Machining Bores with Milldrilling and Millboring

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Abstract
Milldrilling is a combination of both the machining processes internal circular milling and drilling. The operation cycle of millboring is analogous to milldrilling with the difference of the already existing bore in the workpiece. The typical formation of millings allows an automated manufacturing of deep bores with internal contours in solid material in only one setting. This leads to new possibilities to design parts in a lot of engineering areas. Tool monitoring keeps the milldrilling tool and machine tool apart from damage or even breakage and avoids the loss of workpieces. The relative simple design of this equipment accomplishes the requirement for an industrial application.

Keywords: *Production Process, Milldrilling, Millboring*

Introduction

Milldrilling is already employed in industry as an economic alternative to drilling on machining centers for rough-machining of bores in large forgings. With commercially available face milling cutters bores are made in solid material with a diameter range between 100 and 500 mm and a length between 400 and 500 mm. In comparison with conventional drilling operations even in the center of the bore a high cutting speed exists so that the efficiency of modern cutting materials can be utilized. Characteristic for this cutting process are small millings which can be removed easily even out of bottom bores. This is an important prerequire for the automated machining of bores.

In opposition to milldrilling on machining centers with conventional face milling cutters the milldrilling tool designed by the Institute for Machine Tools at the University of Stuttgart is supported in the bore with guide pads directly behind the miller. This feature allows the machining of deep drills with complex contours with a length-diameter-proportion of l/d = 10 in one setting. Such bores are needed in a lot of engineering areas and can satisfy very different functions:

- axles of high-speed trains for reducing unsprung masses,
- landing gears for reducing weight and economizing the consumption or
- moulds for producing bottles in the glass and plastics industry.

In particular, manufacturing bores with internal contours in solid material requires a considerable number of conventional drills, bores and supported internal tools. Usually automated machining is impossible because of the unfavourable chip formation with continuous chips of the most steel qualities and aluminium alloys.

Manufacturing bores with rotationally symmetrical contours is not always possible by casting or metal forming. Casting is suitable for parts with small differences in the wall thickness as high thermal stresses generated by different rates of cooling can cause stress cracks. Metal forming operations are restricted to parts with tubular semifinished products which allow a limited design of the finished parts. Additionally the tolerance of the dimensions and surface quality which can be achieved is not always sufficient or the required material cannot be casted or formed at all.

Milldrilling Operation

Drilling, boring and internal machining is possible with a single milldrilling tool. In contrast to conventionally supported boring bars high allowances are cutted in one operation starting at the bottom of the bore with pulling feed. Hydraulic adjustable supporting guides for machining in multi-cut operations are not necessary. Therefore deformations of thin-walled workpieces made of aluminium alloys or scorings can be avoided.
Additionally, slow rotation of the workpiece causes much less out-of-balance force of asymmetrical parts unlike boring with non-driven boring bars with supporting guides. Workpieces with overhanging parts can be machined on machine tools with divided machine beds.

The milldrilling tool is clamped on the support of the numerical controlled lathe. The bearing of the miller shaft in an eccentric adjustment allows the continuous feed of the radial miller position even during the cutting operation. The workpiece is clamped in the chuck of the lathe and in the centering cone of the coolant supply device. The helical feed of the miller is composed of the axial feed of the tool bar while the circular feed results from the rotating workpiece and the eccentric miller position (Fig. 1).

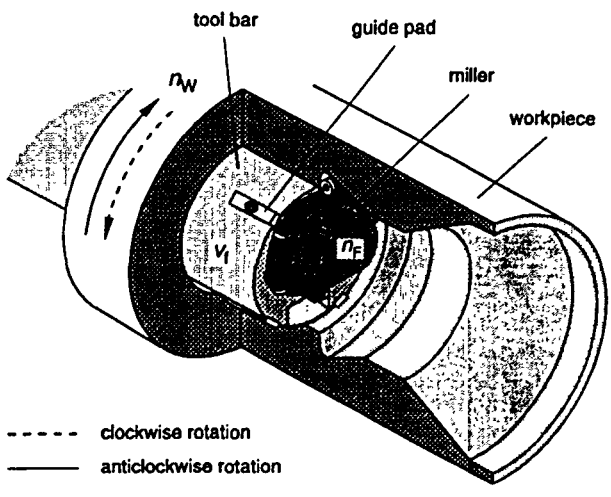

Fig. 1: Machining internal contours with the milldrilling tool

The cooling lubricant supply of both through the miller spindle directly to the miller and through the annulus between the milldrilling tool and the bore wall enables an unproblematic chip removal out of the bore through the chip removal channel of the tool. With this machining equipment bores can be manufactured in a diameter range between 88 and 124 mm and with a length of about 1000 mm.

Milldrilling and Millboring of Cylindrical Bores

Milldrilling cylindrical bores in solid material is only possible if at least one edge of the miller cuts the center of the bore. Additionally the radial miller position is adjusted in a manner so that the bore diameter corresponds with the generating diameter of the guide pads. The whole cross-sectional area of the bore will be cutted then. For this case usually a miller diameter is used which is a little larger than the bore radius. At the beginning of the cutting operation the milldrilling tool is supported with guide pads in a bush and afterwards in the bore.

Provided there is already a bore in the workpiece existing, the millboring procedure depends on the diameter of this bore. If the bore diameter is smaller than the generating diameter of the guide pads, the millboring operating cycle is analogous to milldrilling in solid material. In case the bore diameter is equivalent to the generating diameter of the guide pads, the millboring operation starts at the bottom of the bore with pulling feed (Fig. 2).

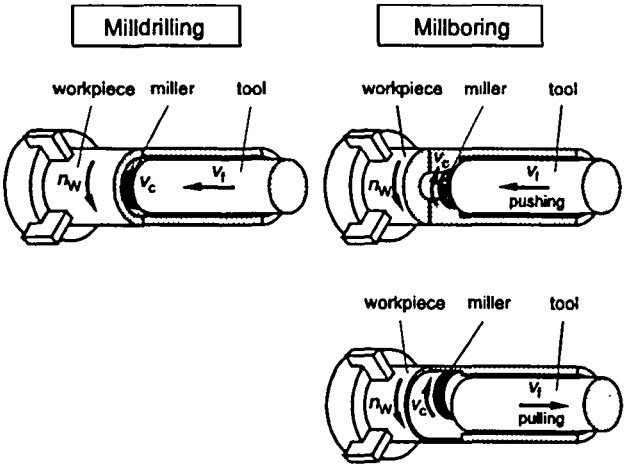

Fig. 2: Milldrilling and millboring of cylindrical bores

In opposition to face milling there is a continuous cut of the cutter teeth during the milldrilling operation. The variation of the miller torque in time depends on the cutting speed, workpiece speed, and feed rate which results in different cross-sectional areas of the cut.

The change of cutting speed v_c causes an inversely proportional change of the milling feed f_c and of the cross-sectional area of the cut A_c. Therefore an increasing cutting speed results in smaller cross-sectional areas of the cut (Fig. 3, above). Analogous to the cross-sectional area of the cut the mean miller torque is decreasing with increasing cutting speed (Fig. 4, above). Because of the higher specific cutting force at smaller milling feed f_c the decrease of the mean cutter torque is not inversely proportional to the cutting speed but less.

Typical of milldrilling with round edges is a high miller torque in the area of the bore wall. This is effected by the large cross-sectional area because of the radius between the bore bottom and the bore wall. The excitation of torsional resonance vibrations of the miller spindle leads to high torsional strains. Compared with the unexcited miller torque in time the oscillation amplitude is high.

Increasing workpiece speed n_W causes a proportional increasing of the milling feed f_c and a proportional decrease of the depth of cut together with a constant cross-sectional area of the cut (Fig. 3, middle).

Increasing workpiece speed leads to an increasing miller torque in the area of the bore wall. Therefore the excitation of torsional resonance vibrations of the miller spindle is increasing with the workpiece speed for the miller angle ϕ_M between 0 and π (Fig 4, middle).

In contrast to that, there is no influence on the miller torque due to this excitation existing for the miller angle ϕ_M between π and 2π.

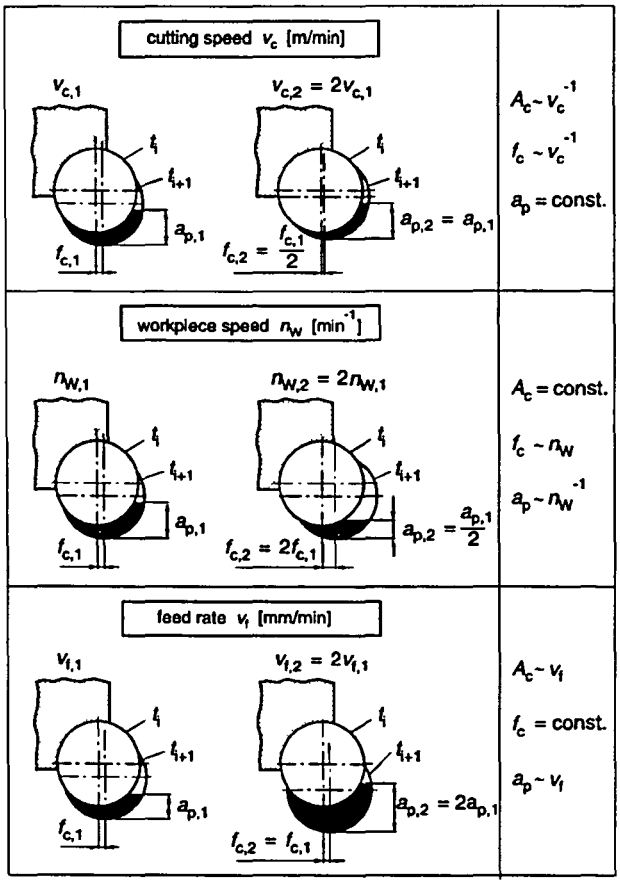

Fig. 3: Cross-sectional area of the cut

The change of feed rate v_f causes a proportional change of the depth of cut a_p parallel to the bore wall and therefore a proportional increasing of the cross-sectional area of the cut A_c (Fig. 3, below). The increasing time-cutting volume caused by an increasing feed rate results in an increasing miller torque (Fig. 4, below). In contrast to the machining parameter workpiece speed the influence of the miller torque in the area of the bore wall is decreasing with increasing feed rate but the excitation of torsional vibrations of the miller spindle is increasing.

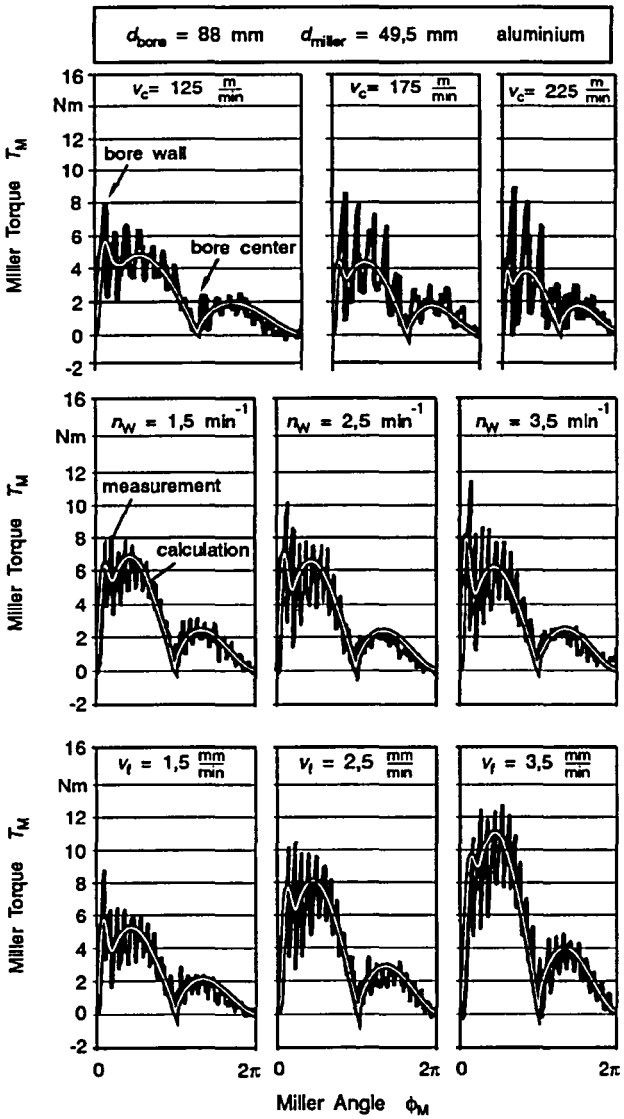

Fig. 4: Miller torque with anticlockwise rotation of the workpiece

For calculating the miller torque depending on the miller angle a software package has been developed in the Institute for Machine Tools at the University of Stuttgart. The complex cross-sectional area of the cut $A_c(\phi_M)$ which depends on the miller angle ϕ_M will be divided in small sections $A_{c,i}(\phi_M)$. Each of these sections is calculated as follows:

$$A_{c,i}(\phi_M) = \iint dx \cdot dy$$

The thickness of the chip h_1 before removing from the workpiece will then be determined for each section $A_{c,i}(\phi_M)$. With the cutting force law of Kienzle and Victor, the cutting force $F_{c,i}(\phi_M)$ is calculated for each section with the following equation:

$$F_{c,i}(\phi_M) = A_{c,i} \cdot k_{c1.1} \cdot h_1^{-z}$$

Hence it follows the calculation of the cutting force $F_c(\phi_M)$ for the miller angle ϕ_M in the following manner:

$$F_c(\phi_M) = \int dF_{c,i}(\phi_M)$$

The following equation describes the cutting torque of the miller $T_c(\phi_M)$ which is calculated by multiplication of the cutting force $F_c(\phi_M)$ with the radius of the center of inertia $r(\phi_M)$ of the cross-sectional area of the cut $A_c(\phi_M)$:

$$T_c(\phi_M) = F_c(\phi_M) \cdot r(\phi_M)$$

The radius of the center of inertia $r_x(\phi_M)$ of the cross-sectional area in the XZ-plane corresponding to the center of the miller spindle is calculated as follows:

$$r_x(\phi_M) = \frac{\iint x \cdot dx \cdot dz}{\iint dx \cdot dz}$$

There is a good consistency of the calculated miller torque with the measurement which is shown in figures 3 and 4. The higher excitation of torsional resonance vibration of the miller spindle during anticlockwise rotation of the workpiece is caused by the steeper gradient of the cutting torque in the area of the bore wall. The investigations of the cutting process with round edges show both the characteristic miller torque of milldrilling which makes this machining operation different to face milling and the parameters influencing the excitation of torsional resonance vibration of the miller spindle.

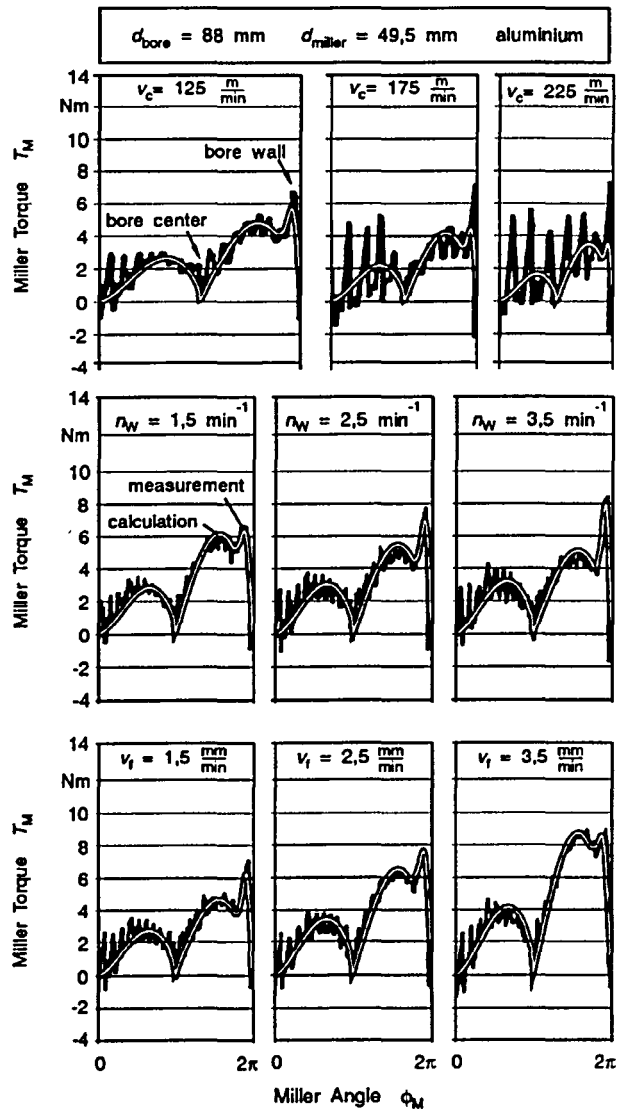

Fig. 5: Miller torque with clockwise rotation of the workpiece

The miller torque in time for clockwise and anticlockwise rotation of the workpiece shows the angle of miller incidence because of the angular assembling of the miller spindle in the milldrilling tool due to the circular feed (Fig. 6). The result is a more constant miller torque in time for clockwise rotation of the workpiece (Fig. 5).

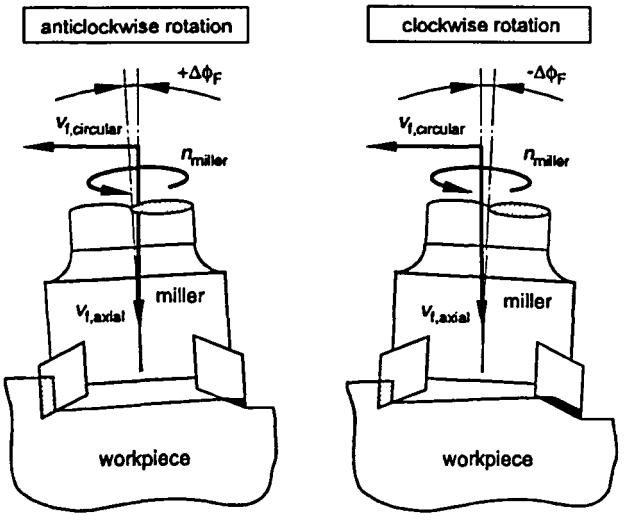

Fig. 6:: Angular assembling of the miller spindle due to the circular feed

Millboring of Internal Contours

For millboring of internal contours, first of all a cylindrical bore has to be made by milldrilling. After finishing this operation the milldrilling tool has to be pulled out of the bore completely. Then the miller has to be replaced by a disk milling cutter. Starting at the bottom of bore, internal contours are made by pulling feed of the milldrilling tool superimposed with the radial miller feed. Internal contours consisting of cylindrical sections, cones, radiuses and even grooves enable an almost free design of the bore (Fig. 7).

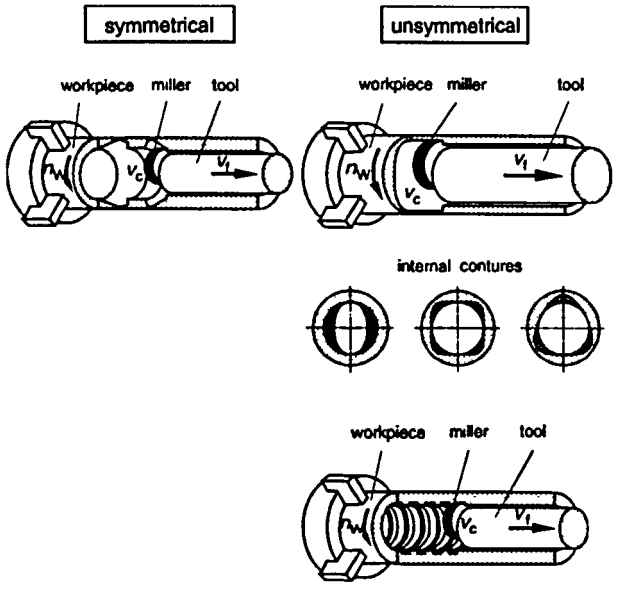

Fig. 7: Examples for internal contours

Machining unsymmetrical contours, for example lubrication bore reliefs, conical threads or twisted spline profiles require a controlled feed motion of the workpiece feed and the radial miller feed which results from the circular movement of the eccentric adjustment. Otherwise the feed motion generates a deformation of the contour.

The restriction of the present numerical control to only two simultaneously moved axis enables the machining of unsymmetrical internal contours only step-by-step for short axial sections corresponding to the edge length parallel to the bore wall.

Tool Monitoring

Tool monitoring of the milldrilling tool includes measuring of feed force, cutting power and acoustic emission of the chip removal operation. Feed force measured by strain gauches is compared with a rigid threshold. If the threshold is crossed by the feed force signal, the feed drive will be switched off. Avoiding miller spindle breakage is enabled by measuring cutting power. In opposition to cylindrical bores machining internal contours causes very different feed forces and power in time because of the changing machining parameters. Therefore detecting breakage events of carbide inserts is realized by measuring accoustic emission. The acoustic emission sensor fixed on the tool bar causes no loss of stiffness. Furthermore the piezo sensor is resistant to wear and also operative in dirty environmental conditions.

Summary

Manufacturing of deep bores with symmetrical and unsymmetrical contours in solid material is possible with a single milldrilling tool in only one setting. This leads to new possibilities of designing parts in a lot of engineering areas. The typical formation of millings allows an automated manufacturing. Tool monitoring keeps the milldrilling tool and machine tool apart damage or even breakage and avoids the loss of workpieces.

Investigations were carried out with different machining parameters which show the characteristic miller torque of the milldrilling process with round edges. Because of length and little torsional stiffness of the miller spindle the high miller torque in the area of the bore wall causes an excitation of torsional resonance vibration. Compared with the unexcited miller torque in time the oscillation amplitude is high and leads to high torsional strains in the miller spindle. The higher torsional vibration during anticlockwise rotation of the workpiece is caused by the steeper gradient of the cutting torque in the area of the bore wall.
Further investigations will be involved with the increase of time-cutting volume and also with the concentricity and roughness of the bore which can be achieved by milldrilling and millboring.

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