

Modelling of dimensional influences in drilling and threading – scaling effects in drilling of steel

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Summary

The major aim during the first year of research was the conception and construction of set ups for basic and analogical experiments as well as first experiments to ascertain dimensional effects during drilling processes. One major focus of the experiments has been to determine the influence of web thinning on cutting torque and feed force with regard to the diameter of the tool during drilling. The basic experiments focused on employing drills with and without web thinning. The analogical experiments aimed at determining the shares of major cutting edge, chisel edge and heels in the mechanical load (cutting torque and feed force).

The results may be summarised as follows:

In the investigated diameter of $d = 0.5 - 10$ mm web thinning of the chisel edge has no demonstrable influence on the height of the operative cutting torque. The facts lie differently with the feed force. Compared to web thinned drills, the drills that have not been web thinned display data that are higher by a factor of 1.5. These results show that web thinning of the chisel edge can reduce the mechanical load of the tool considerably. The non-linear decrease of the related feed forces which may be observed above a diameter of $d = 0.5 - 10$ mm primarily goes back to the relation of the chisel edge to the exterior diameter of the drills. As the results obtained on the basis of the previous experiments demonstrate, a linear scaling of the related feed force in the investigated area of $d = 0.5 - 10$ mm is not possible due to the chisel edge length dependent on the tool diameter.

Basis of the analogical experiments carried out so far have been tools with a diameter of $d = 1$ mm. One working operation employs the three areas of major cutting edge, chisel edge and heels of the drilling tool successively. The chisel edge of the tool applied shares approx. 40 % of the cutting torque and approx. 80 % of the feed force. The comparably small share of the chisel edge in the cutting torque may be attributed to the different lengths of lever arms of main cutting edge and chisel edge. The large influence of the chisel edge on the feed force originates in the fact that due to the geometry of the chisel edges the material cannot be cut, but has to be formed and squeezed in direction of the tool slot.

1 Introduction

Drilling is a complex manufacturing process which is characterised by forming, cutting, turning round of material and friction processes. In the past, drilling processes have been the target of various investigations [1, 2, 3, 4, 5]. In spite of far-reaching research in development and optimisation, effects of dimension and their influence on scaling have not yet been looked into systematically. One of the reasons is that the effects of dimension are dependent on material as well as manufacturing influence variables. With regard to scaling drilling processes, there are to a

high extent no quantifiable data that sufficiently describe forming, cutting, turning round of material and friction processes. As a result, the transfer of data from one order to the next lower down or higher up has so far been just as impossible as modelling the process itself.

The aim of research is the investigation of dimensional influences on scaling during the process of drilling steel (C45E / AISI 1045) with a diameter of $0.5 \text{ mm} \leq d \leq 10 \text{ mm}$ and the resulting modelling. To this, investigation shall be conducted to determine basic and verification data for the construction of a model.

2 Material and Samples for Experiments

2.1 Material

The tryout material employed is the quenched and normalised steel C45E. Its chemical composition and the mechanical characteristic values are displayed in **table 1** and **table 2**.

Table 1 Chemical composition of AISI 1045

	C [%]	Si [%]	Mn [%]	P [%]	S [%]
AISI 1045	0,45	0,22	0,63	0,016	0,026

Table 2 Mechanical properties of AISI 1045

	Heat treatment	tensile strength R_m [MPa]	yield stress $R_{p0.2}$ [MPa]	flexural strength A [%]	necking Z [%]	Hardness HV 30
AISI 1045	normalised	627	334	17	23,5	169,5

2.2 Samples for Experiments

The investigations comprise the realisation of basic as well as analogical experiments. In the basic experiments (centre drilling) the bore holes are inserted in a universally machined rectangular plate with the measurements $15 \times 12 \times 100 \text{ mm}^3$. A special sample geometry was developed for the analogical results (**Fig. 1**).

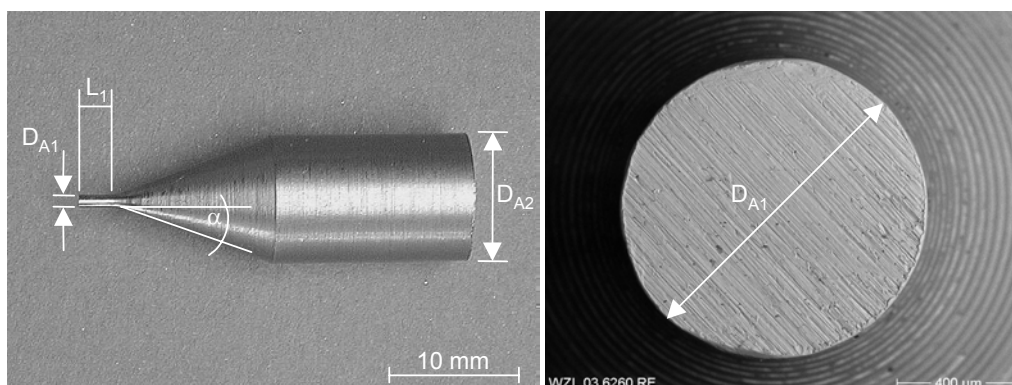


Fig. 1 Workpiece for analogical tests (step tests)

The sample consists of a cylindrical part with $D_{A2} = 10$ mm enabling fixation in a collet and which joins to a cone with a nose angle of $\alpha = 20^\circ$. There is a cylinder at the tip of the cone with an outside diameter of $D_{A1} = 1$ mm measuring a length of $L_1 = 2.2$ mm. Prior to carrying out the experiments a boring hole is inserted 1.5 mm deep into the centre of the little cylinder with $D_1 = 0.3$ mm.

3 Machines

Two machine tools are employed in the experiments in order to cover the required speed while working with tools bearing a diameter of $d = 0.5 - 10$ mm. One of the machines is a high-speed milling machine with a possible spindle speed of $n = 50,000 \text{ min}^{-1}$ covering a bore hole diameter of $d \leq 3$ mm. Experiments with drills $d \geq 2$ mm are carried out on a five-axis machining centre with a possible spindle speed of $n = 20,000 \text{ min}^{-1}$. Employing tools with diameters of $d = 2$ mm and $d = 3$ mm on both machines may give evidence of possible influences the machines have on the experiments. The measurement of the cutting torques and feed forces takes place through a two-component dynamometer.

4 Tools

The tools selected for the first phase of investigation have the same geometries and grain sizes for a diameter of $0.3 \leq d \leq 20$ mm. Standard tools with a diameter of $d = 2$ mm minimum have a web thinned chisel edge. For these investigations special tools which are not web thinned are employed apart from standard drills. The geometrical data of the drills are displayed in **table 3**.

Table 3 Geometrical data of drilling tools

Drill-point angle σ	Major clearance angle α_{01}	Major clearance angle α_{02}	Helix angle ϵ	Grain size [μm]
118°	10°	30°	35°	0,5 - 0,7

5 Experimental Set Up

For the realisation of both the basic and analogical experiments there are comparable set ups available on the two machines described in chapter 3.

5.1 Set Up Basic Experiments

A sampling device is attached to a dynamometer, which enables fixing and a flexible positioning of the workpiece. This experimental arrangement guarantees that the bore holes are drilled in the centre of the dynamometer alone and that no additional cutting torques and feed forces appear through uncentered chucking. A cooling tub adapted to the arrangement contains the cooling fluid.

5.2 Set Up Analogical Experiments

For the analogical experiments the workpiece described in chapter 1.2 is fixed to a precision collet chuck in the centre of the dynamometer (**Fig. 2**, left). The decision to use a precision collet was

made in order to achieve a high repeatability in centring when changing the workpieces. An aluminium container surrounding the sampling device serves to hold the cooling fluid (Fig. 2, centre and right).

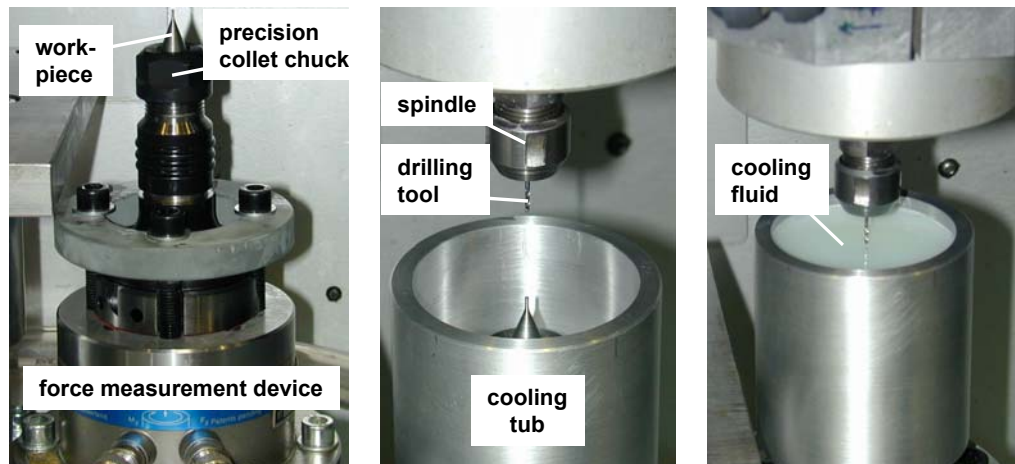


Fig. 2 Experimental set up for analogical tests

5.3 Set Up Tool Life Tests

In order to cover the influence tool wear has on cutting torque and feed force, a major amount of bore holes are made with specially selected tools and the tool life is determined. For the realisation of these tool life experiments a three-step arrangement was constructed and built (Fig. 3).

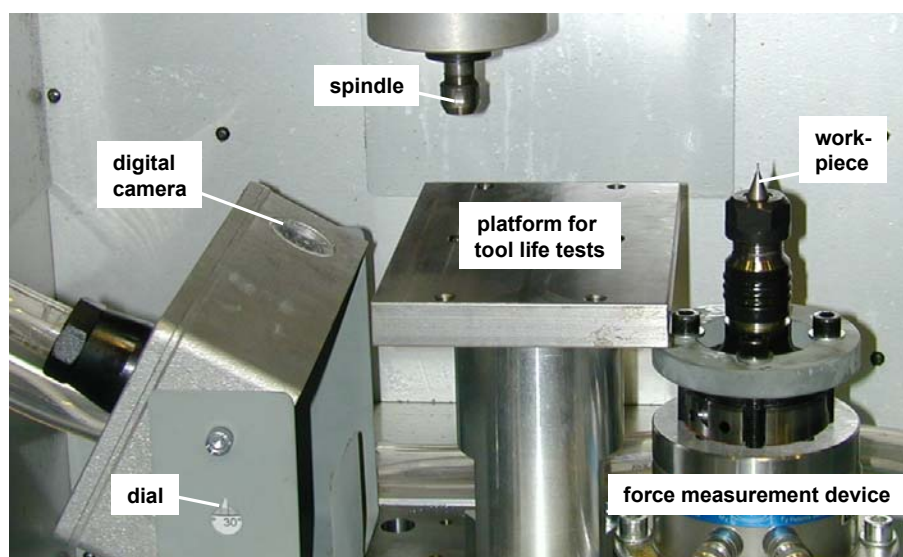


Fig. 3 Experimental set up for tool life tests

It consists of a platform, in which a large amount of bore holes can be placed one after the other (Fig. 3, centre). Measurement of cutting torque and feed force takes place on the arrangement constructed for the analogical experiments (Fig. 3, right). For the recording and documentation of tool wear a splash-proof digital camera with a magnification of x200 is employed. To compensate the digital camera's poor definition of the image during high magnification, it is swinging, run on bearings and may be adapted to the tool point angle by means of a dial (Fig. 3, left). With the aid of this experimental set up it is possible to measure feed force, cutting torque and tool wear in any given intervals.

6 Realisation and Results

The drilling depth was $l = 4xd$ for all experiments. Drilling took place in cutting with exterior cooling fluid supply and a 7% emulsion.

6.1 Basic Experiments

Realisation

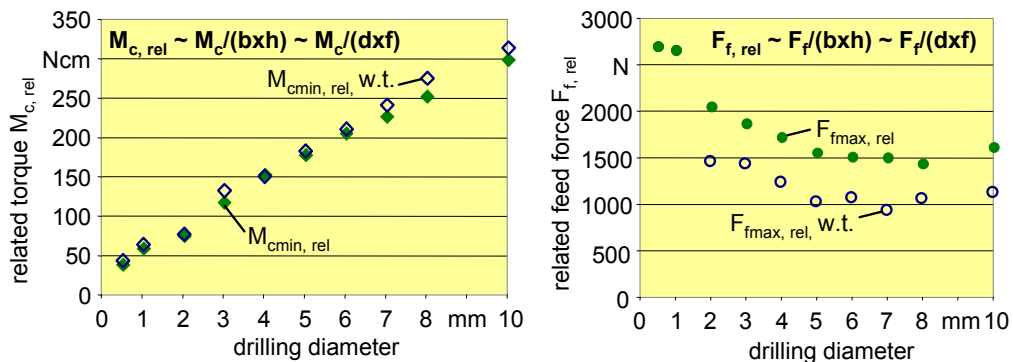
The drilling tools were employed with constant cutting speed of $v_c = 35$ m/min independent of diameter. Due to the different mechanical loading capacity of the drills, the feed was selected depending to their diameter. To ensure the comparability of the results, a diameter-dependent feed of $f = 0.012$ mm/(mm*d) was set, resulting in a feed of $f = 0.012$ mm for drills with $d = 1$ mm and a feed of $f = 0.024$ mm for tools with $d = 2$ mm. Measurable variables and thus also reference and evaluation variables were cutting torque M_c and feed force F_f . For a better comparability of the measured values for M_c and F_f , they were related to $d*f$ ($M_{c,rel}$, $F_{f,rel}$).

Results

Focal point of this phase of investigation was to determine the influence of the chisel edge length on cutting torque and feed force. Drills with and without web thinning were employed. The determined values for M_c and F_f for the tools related to $d*f$ are outlined in Fig. 4 above the tool diameter.

The results may be summarised as follows:

- The influence of the chisel edge length on the cutting torque is extraordinary small with the tools employed (Fig. 4, left). The determined cutting torques for the web thinned drills and the drills without web thinning are largely identical. The related cutting torque increases almost linear to the diameter. These results were expected, as the lever arm of the chisel edge is only small in comparison to the diameter of the tool and as a result has a negligible small share in the total cutting torque.



$M_{cmin,rel}$:	related cutting torque	parameter:	
$F_{fmax,rel}$:	related feed force	cutting speed:	$v_c = 35$ m/min
w.t.:	web thinning	feed:	$f = 0,012$ mm/(mm*d)
process:	centre drilling		
workpiece material:	AISI 1045		
cutting material:	HW-K10		
coolant:	emulsion, 7%		

Fig. 4 Comparison of cutting torque and feed force

- In opposition to the cutting torque, the chisel edge length indeed has a significant influence on the level of feed force. The related feed force was higher by a factor of 1.5 for drills without web thinning as in comparison to web thinned drills (Fig. 4, right). The cause may be found in the fact that in the centre area of the drill the cutting speed advances towards zero and the chisel edge does not cut the workpiece material due to its geometry, but merely squashes it and pushes it aside.
- Up to $d = 5$ mm the related cutting torques outlined above the diameters decrease linearly. This is true for the web thinned tools as well as the tools without web thinning. Outlining the relation of chisel edge length $d_{c.e.}$ to drill diameter d above the tool diameter leads to a similar course (Fig. 5, left). The web thinned tools as well as the tools without web thinning display an almost linear decrease of the relation $d_{c.e.}/d$ up to a drill diameter of $d = 6$ mm. Fig. 5, right shows the relation of web thickness d_w to drill diameter d additionally in dependence to the tool diameter. An almost linear decrease is also displayed here, this time over the whole tool diameter. These results allow the conclusion that the in fig. 4, right observed linear decrease of the related feed force up to $d = 5$ mm can be traced back primarily to the chisel edge length which in this area becomes shorter in relation to the outside diameter. This emphasizes the significance of the chisel edge for the mechanical loading capacity of the drill. As the results obtained on the basis of the previous experiments demonstrate, a linear scaling of the related feed force in the investigated area of $d = 0.5 - 10$ mm is not possible due to the chisel edge length dependent on the tool diameter.

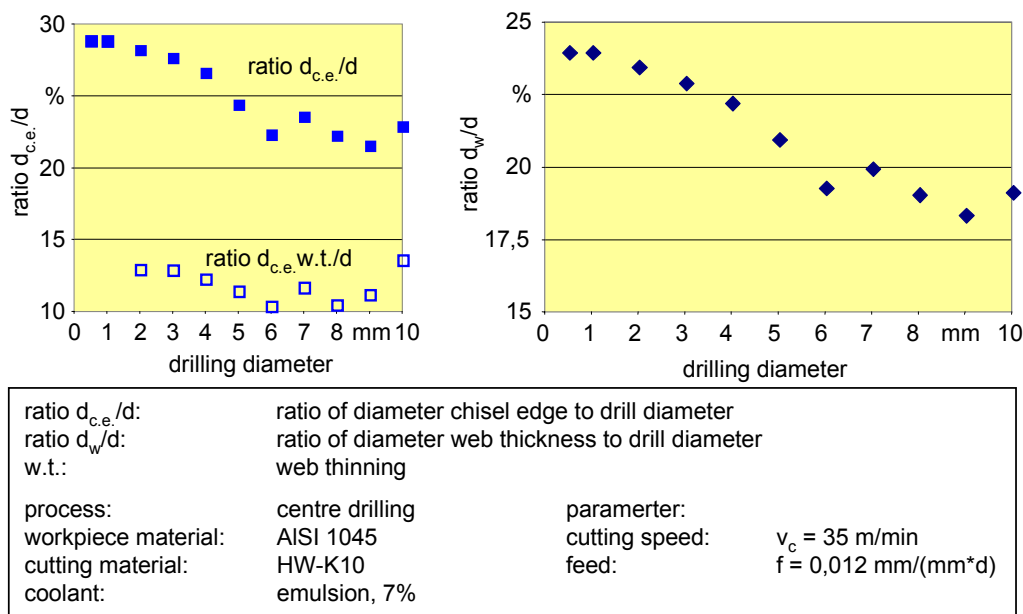


Fig. 5 Ratio of chisel edge and web thickness to drill diameter

6.2 Analogical Experiments

For the separate investigation of the influence of major cutting edge, chisel edge and heels on cutting torque M_c and feed force F_f a step test was developed. This test enables to determine the influence of the named drill areas M_c and F_f in one drilling procedure.

In the 2.2 mm long cylinder with $D_{A1} = 1$ mm placed on top of the cone a 1.5 mm deep boring hole is inserted from the face with $D_l = 0.3$ mm. The diameter of $D_l = 0.3$ mm largely corresponds to the chisel edge length (measured: $d_{c.e.} = 0.29$ mm) of a drill with 1 mm thickness.

Three areas may be distinguished when drilling in these samples:

- Area A – B: Drilling of a cylindrical pipe with $D_{A1} = 1$ mm and $D_1 = 0.3$ mm. In this area only the major cutting edges are employed.
- Area B – C: Drilling of a cylinder with $D_{A1} = 1$ mm. In this area both major cutting edge and chisel edge are employed.
- Area C – D: Generating a boring hole with $D = 1$ mm. While centre drilling not only the major cutting edge but also the chisel edge and the heels come into operation.

In this way, cutting torques and feed forces can be determined one after the other in only one chucking: firstly for the major cutting edge, then for the major cutting edge and the chisel edge and finally for the major cutting edge, the chisel edge and the heels. The results of the step test are displayed in Fig. 6.

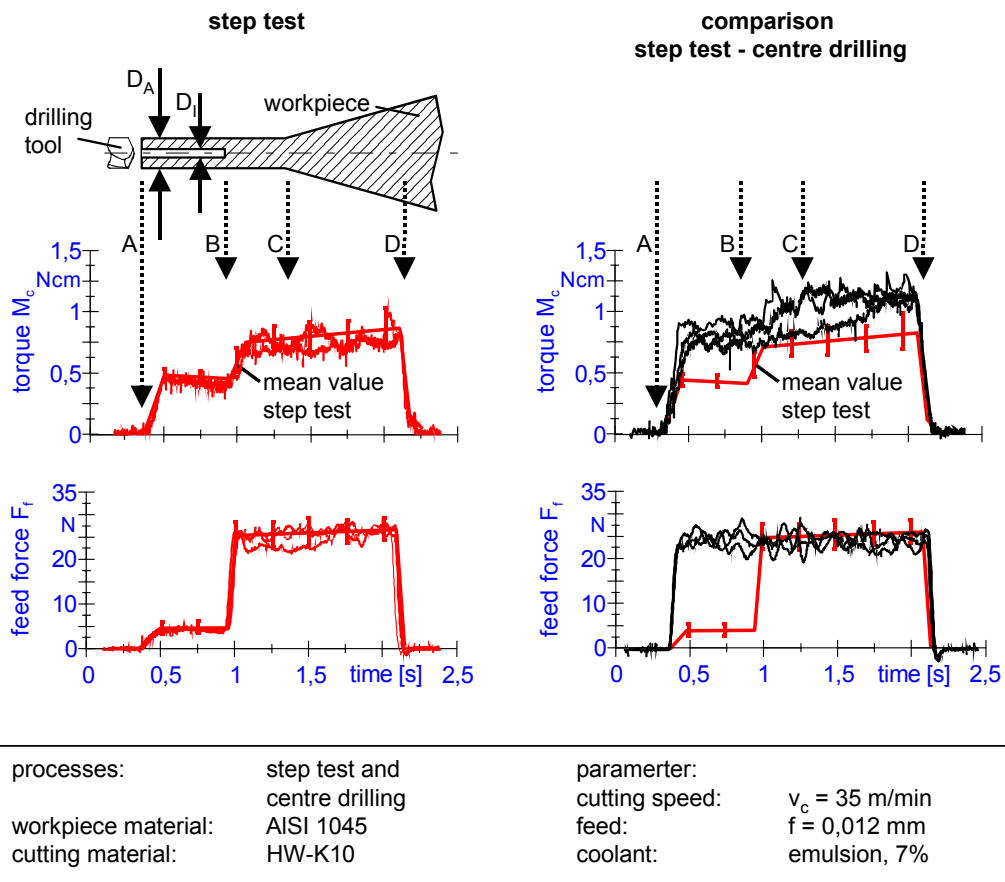


Fig. 6 Results step test and comparison step test – centre drilling

The left hand side outlines the cutting torques and the feed forces which have been recorded during the step tests. The right hand side contrasts the mean value fashioned from several series of measurements of the step tests with the cutting torque and feed forces from the basic experiments (centre drilling) applying the same drills under identical circumstances.

From these results the following conclusions may be drawn:

- The chisel edge coming into operation in area B – C leads to an increase of cutting torque by approx. 40% and an increase of feed force of approx. 400% contrasted to area A – B, in which only the major cutting edge comes into operation.

- The influence of the heels on the cutting torque and the feed force is extraordinary small and in comparison to the influence of the major cutting edge and the chisel edge negligible and insensitive to measurement techniques.
- The diagrams of the analogical experiments and those of the step tests correspond to each other when compared. It must be noted that the values for cutting torque and feed force determined in the analogical experiments can only be compared to the measured value of the step tests from the area C – D up to a drilling depth of $l = 1.8$ mm. The increase and irregular course of the cutting torque observed during the analogical experiments with a drilling depth larger than $l = 1.8$ mm is attributed to strong friction and obstruction during transport of the chips with increasing drilling depth.

The high correspondence between the basic experiments and the analogical experiments justifies a pursuit of the research done in the set ups described here. However, the spectrum of the diameter has to be extended with regard to scaling of drilling processes.

6.3 Tool Life Tests

Research has been concentrating on the realisation of basic experiments with tools that have web thinned chisel edges and tools that do not have web thinned chisel edges and also on analogical experiments in order to determine separately the influence of chisel edge, major cutting edge and heels on cutting torque and feed force. For extension and securing the basis of the results further tool diameters shall be included into research. Experiments to determine the tool life behaviour will be linked up in the following project phases.

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