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PREVENTION AGAINST BREAKAGE OF MINIATURE DRILLS

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Abstract

Mechanical drilling is a fundamental machining technique of cylindrical holes with diameters of less than 1 mm. During the drilling on the miniature drills there act relatively large cutting forces, which, in presence of many disturbances, often cause tool breakage. The paper describes investigations into the thrust and the torque changes and fluctuations, depending on drilling parameters and process conditions. The various possibilities of reduction of the tool loading are discussed, like using the lubricants and interrupt drilling cycle. However, in some cases the effective breakage prevention requires special control systems installed in the drilling machine.

Keywords: cutting, drilling, miniature drills, breakage, prevention.

1. Introduction

1.1. Description of the Problem

Holes with diameters of less than 1mm have been drilled in various components, like spinnerets, nozzles and tooling plates with precise multihole perforation [1]. The drilling is performed using miniaturized twist, spade or gun drills (D-shape). The miniature drills are the cutting tools with determined edge geometry. Therefore in conventional drilling and in drilling of holes with diameters smaller than 1 mm, many effects are similar or even the same [2]. But there are also important differences. The small dimensions of the holes and the miniaturization of the drills entail intensification of problems caused by close relation between tool strength and cutting forces [3]. The miniature drills are exposed to the action of comparatively large thrust and torque. In such situation every way involving reduction of the tool load is indispensable. Optimization of drill shape and geometry interrupt micro-stroke drilling cycle and the other options are in use [4, 5]. The smaller the diameters, the more difficult the execution of technically and economically effective drilling process is. The reason is higher risk of drill breakage, because besides regular cutting forces many disturbances are present during the drilling. In consequence it is difficult to predict the tool life of miniature drills [6, 7]. If only regular wear is expected, the determination of the number of holes, done before the drill needs to be replaced is important. If cutting load of the miniature drill is close to its strength limits and next if large additional fluctuations of the forces are forecasted, the in-process breakage prevention systems are necessary. Unfortunately, the changes of detected signals are very small and it is difficult to propose an effective method and supervising equipment [8, 9]. Therefore in the practice only drill breakage detectors are sometimes installed in the drilling machines.

1.2. Basic Phenomena in Drilling

During the drilling various phenomena appear. The first one is the cutting, causing the plastic deformation and shearing of the machined material, next chip formation and removal. The friction of the drill surfaces and edges against bottom and wall of the drilled hole accompany the cutting. Evacuated chips clogie the flutes and enlarge the friction against its surfaces and hole wall. The shearing, the chip formation and the friction, create the forces on cutting edges, on chisel edge, on land surface and in the flute. After superposition they are detected as the resultant cutting forces. Generally, in simplified model, it is taken as granted that the tool is exposed to the action of thrust F, torque M and in particular cases also of the radial force R – *Fig. 1*.

The tool wear causes continuos and increasing growth of the forces. Simultaneously with the cutting, internal and external friction generates significant amount of the heat, entailing temperature growth in the cutting zone. Forces acting on the drill are relatively large and comparable with the drill strength indexes. It can be especially visible in case of microdrilling, when the diameters are smaller than 0.5 mm. If the stresses exceed the mechanical strength of the tool, the drill suffers breakage.

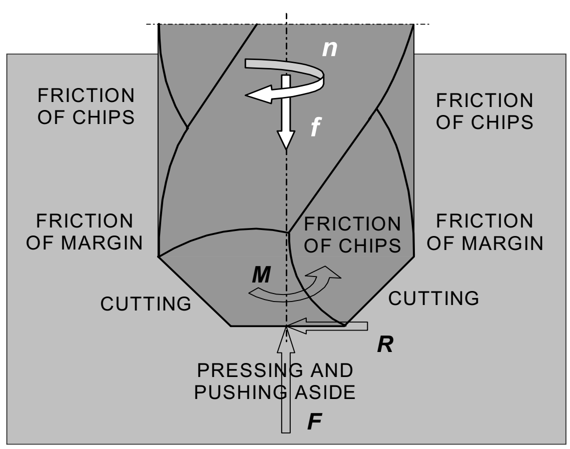

Fig. 1. Motions, basic phenomena and resultant cutting forces in drilling process

Usually the broken drill tip interlocked the partly machined hole – *Fig. 2.* As a result the drill failure means the loss of the tool and of the workpiece.

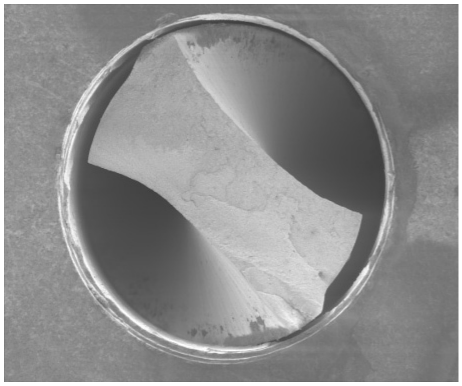

Fig. 2. Drill with d=0.5 mm made of tungsten carbides broken by drilling in metal matrix composite

For comprehensive evaluation of cutting forces the drilling diameter and the length of the hole, influence of workpiece material properties (structure, hardness, plasticity, friction coefficient), influence of the drill geometry and quality (value of angles, web thickness, flute profile, presence of margin, flute/land ratio, correction of drill tip), influence of main cutting parameters (cutting velocity and feed), influence of process execution (intermittent drilling cycle for larger aspect ratios, number of hits) and influence of other cutting conditions (lubrication, amplitude of vibrations, drill-spindle eccentricity etc.) should be taken into account.

Main equations describing the drilling process (material removal rate – *MRR*) and the cutting forces (thrust – feed force F and torque – torsion moment M) are:

$$MRR = Afn = \pi r^2 fn = 0.5rf\upsilon_c \tag{1}$$

$$F = k_{sF} a_p f C_F = k_{sF} r f C_F \tag{2}$$

$$M = k_{sM} a_p f C_M = k_{sM} r f C_M \tag{3}$$

where:

A – field of hole cross-section,
f – feed,
n – rotation,
r – drill radius,
υ_c – cutting speed,
k_{sF}, k_{sM} – specific cutting forces for thrust (feed force) F and torque (moment) M,
a_p – cutting depth (equals the drill radius r),
C_F, C_M – products of correction factors.

An achievement of the reasonable efficiency in machining process makes it necessary to use high values of cutting parameters: speed υ_c (or n) and feed f – *Eq.* **??**. On the other hand, the values of cutting parameters affect the values of forces acting on the miniature drills – *Eq.* **??** and *Eq.* **??**. In general, the active minimization of the thrust and torque is exclusively based on reducing of the feed (in some cases also of speed n or υ). It derives from the fact that the properties of workpiece material (representing by k_{sF}, k_{sM}) and drilling diameter are fixed.

1.3. Reduction of Drill Breakage

The drill failure happened when the stresses caused by cutting action and additional disturbances are larger than the limits of drill strength. The analysis of common situations displays that the most dangerous conditions are when the load stresses are close to the limits of strength and the range of the load fluctuations is wider – *Fig. 3*. In such case a typical reduction of cutting forces could be insufficient.

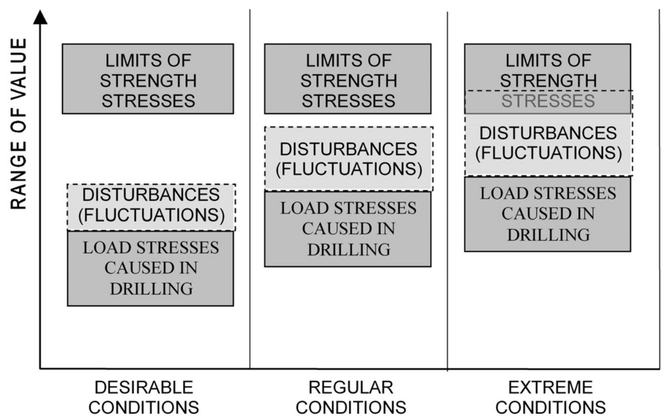

Fig. 3. Drill strength – cutting forces relations in microdrilling

The diminishing of the cutting forces, especially of the constant forces portions, could be achieved in many ways, depending on the drill geometry, roughness of its surfaces, sharpness of the edges and so on – *Fig. 4*. Very important factor is the using coolants, like water-oil mixtures, alcohol or even the blow of nitrogen by drilling in brass. They could reduce the friction of the tool against drilled material and of the chip against the drill and the hole wall. For effective penetration of lubricants into the spaces between the drill and the workpiece enlarged pressure is necessary. Each way is useful and should be applicated if possible.

In microdrilling, except decreasing of the feed, very significant is the question of chips removal from the flutes. There are the following mechanisms of chip evacuation: action of centrifugal forces involved by rotation and jointed with specially

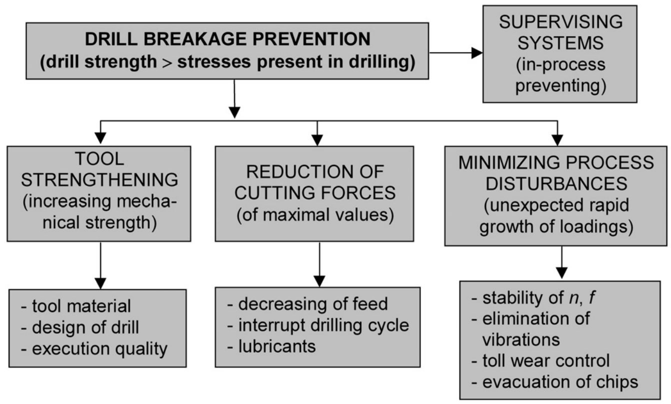

Fig. 4. Courses of reduction or prevention against drill breakage

profiled shape of the flutes [4], action of gravity and additional suction. All of them together could be applicated only in selected realization of micodrilling operations. In the feed execution widespread is so called 'peck' drilling, even with very short feed strokes [5]. When using an intermittent drilling cycle, the maximum values of the forces are decreased in result of better chip evacuation and therefore smaller friction.

Prevention against the breakage of miniature drills is also possible by using supervising systems – *Fig. 5*. Few process signals are reliable for the detection of the prefailure phase of miniature drills, but in some cases they are too small and signal/noise ratio is too low. They are signals of cutting forces (F, M, R), amplitude of drill vibrations, number of drilled hole (or executed hits) and temperature of drill tip. Next are the power or the current increase in supply unit of feed drive. The signal of acoustic emission, following the damage of the edges, is not measurable in the case of microdrilling [8]. In more complicated systems it is possible to record in the memory the sample diagram to compare the values in selected points.

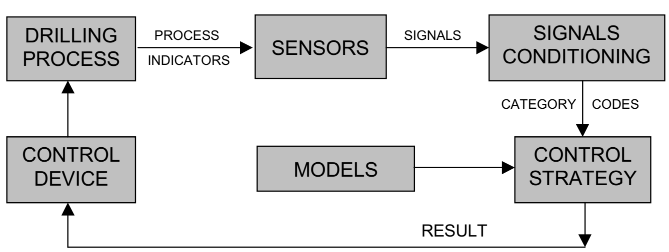

Fig. 5. General structure of supervising systems

Since in microdrilling the torque values are minute, more sensitive transducers are necessary. They could be specially prepared for this particular application in various ways. But most often the feed force signal is only taken into account. Nevertheless, in laboratory conditions the systems using combinations of many signals are investigated. To avoid the noise the additional electronic band-pass filters are switched into the equipment [9]. Also various possibilities of development of more effective strategy are proved.

2. Experiments

2.1. Tools and Specimens

The miniature drills made of high speed steel like HSS-E (Cr4W6Mo5Co5V2) and of sintered micrograin tungsten carbides like K10 (∼WC95%Co5%) or with higher cobalt phase content like K20/K30 (∼Co 8–12%) were used in the experiments. The investigation into the tools strength properties and the drilling tests were done using the twist drills, because the majority of microdrilling operations are executed just with these drills.

The values of cutting forces and therefore also the risk of drill breakage depend on the mechanical properties of the material to be drilled. In general the specimens made of metal alloys have been investigated. They were brass CuZn39Pb1 (R_m ≈440 MPa), carbon steel ∼C0.45% (R_m ≈600 MPa) and stainless steel Cr18Ni9Ti (R_m ≈684 MPa). Selected metal matrix composites and laminates used for printed circuit boards were partly taken into account.

To determine the contribution of cutting edges, chisel edge and margins in creating of cutting forces a special specimen has been prepared (*Fig. 6*). It was composed of three sections corresponding with main geometrical components of the drill cutting part. By drilling in such specimen in the first step only a force portion caused by the cutting edges is measured. Further step adds the margin and at the end operates the complete cutting part – cutting edges, margins and chisel edge.

2.2. Experimental Setup

The investigation into the thrust and the torque was carried out using the special experimental setup composed of drilling unit (spindle and feed device), tensometric forces sensors and transducers, amplification equipment and data acquisition and analysis (*Fig. 7*). The special dynamometer has been also designed.

To achieve speeds ranging $n = (2 \dots 7) \times 10^4$ rpm, high frequency spindle was applied. The feed drive was equipped in DC or stepping motor, controlled with PC unit. In both cases there was a possibility of considerable change of the feed rate. A typical diagram recorded by the continuous drilling is shown in *Fig. 8*. The growth of the torque took place not only during the drilling but also during the

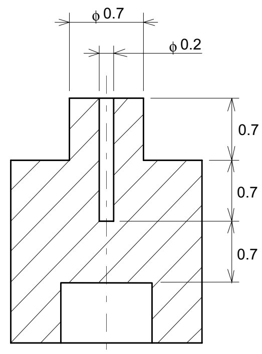

Fig. 6. Specimen used for measurement of contribution of forces

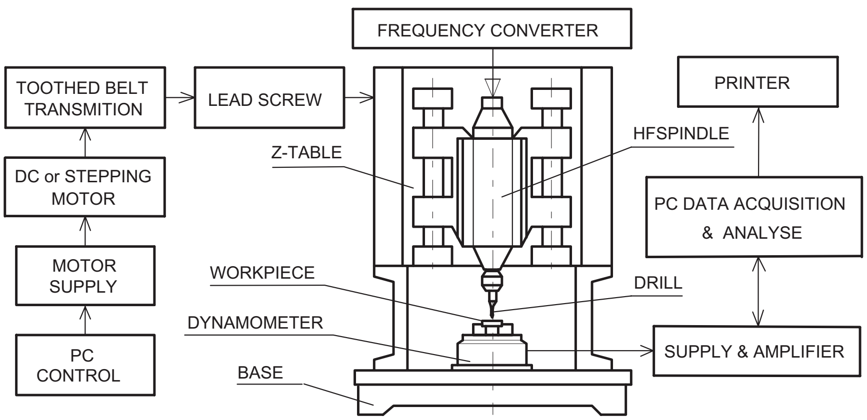

Fig. 7. Experimental setup for investigation of cutting forces in microdrilling

retraction of the drill. The force achieved certain value at the beginning of operation and increased with enlarge penetration of the tool. Noticeable is the value of the torque, which is much smaller than the thrust signal and comparable with the noise generated in electronic circuits. In another example, when drilling in Al-alloy holes with d=1.0 mm, the values of cutting forces were $F_{\max} \approx 15$ N, $M_{\max} \approx 9$ mNm and R=0.2 N for $\upsilon_c \approx 10$ m/min and f=0.005 mm/rev. The radial force was defined as maximal amplitude of force vibrations detected in radial directions. In correct executed process its value is negligible because asymmetry of cutting part, spindle-drill eccentricity or deviation of drilling axis are minute.

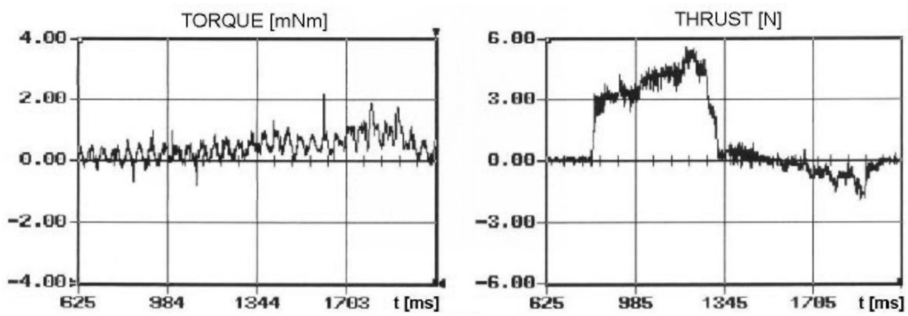

Fig. 8. Diagrams of torque and thrust recorded in drilling of hole with a diameter of d=0.4 mm in brass CuZn39Pb1, thickness L=1.5 mm, n=42000 rpm, f=0.004 mm/rev

3. Results and Discussion

The values of the torque, measured in the drilling experiments, have been compared with chosen limits for torsion for the drills used. The limits could be the maximum values of the torque (breaking torque), the yield point values from the deformation – load strength curves or certain percentage of maximal torque [10]. In the diagrams depicted in *Fig. 9* line designed T_L represents 50% of the breaking torque. The line M_c consists of real values of the cutting torque recorded during the drilling in carbon steel. Thin lines correspond to the nominal fluctuations (±20%) of the strength and of the cutting torque. The critical point (cross section of nearest lines) is between d=0.3–0.4 mm. Therefore the drilling of the holes with smaller diameters needs decreasing of the feed or availing the other measures.

The diagrams achieved in the experiments with special specimens enabled the evaluation of the thrust and the torque percentage produced by main geometrical portions of the drill cutting part (*Fig. 10*). The drilling has been executed by following conditions: drill diameter d=0.7 mm, spindle speed n=32x10^3 rpm, feed f=14 μm/rev. According with expectation the cutting edges and the chisel edge are most responsible for the creating of both forces.

The values placed in *Table 1* demonstrated that in microdrilling the torque and the thrust caused by the edges are smaller than in conventional range of diameters.

The friction components correspond to the margin and are of similar percentage, but the participation of the chisel edge is of the biggest importance. Therefore the minimizing of the chisel edge length should cause considerable changes of the loading.

The application of the proper lubricant could reduce the feed force and the torque as well. In *Fig. 11* there is shown the comparison of the values of the forces measured during dry drilling and when emulsion has been delivered. In the presented example the absolute differences are not too large but relative reduction achieves noticeable values of 26% (F) and 6% (M). In the other experiments it

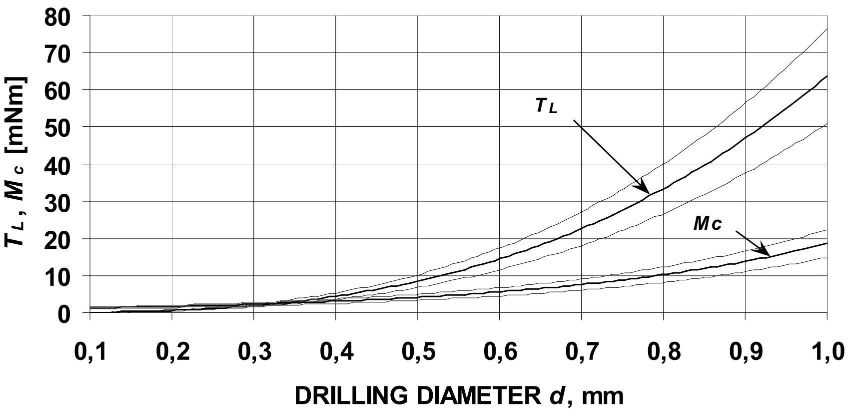

Fig. 9. Comparison of limit of torsion T_L evaluated for steel drills with cutting torque (moment) M_c measured during drilling in carbon steel, $n = 32 \times 10^3$ rpm, feed f=8 μm/rev, L/d=2, dry drilling

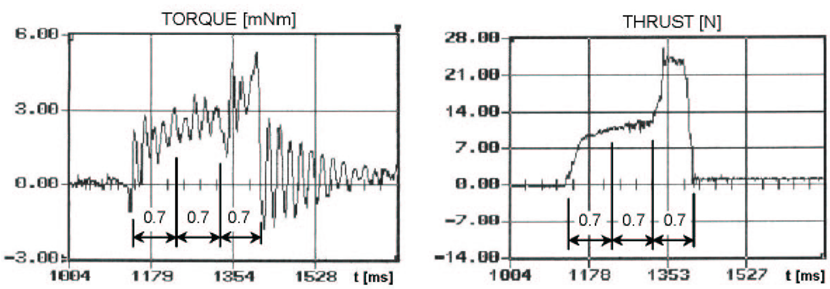

Fig. 10. Increase of cutting forces when drilling in specimen shown in *Fig. 6*

often happened that the reduction level of the torque was larger than that of the feed force.

To explain a role of the intermittent drilling method, the comparative tests have been carried out. In *Fig. 12* and *Fig. 13* diagrams recorded in the similar cutting conditions (n=32000 rpm, f=8 μm/rev) are shown, but once with continuous and next with interrupt process realization. It is seen that the interrupt drilling caused slight diminishing of maximum values of the torque and the thrust.

Prevention against the breakage by using supervising systems showed some problems in various experiments. The simplest way of the counteraction against drill failure is using of certain threshold value of the torque L_M or of the thrust L_F. They could be chosen at the selected level of the breaking torque T_B or of the recorded maximum feed force $F_{\max}$ – *Eq. (4)* and *Eq. (5)*.

$$L_M \approx (0.5...0.6)T_B \tag{4}$$

Table 1. Values and percentage of cutting forces determined during the drilling with drill of d=0.7 mm using prepared specimen made of brass CuZn39Pb1

TORQUE *M*				
Geometrical component	EDGES	MARGIN	CHISEL EDGE	SUM
Value M [mNm]	1.7	0.9	2.2	4.8 mNm
Value M [%]	35	19	46	100 %
Conventional range of d [%]	80	12	8	100 %
FEED FORCE *F*				
Value of F [N]	9.1	2.6	17.4	29.1 N
Value of F [%]	31	9	60	100 %
Conventional range of d [%]	50	10	40	100 %

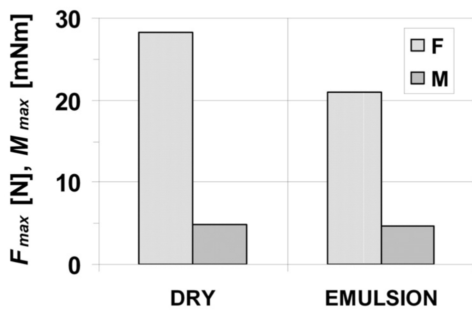

Fig. 11. Decreasing of cutting forces when using lubricants – drilling in carbon steel d=0.5 mm, n=32x10^3 rpm, f=9.5 μm/rev

$$L_F \approx (0.5...0.7)F_{\max} \tag{5}$$

The time of thrust or torque increase until the breakage is very short. The values of the boundaries of these time segments, read from diagrams, show that they were in the range of 6...27 ms. Thus the destruction preventing system must be provided in effective control of feed drive, which enables a reaction in a time of a few milliseconds. On the other hand the system should not be too complex. Very difficult question is the exact evaluation of the selected threshold values. When they are too small many retractions are present in the cycle and duration of the idle motions is much larger than that of the drilling. As a result the process is not effective. On the other hand, when the limits are too high, the protection against

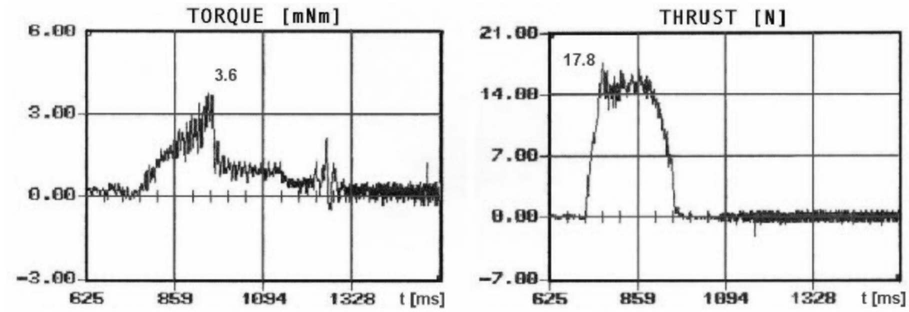

Fig. 12. Torque and thrust diagrams recorded during the continuous drilling of a hole d=0.6 mm, L=1 mm, in stainless steel Cr18Ni9Ti

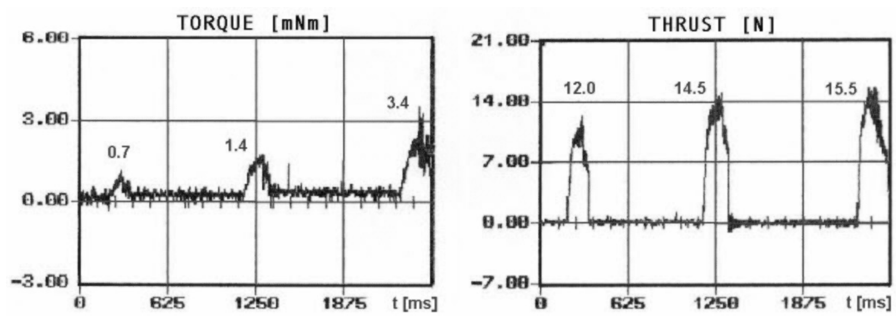

Fig. 13. Diagrams recorded during intermittent drilling of a hole d=0.6 mm L=1 mm in stainless steel Cr18Ni9Ti in 3 steps with equal lengths of 0.35 mm

overload is insufficient.

4. Conclusions

Drilling of holes with diameters of less than 1 mm requires the careful prevention against the breakage of the miniature drills. To reduce the constant portion of the cutting forces, various measures, like application of lubricants, changing of tool geometry and interrupt drilling cycle are useful. The application of lubricants caused only slight reduction of the maximum values of the cutting forces, but their decreasing in the range of 5–25% represents often a significant level and enables more effective machining. Similar conclusion concerns the interrupt drilling cycle when the steps are too long. For more radical reduction of the maximum values, the presence of many short steps is necessary. Such realization of the process enables the drilling of microholes even in very extreme situations but the duration of the idle motions is enlarged. Greatest dangers for tool integrity are process disturbances and unexpected growth of loading. The torque signal is very small and for the smallest diameters the signal/noise ratio is too low. The force signals are reliable for the detection of prefailure phase of miniature drills, but for their measurement sensitive dynamometers and complex devices are necessary. The time of increase of the thrust or the torque to the drill destruction is very short. As a consequence the prevention systems should work very fast.

References

[1] KUDLA, L., *Jour. of Engineering Manufacture*, **217** No 11 (2003), p. 1581.
[2] GRZESIK, W., *Fundamentals of Metal Cutting (in Polish)*, WNT, Warszawa, 1998.
[3] KUDLA L., *Jour. of Materials Proc. Technology*, **109** No 3 (2001), p. 236.
[4] MELLINGER, J. C.– OZDONANLAR, O. B.– DEVOR, R. E. – KAPOOR, S. G., *Transactions of ASME*, **125** (February 2003), p. 405.
[5] IWATA K. – MORIWAKI, T., *Annals of CIRP*, **30/1** (1981), p. 27.
[6] BANG, Y.-B.– HIGUCHI, T., *Int. J. Japan Soc. Prec. Eng.*, **33**, No. 1 (Mar. 1999), p. 15.
[7] OHSIMA, I.– MAEKAWA, K., *Int. J. Japan Soc. Prec. Eng.*, **33** No.2 (June 1999), p. 94.
[8] JEMIELNIAK, K., *Jour. of Materials Proc. Technology*, **109** No 3 (2001) p. 242.
[9] TANSEL, I. N., *Key Engineering Materials*, **138-140** (1998), p. 575.
[10] KUDLA L., *Advances in Manuf. Science and Techn.*, Polish Academy of Science, **25** No. 2 (2001), p. 37.