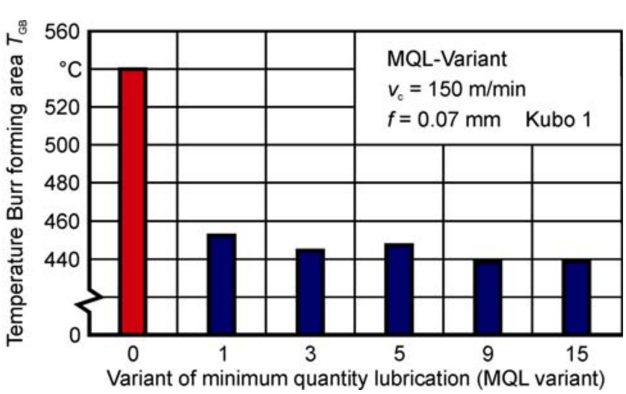

Fig. 13 Influence of machining variant on the temperature in the burr forming area

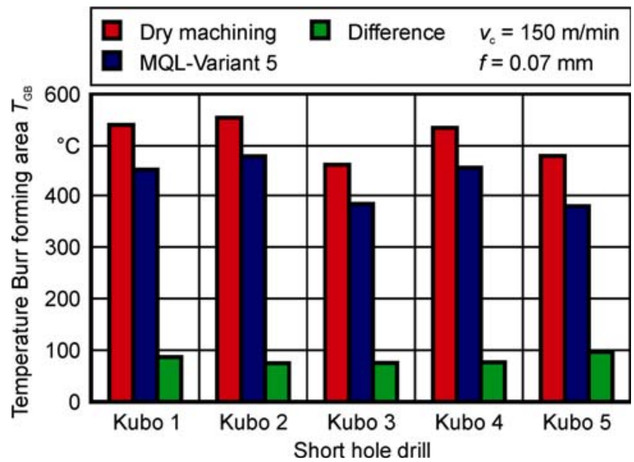

Fig. 14 Influence of drill on the temperature in the burr forming area

7 Measurements of resultant force

The choice of lubricant variant does influence the temperature in the burr forming area, but burr formation changes only insignificantly through this. In the following, it will be examined to what extent the change in friction conditions, shown in Fig. 11, affect feed force and cutting torque.

As can be seen from Fig. 15, cutting torque decreases only slightly with growing lubricant quantity. Furthermore, if feed force is taken into account, then it is more likely that the changes are attributable to fluctuations and inaccuracies of measurement when determining the measured values [16].

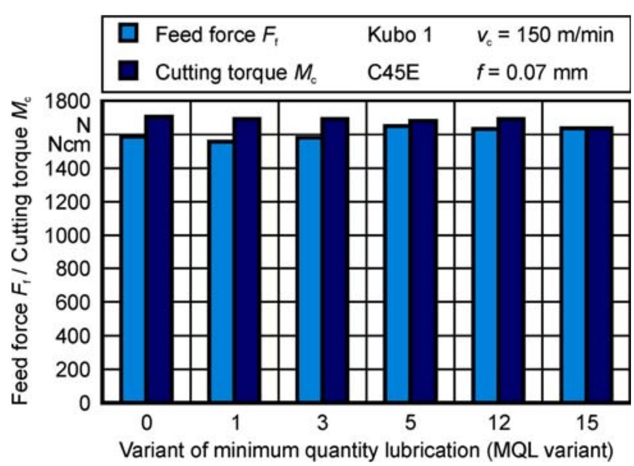

Fig. 15 Feed force and cutting torque in drilling with and without minimum quantity lubrication

8 Conclusion

The investigations into the influence of MQL on burr formation have shown that burr formation does not change noticeably by the application of MQL. There is only a slight increase in the burr value.

It was examined which influences the process parameters of cutting speed and feed have in the machining with MQL. Apart from that, tests were carried out in dry machining, with the supply of compressed air as well as with different variants of minimum quantity, differing in volume flow and the saturation of the air with fluid. For this, the lubricant quantities of the drills were determined and analysed in a first step.

The tests show that cutting speed does not influence burr formation in the machining with MQL. However, the burr values increase with growing feeds. No significant influence of the machining variant on burr formation can, however, be detected. Burr formation is considerably influenced by the choice of the tool or rather the geometry of the indexable insert. The burr formation with the short hole drill Kubo 3 is clearly lesser than with the short hole drill Kubo 5.

Differences between dry machining and the machining with MQL or compressed air could be detected when measuring the temperature in the burr forming area. Applying compressed air reduces the temperature by more than 90°C compared with dry machining. However, the temperature in the machining with MQL is only insignificantly lower compared to the machining with compressed air.

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