Tool stability analysis for deep hole drilling

Sergey Gorbatyuk[1], *Valery* Kondratenko[1], and *Larisa* Sedykh[1,*]

[1]The National University of Science and Technology "MISiS", 4 Leninsky prospect, Moscow, Russia 119991

Abstract. A large number of parts have deep holes, therefore, rotary cutting tools, which represent relatively long and thin columns are used for holemaking. In this article we analyze the behavior of such tools under the influence of an axial compression load, in our case, the axial cutting force F_p , which differs fundamentally from the compression of short tools. Moreover, experience shows that when the cutting force F_P reaches a certain critical value equal to $F_{кр}$, a long straight column becomes unstable.

Among the procedures of processing metals by cutting [1-5] deep drilling takes a special place. The unique feature of this operation is that the tool does not have a pre-prepared support and a fixed direction. It is also typical of deep drilling not to be able to directly monitor the progress of the procedure and to experience difficulties with performing this procedure with the help of universal equipment without its thorough preparation [1-5].

A large number of parts have deep holes. Therefore, rotary cutting tools are used for holemaking. These tools represent relatively long and thin columns, in which one or two sizes of the cross-section are small in comparison with the length of the column. The behavior of such tools under the action of an axial compressive load, in our case the axial cutting force F_p, is fundamentally different from the compression of short tools. Experience shows that when the cutting force F_p reaches a certain critical value equal to F_кр, the rectilinear equilibrium form of the long column turns out to be unstable.

When $F_P > F_{кр}$, the tool acquires a new curved shape. This phenomenon is called the loss of stability, which leads to the drift of the drill axis and the decrease of processing accuracy. (Fig. 1).

* Corresponding author: lvsedykh@mail.ru

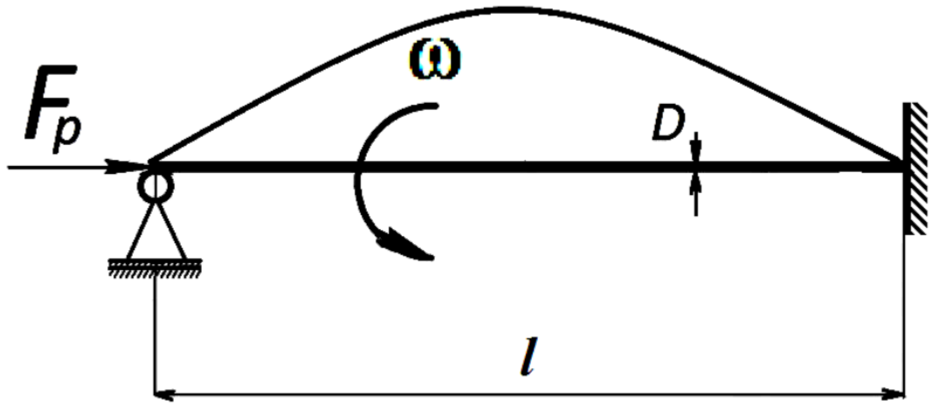

Fig. 1. Structural design for conventional deep hole drilling technology

Let us calculate the cutting force for a deep-hole drilling operation:

$$F_P = 10 \cdot C_p \cdot D^{qp} \cdot S^{yp} \cdot k_p = 10 \cdot 68 \cdot 30^1 \cdot 0{,}05^{0{,}7} \cdot 0{,}79 = 1{,}97 \cdot 10^3 H, \quad (1)$$

where D – the drill diameter, mm.

The values of coefficients, as well as exponent quantities are given in Table 1 [6].

Table 1. The values of coefficients and exponent quantities in the formulas of torque and axial force when treating with a rotary cutting tool

Treated material	Type of treatment	Tool material	C_p	qp	xp	yp
Structural steel, $\sigma_в$=750 MPa	Drilling	P6M5	68	1	–	0,7

The coefficient k_p in this case depends only on the material of the raw part being treated.

Let us express the cutting force (1) through the drill diameter D, m [7]:

$$F_p = \frac{1{,}97 \cdot 10^3}{30 \text{ mm}} (D \cdot 10^3 \text{mm}) = 0{,}65 \cdot 10^5 \cdot D, H. \quad (2)$$

1 Calculation of compression stress

Now we determine the compression stress in the drill:

$$\sigma = \frac{F_P}{A} \; MPa,$$

where A is the cross-sectional area of the drill, m^2.

$$A = \frac{\pi \cdot D^2}{4} = \frac{3{,}14 \cdot 30^2 \cdot 10^{-6}}{4} = 7 \cdot 10^{-4}\ m^2,$$

Let us determine the diameter of the drill D, at which the compressive stresses will exceed the allowable stresses $[\sigma]$ for compression, (let us assume $[\sigma] = 300$ MPa):

$$\frac{F_P \cdot 4}{\pi D^2} = \frac{0{,}65 \cdot 10^3 \cdot D \cdot 4}{\pi D^2} > [\sigma]\,, \quad (3)$$

where

$$D < \frac{0{,}65 \cdot 10^5 \cdot 4}{\pi \cdot 300 \cdot 10^6} = 0{,}28 \cdot 10^{-3} m = 0{,}28\ mm.$$

It is obvious that for real drill sizes, when $D < 0{,}3$ mm, the compression stresses in the column are less than the allowable ones.

2 Calculation of stability

Critical force $(F_{кр})$ is a load, the exceeding of which causes loss of stability of the original shape of the part. Using the Euler formula, we determine the critical force:

$$F_{кр} = \frac{\pi^2 E \cdot J}{(\mu \cdot l)^2}, \quad (4)$$

where E is the Young's modulus for tool steel, $2 \cdot 10^5 \text{MPa} = 2 \cdot 10^{11} \frac{H}{m^2}$;

μ – column length reduction coefficient, depending on the fixing condition (Fig. 1), let us assume that $\mu = 1$;

l – drill length, mm.

$J = \frac{\pi D^4}{64}$ – axial moment of inertia of the drill section, m^4.

Condition of column stability:

$$F_{кр} \le F_P\,.$$

We insert the values of the forces according to formulas (4) and (2) into this equation:

$$\frac{\pi^2 E \cdot J}{(\mu \cdot l)^2} \le 0{,}65 \cdot 10^5 \cdot D,$$

$$\frac{\pi^2 \cdot 2 \cdot 10^{11} \cdot \pi D^4}{64 l^2} \le 0{,}65 \cdot 10^5 \cdot D,$$

from where, after simple transformations, we get:

$$D \le 6{,}62 \cdot 10^{-7} \cdot c^2, \quad (5)$$

where $c = \frac{l}{D}$.

By setting the value c, it is possible to determine the critical value of the pair of parameters $D - l$, when the loss of stability occurs.

For example, setting the value c, we get:

$$c^2 = 2 \cdot 10^4 \quad (c = 1{,}41 \cdot 10^2),$$

$$D \leq 6{,}62 \cdot 10^{-7} \cdot 2 \cdot 10^4 = 13{,}2 \cdot 10^{-3}\text{m} = 13{,}2 \text{ mm}.$$

Using the inequality (5), we obtain the boundary values of the drill length:

$$D = \frac{l}{c} \leq 13{,}2 \text{ mm},$$

whence we determine:

$$l \leq c \cdot D = 1.41 \cdot 10^2 \cdot 13{,}2 = 1861 \text{ mm} \approx 1.87\text{m}.$$

The diagram of the dependence of critical values $D - l$ is shown in Fig. 2. The shaded zone represents a combination of parameters $D - l$, when the drill loses stability.

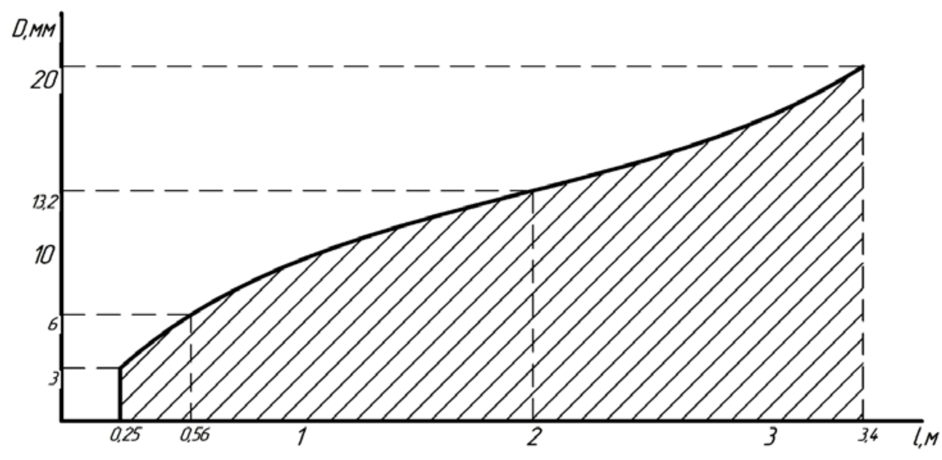

Fig. 2. Dependence of critical values $D - l$

If there is a need to use a drill with parameters outside the shaded zone, i.e. in the case when the nominal dimensions of the tool (diameter $D_н$ and length $l_н$) result in instability of drilling process, measures that eliminate the loss of stability should be applied.

Option 1 The drilling is performed in two manufacturing operations.

In the course of the first manufacturing operation the hole treatment is performed with a drill of diameter $D_1 < D_н$ to the depth l_1 smaller than $l_н$ and ensuring the drill stability (Fig. 3).

Here:

$$D_1 = D_н - \delta \text{ mm},$$

where δ is allowance, which is left for hole treatment during the second manufacturing operation

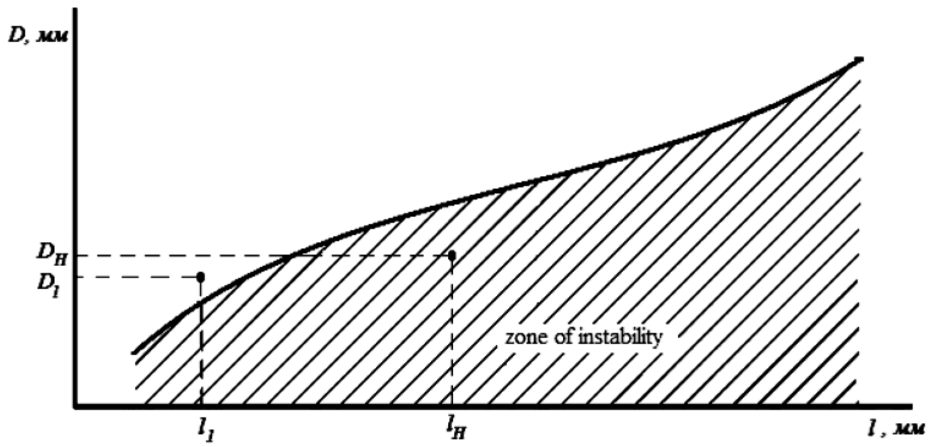

Fig. 3. Choice of drill parameters for the first manufacturing operation.

During the second manufacturing operation, the drilling is performed with a drill $D_H > D_1$ ($D_H = D_1 + \delta$) in diameter , and the cutting force F_P for channel drilling is less than the value of the critical force $F_{кр}$, when the shank bit loses stability (Fig. 4).

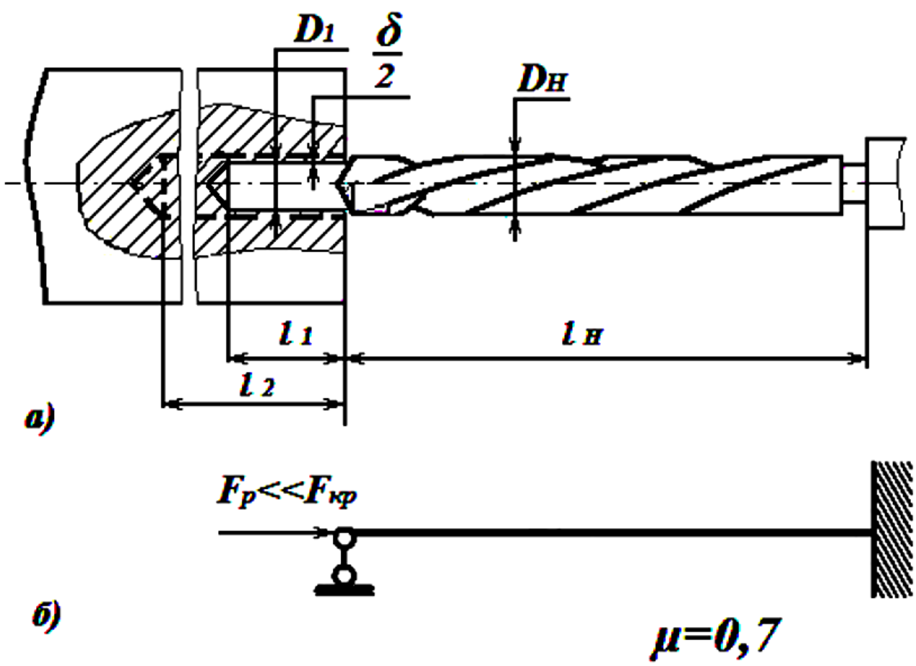

Fig. 4. Structural design for the second manufacturing operation: a) drilling diagram; b) structural design

Later on, when the drill enters the part (Fig. 5, a), the boundary conditions of the structural design change (Fig. 5, b) as well as the coefficient μ in the Euler formula. At the same time, the critical force value in accordance with the last structural design doubles.

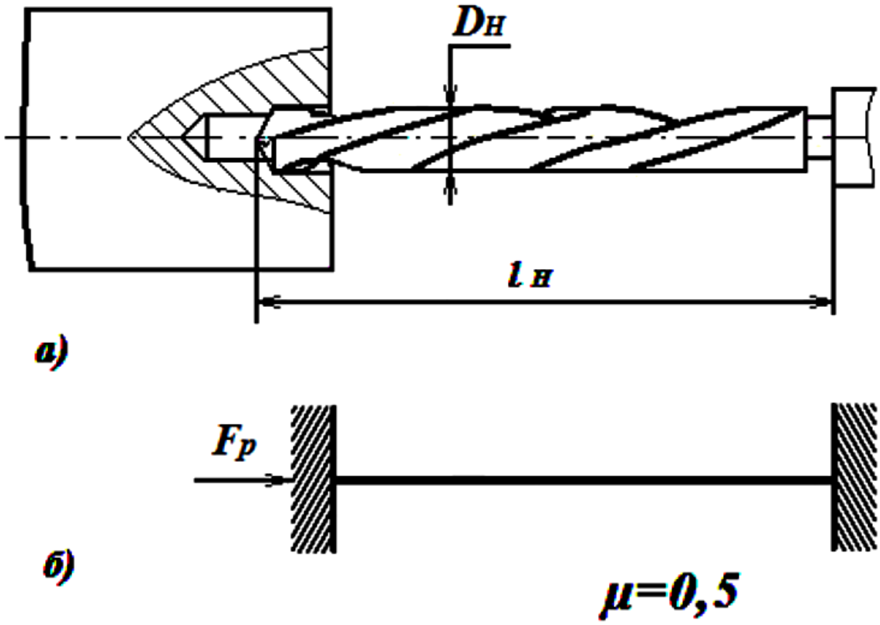

Fig. 5. Structural design for the second manufacturing operation when the shank bit enters the part: a) drilling diagram; b) structural design

Option 2 When processing a deep hole, we enter an additional support into the system – a drill steel guide (Fig. 6)

In this case, the structural design for determining the critical force is as shown in Fig. 6

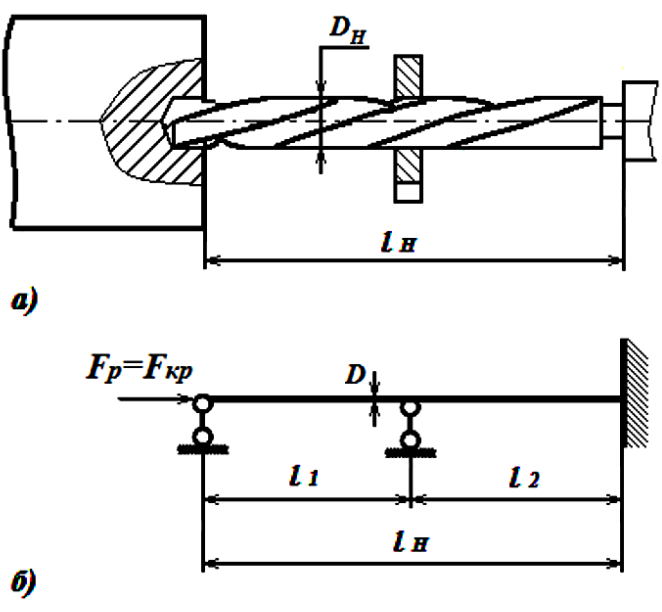

Fig. 6. Structural design for deep-hole drilling technology using a drill steel guide.

3 Conclusion

If there is a need to use a drill with parameters outside the shaded zone (in deep-hole drilling), a drill steel guide for tools should be installed.

A pattern of using the drill steel guide is shown in Fig. 6. For this pattern, which has an intermediate support, the critical force cannot be calculated by the Euler's formula. Further research is required in this respect.

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