An Investigation into the Optimum Geometry of Extra Long Series Drills

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INTRODUCfiON

Conventional standard twist drills are normally used for holes of depth less than 5 diameters. When the hole depth is between 5 and 10 diameters, drills are said to be 'long'. 'Extra long' drills are used for holes of depth larger than 10 diameters. Every thing else being equal, short drills produce more holes of the same length per sharpening than longer drills [1] mainly because the stiffness of a drill linearly decreases with flute length [2]. Longer drills are more prone to 'wind-up' and chatter due to the lower torsional stiffness of the drill body which acts as a spring system supporting the two cutting sides [3]. As a result, the probability of chipping at the cutting edges or drill breakage increases rapidly with increasing length of the drill. For instance, a decrease in flute length by 40% typically increases the drill life by a factor of 8O [3]. Thus, the maximisation of torsional stiffness has been a major objective in the design of extra long series drills.

Figure 1 shows the typical cross-sectional geometry of twist drills. poor torsional stiffness of these drills results from the flutes which are needed to provide adequate chip space. It has been found that the typical fluted section has about 1/10th the stiffness of the corresponding solid section [3). Clearly, the larger the sectional area of a drill the greater is its stiffness.

However, when the sectional area is increased, the chip space available flutes is correspondingly reduced thus increasing the likelihood of the chips clogging in the flutes. When the chips clog, there is an abrupt rise in the cutting forces and the drills tend to chip or break. These problems are accentuated while using extra long drills since such drills are prone to bending and runout which lead to uneven chip formation between the two edges. This increases the likelihood of uneven chip clogging, an abrupt rise in force imbalance and, therefore, of drill failure. Thus, the problem of achieving the correct balance between the sectional area and flute becomes more critical with increasing drill length.

Since the magnitudes of chip length and other chip curl parameters are different for different work materials, the minimum flute space requirement is work material dependent (it is possible, in principle, to control chip geometry by modifying the cutting angles through suitable point grinding but this approach has practical limitations). Thus, short drills (which, owing to their inherently higher stiffness, can have thinner drill sections and flute areas) can accommodate the chip space requirements of a wider range of work materials. However, this ability for accommodating a range of work materials decreases with increasing drill length because of the increased criticality of flute space.

Thus, while comprehensive standards exist for the geometry of conventional drills (hole depths up to 5 diameters), the standards for long and extra long drills are confined to the flute length and the overall length (e.g. DIN: 1869 and IS: 7823). In consequence, manufacturers of long and extra long drills are forced to adopt experience-based in-house 'standards' for drill section parameters. Figure 2 shows the in-house 'standard' for the web diameter adopted by one such company for its extra long series drills. However, the company often found itself engaged in protracted and wasteful negotiations with its customers on the validity of the in-house standard. It therefore sought scientific verification in the context of at least one widely used work material. This paper describes the investigative work undertaken by the authors for determining the optimum sectional geometry of extra long series drills for machining one such widely used material - 0.45% C steel (the work material quoted in IS: 5099 for standard drills).

SOME CONSIDERATIONS IN THE SPECIFICATION OF TEST DRILLS

Drills are complex tools and their performance is influenced by a number of interrelated parameters. Further, the manufacture of drills of special geometry is an expensive process involving costly tooling and resetting of machines. Hence it is particularly desirable to reduce the variety of test drills needed in the determination of the optimum compromise between drill stiffness and chip space.

The area of cross-section of a twist drill is typically bounded by the lands of width, w, and the flute contours camprising the cutting edge side and heel side profiles (see Figure 1). Previous work [3] on standard drills has shown that the torsional stiffness, k, of such drills is proportional to the web diameter, d, raised to power 4/3 and the diameter, d_i, of the 'inscribed circle' (i.e. of the circle which simultaneously touches the land, cutting edge side profile and heel side profile at one or other of the lips) raised to the power 4. It is therefore reasonable to assume that the torsional stiffness of extra long drills also increases with increasing d and d_i. However, when d or w is increased, the chip space, A_{cs}, is decreased (see Figure 1). Hence, in order to find the optimum compromise between drill stiffness and chip space, it is useful to study the sensitivity of d_i and A_{cs} to d and w.

With the above objective, the sectional geometries of twist drills for a range of values of d and w (d=0.15D to 0.55D and w=0.4D to 0.85D where D is the drill diameter) were drawn and the corresponding values of d_i and A_{cs} were determined by graphical means. In this, the cutting edge side flute profile was determined by using Arshinov's method [4] for the case of flute helix angle equal to 400 and point angle equal to 118° (these values are taken from industrial practice for drilling extra long holes in 0.45% C steel) while maintaining a straight cutting edge on the point (a straight cutting edge is said to perform better than a curved one [5]). The heel side flute profile was drawn as a circular arc that passes through the end point of the land while being tangential to the web circle and has a radius determined by the profile of the flute milling cutter used in industrial practice. A regression analysis of the results so obtained provided the following relationships with a correlation coefficient better than 0.97:

$$d_i = -0.037 + 0.901\,\underline{d} + 0.1451\,\underline{w}\,d^{-0.5196} \text{ when } \underline{d} \leq 0.42$$
$$= 0.203 + 0.336\,\underline{d} + 0.3609\,\underline{w}\,\underline{d}^{0.606} \text{ when } \underline{d} > 0.42 \qquad (1)$$

$A_{cs} = 1.0972 - 0.912\,\underline{d} - 0.7126\,\underline{w} + 0.4578\,d\,w$ (2)
where $\underline{d} = d/D$, $\underline{w} = w/D$, $\underline{d_i} = d_i/D$ and A_{cs} = Acs/ (nEY2/4) .

Now, from industrial practice for drilling extra long holes in 0.45% steel, it is known that , generally, the drilling performance is acceptabl when the flute space is at least 40% of cross-sectional area of the hole. Tus, we could maximise the torsional stiffness of the drills within the constraint of minimum chip space requirement if we substitute A_{cs}= 0.4 in eqaution 2. This substitution results in the following relationship:

$$\underline{w} = (0.6972 - 0.912\,\underline{d}) / (0.7126 - 0.4578\,\underline{d}) \qquad (3)$$

It is clear from equation 3 that the above procedure enables the deteermination of the drill section uniquely in terms of a single parameter - namely, the relative web diameter, $\underline{d}$, while maximising the torsional stiffness. As a result, the number of test drills required has been significantly reduced by eliminating the need for producing test drills of varying land width, w, for the same web diameter, d.

THE EXPERIMENTS

Description of Test Drills:

In order to meet the specific needs of the drill manufacturer supporting thisproject, extra long test drills were specially designed and manufactured forhole sizes (D) of 4, 6, 8 and 9 mm. All drills were made from M2 type High Speed Steel hardened to RC65. For each drill size, D, several web diameters (d=30, 0.35, 0.4, 0.45, 0.5 and 0.55) were tried. The land width, w, for each drill was selected according to equation 3. The flute angle and the point angle were kept equal to 40^0 and 118° respectively for all drills in accordance with industrial practice for drilling extra long holes in 0.45% C steel. The flutle lengths were selected according to IS: 7823-1975. The flute profiles were adjusted to provide a straight cutting edge on the point. All drills were web-t.hinned using the modified split-point method on a Hertlien Split-Point Grinding Machine.

Trosional Stiffness Tests

Each 9 mm diameter test drill was tested using a strain gauge type drill dynamometer mounted on a radial drilling machine. The point-end of the drill was gripped in a special fixture mounted on the dynamometer whereas the shanrk-end was gripped in a drill chuck held in the machine spindle. Care was taken to ensure proper alignment between the axes of the machine spindle, drill, and dynamometer. The torque was varied manually by giving incrementa1 rotational displacement to the spindle while monitoring the torque as read by lnE dynamometer. At the same time, the angular twist of the drill, over a 100 mm gauge length, was measured with the help of a pair of suitably mounted dial gauges. Measurements were carried out during the loading as well as the unloading cycles. The resulting torque-twist relations were remarkably linear The torsional stiffness, k, for each test drill was obtained as the slope of the torque-twist curve for the drill.

Tool Life Tests:

Each test drill was tested for tool life by drilling specially prepared 200 mm square workpieces made fium C45 steel of 200-215 BHN and No. 3-6 grain size (ASIM). 5% emulsion was used as the cutting fluid. The hole depth for each drill was selected according to IS: 7823-1975 as the flute length less than 5diameters for swarf clearance and regrind allowance.

The drills were guided by special jig plates during drilling. The torque and thrust were monitored during drilling with a view to refining the wood-pecking procedures which were generally based on industrial practice. Depending on the drill size, the withdrawal depth varied between 5D to 12D for the first hole and between 1D to 1.6D for the subsequent holes made by each drill. The cutting speed was selected at 25 m/min and the feed rate was set at 0.06 mm per revolution (being equal to the minimum values specified in Russian/Indian standards for extra long drilling in 0.45% C work material).

Preliminary tool life tests in extra long drilling indicated the dominance of different modes of drill failure in different situations. For instance, when either the web diameter or the chip space was too small (i.e. the web diameter was too large), the chips from one or both edges were discontinuous (broken) and tool failure mainly occurred in the form of edge-chipping or drill fracture. This may be classified as premature failure. However, between the extremes of web diameter, there usually was a more steady-state cutting range with long continuous chips from both edges and regular flank wear at the cutting edges. Figure 3 shows the typical variation of flank wear and length with the number of holes drilled for the cases of premature failure (curve A) and regular flank wear (curve B). These curves were obtained by periodically measuring the wear land at both lips and noting the maximum wear land length, l_f at either lip. Curve B, representing regular flank wear, clearly shows the traditional wear regions consisting of initial wear, steady state wear and catastrophic wear. While there exist standards for permissible l_f for standard drills and other tools, no such standards exist for extra long drills. Further, even for standard drills, the limiting magnitude, l_0, of the flank wear land, l_f, is usually specified as independent of the drill diameter, D, which, intuitively, appears to be unreasonable in the case of extra long drills. Hence, for the test situations where regular flank wear was manifest, the limiting wear land, l_0, was taken as that at the onset of catastrophic wear.

RESUITS AND DISCUSSION

Torsional Stiffness:

Figure 4 shows the variation of the measured torsional stiffness, k, with the web diameter, d, and the inscribed circle diameter, d_i, on a log-log plot for the case of D=9 mm. It is seen that k is approximately proportional to the 2.46th power of d and the 9th power of d_i. It is also seen that these power indices are much larger than those for standard drills (where the index of d is ≈1.33 and of d_i is ≈ 4 [3]). Further, in the case of extra long drills, the inscribed circle diameter, d_i, is uniquely determined by the web diameter, d (see equation 2). Hence, it may be concluded that the main geometric parameter to be optimised in extra long drills is the web diameter. Clearly, this optimisation must involve tool life tests.

Tool Life Criterion Based on Flank Wear:

When the flank wear land, l_0, at the onset of castastrophic wear was plotted against drill diameter, D, it was seen that l_0 increased with increasing D. Therefore a tool life criterion that is independent of the drill size, as usually specified for standard drills, is not applicable in the case of extra long drills. A regression analysis of the data on l_0 provided the following relationship with a correlation coefficient better than 0.997:

$$l_0 = 0.005 + 0.0424D \qquad (4)$$

(l_0 and D in mm.)

The Optimum Web Diameter:

Figures 5a to 5d show the variation of drill life (expressed as the number of holes drilled by a sharpened drill prior to premature failure due to edge chipping/drill fracture or to the onset of catastrophic wear) with d for D=4, 6, 8 and 9 mm respectively. The Figures also illustrate the nature of failure for each drill type. It is seen that

(i) premature failure occurs more often with smaller drills.

(ii) for each drill diameter, with increasing web diameter, the tool life increases initially, reaches a maximum and then decreases.

(iii) the optimum d (the value of d when the tool life is maximised) increases with decreasing D, i. e., smaller drills need relatively heavier webs.

The curves that join the data points in Figures 5a to 5d are, at best, approximations since only a few data points are available in each case. Hence, any estimation of optimum d from these figures needs to be supported by a suitable regression analysis. Fortunately, it is the usual practice in international standards for short drills to specify an upper and a lower limit for the optimum web diameter corresponding to a given drill diameter. This is obviously in recognition of the fact that tool life results in drilling usually have a high scatter (of the order of 50% [6]) and any conclusions need to be reached from limited test data. Further, it is the usual practice that the upper and lower limits are determined from the condition when the tool life is 80% of the maximum anticipated value.

Table 1 Shows the variation of the lower, nominal and upper values of the optimum web diameters as obtained from Figures 6a to 6d:

Table 1

Web DiameterEstimation

Drill Diameter, D mm	Optimum d (nominal)	Optimum Web Diameter (mm)		
		lower	nominal	upper
4	0.50	1.92	2.00	2.07
6	0.45	2.42	2.70	2.86
8	0.40	2.76	3.20	2.74
9	0.35	2.85	3.25	3.38

When the above values of d are subjected to a regression analysis, it is found that a linear correlation exists between (log D) and (log d_{opt}) with a correlation coefficient better than 0.999. The resulting linear approximations give the following expressions:

$$\log(\text{lower limit of } d_{opt}) = -0.0026 + 0.4834 \log D \quad (5)$$

$$\log(\text{nominal value of } d_{opt}) = -0.0012 + 0.5377 \log D \quad (6)$$

$$\log(\text{upper limit of } d_{opt}) = -0.001 + 0.58 \log D \quad (7)$$

Their relationships are shown as the 'recommended values' in Figure 2. It is seen that the recommended web diameters are significantly higher than those being practised in the company as an 'in-house' standard (see broken lines in Figure 2). It is therefore not surprising if the customers found a number of drills to be failing prematurely.

CONCLUSIONS

The following conclusions are applicable in the case of extra long drilling in 0.45% C steel:

(i) when the drill geometry is based on industrial practice (as quoted) and the torsional stiffness in maximised within the constraint that the chip space should be at least 40% of the hole area, there exists a unique relationship between the land width, w, and the web diameter, d (see equation 3).

(ii) the drills are likely to failure prematurely due to edge-chipping and drill fracture when the web diameter is either too large or too small. Premature failure occurs more often for drills with small diameters. When the web diameter is of moderate magnitude, drill failure occurs mainly because the length of flank wear land has exceeded a permissible value, l_0.

(iii) the permissible length of flank wear land, l_0, increases linearly with increasing drill diameter (see equation 4).

(iv) the recommended values for the optimum web diameter, from the point of view of maximising drill life, are as given in equations 5 to 7.

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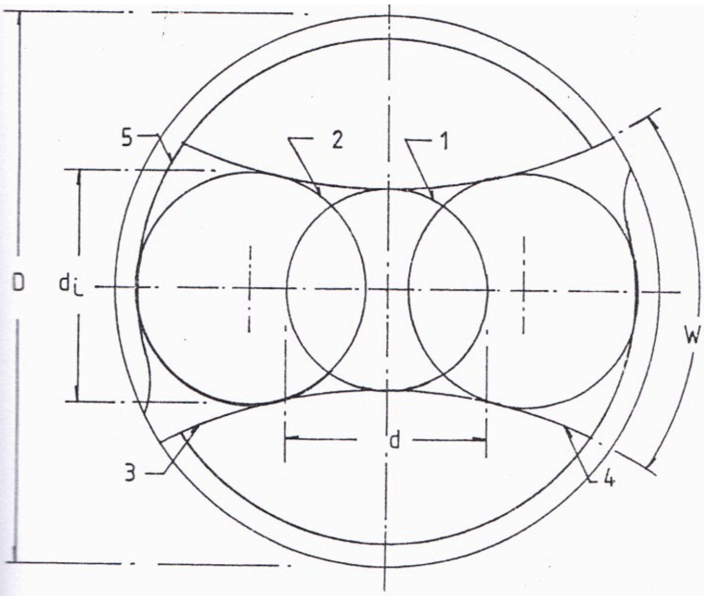


1: WEB CIRCLE
2: INSCRIBED CIRCLE
3: CUTTING EDGE SIDE FLUTE PROFILE
4: HEEL SIDE FLUTE PROFILE
5: LAND

FIGURE 1: TYPICAL SECTIONAL GEOMETRY OF A TWIST-DRILL

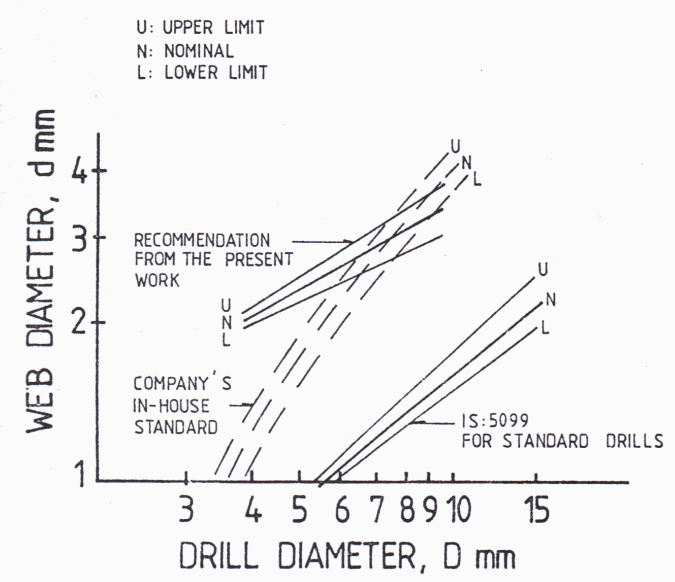
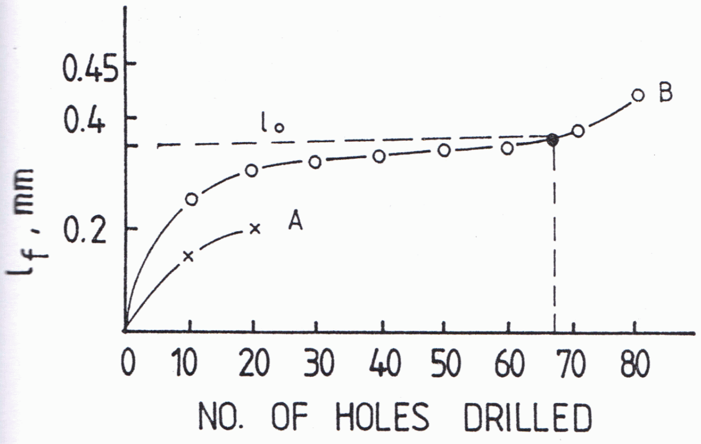


FIGURE 2: STANDARDISATION OF WEB DIAMETER FOR EXTRA LONG SERIES DRILLS FOR 0.45 % C STEEL



A: D=4mm, $\underline{d}$=0.45, FAILED PREMATURELY AT 22^{nd} HOLE

B: D=8mm, $\underline{d}$=0.45, REGULAR FLANK WEAR

FIGURE 3: WEAR AND FAILURE OF EXTRA LONG DRILLS

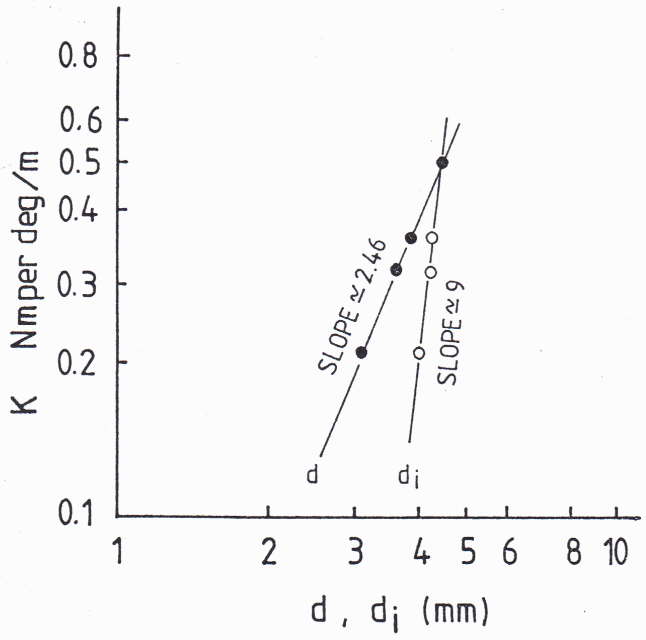


FIGURE 4: INFLUENCE OF WEB DIAMETER, d, AND INSCRIBED CIRCLE DIAMETER, d_i, ON TORSIONAL STIFFNESS, K, FOR EXTRA LONG DRILLS

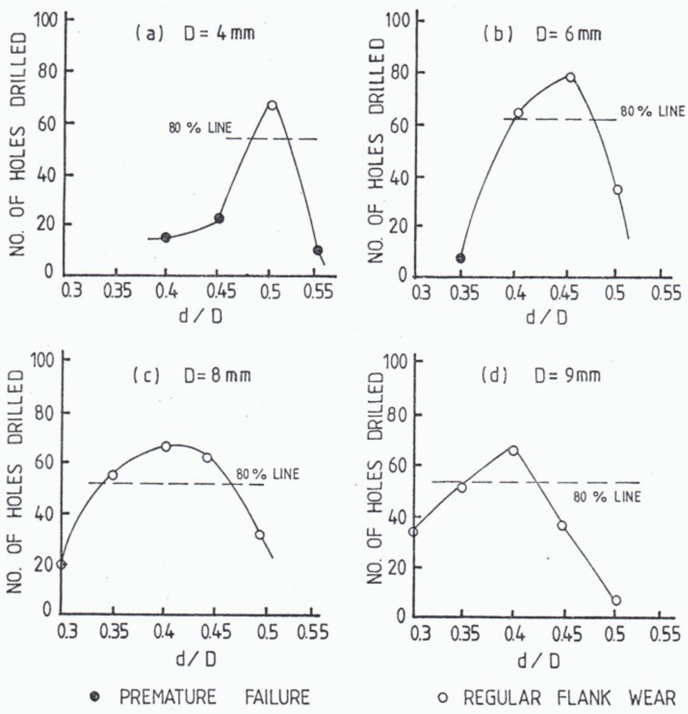


FIGURE 5: VARIATION OF DRILL LIFE WITH WEB DIAMETER FOR DIFFERENT DRILL SIZES