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OPTIMIZATION OF CUTTING CONDITIONS AT DRILLING

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Abstract. In the paper the long term tests results of twist drill cutting life are summed up. The were tested drills were made from improved high speed steel in two versions – HSS uncoated and HSS Co coated by PVD process with TiN. On basis of these tests the cutting conditions optimizations were calculated for the minimum machining costs criterion using the basic economic indexes of the workshop. It was determined, that the use of more expensive HSS Co drills coated with TiN with longer cutting life yielded lower total production costs than the use of uncoated HSS drills. These lower costs were reached at higher cutting speed.

Keywords: machining, twist drill, drilling, costs calculation at drilling

1. Introduction

The hole production, of clear or dead holes, is one field of engineering. For drilling of minor diameter holes there are mostly used twist drills. They are mostly made from high speed steels (HSS), from improved high speed steels (HSS Co or HSS - ECo) or from cemented carbides. Holes of large diameters (over approx. 12 mm) are drilled mostly using tools with inserts. The majority of modern tools for cutting or chipless working are coated using PVD or CVD process. These very thin coatings (thickness in µm) influence very positive the cutting process. In consequence of that the labour efficiency of tools increases. The production of tools with coatings demands evidently specifical costs and therefore these drills are more expensive than the drills without coatings.

2. Material and Methods

Tool-life tests

Knowledge of the relationship between tool-life and cutting conditions $T = f(v_c)$ is one of the basic elements needed for the optimization of the cutting conditions. This relationship is one of the most important relationships in cutting theory. These equations are the basis both for selection of the optimum cutting conditions, from the point of view of cutting economy, and for the determination of the cutting property of the tool material and machinability of the machined material etc.

The relationship tool-life – cutting speed is determined experimentally by so-called tool-life tests. In principle, we distinguish two basic classes of these tests: long-term and short-term tests.

The procedure for the long-term tests is as follows:

- determination of the time course of wear (figure 2), e.g. VB = f (t) for different cutting speeds v_{c1}, v_{c2}, ... (the other parameters are constant),
- determination of the terminal flank wear, e.g. VB_{adm}, and from the characteristic wear curves, the tool-life values reading relevant to single cutting speeds and measurements,
- plotting the tool-life values of single cutting speeds using logarithmic coordinates T - v_c (see figure 3),
- through these points, the straight line interlaying and determining equations of relationship T - v_c in table 2 and the rotation speed was calculated.

For an increase in accuracy it is necessary to repeat the whole process in order to eliminate the influence at least some of unforeseened random events that induce scattering when determining the tool-life values. The results acquired by long-term tests are relative accurate, but very time – and material – consuming.

Optimization of the cutting conditions

Optimization of the cutting conditions is one of the most important elements in the manufacturing process (optimization of technological process, of tools, of machines, of handling etc.). Optimum cutting conditions are closely connected with the economic, quantitative and qualitative aspects, and in this way they affect the price of individual parts, and so the price of the whole product.

Optimization of the cutting conditions is understood as the determination of the optimum cutting conditions with regard to technical limitation, organizational limitation and the criterion of optimum cutting process course and result. In this way the optimization of the cutting conditions is not the ideal state, but the state with regard to above mentioned facts.

It is possible to consider the cutting process by different optimization criteria, according to its course, result requirement, respectively. For the calculation it is possible to use the following criteria: the criterion of minimum production costs, the criterion of maximum productivity or the criterion of maximum profit. The criterion of minimum production costs is considered as the most important. As far as it is not necessary to use other criterion, it is used in principle this one.

The criterion of minimum production costs is graphically represented in figure 1. Line K_1/n**,** decreasing when the cutting speed increases, represents machine-tool service costs. Line K_2/n.T, increasing when the cutting speed increases, represents tool service costs. Line K represents costs that do not depend on the cutting speed (e.g. workpiece clamping, size measuring etc.), which have no influence on the calculation.

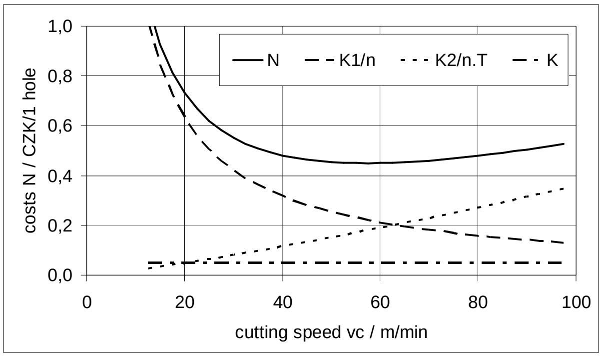

Figure 1. Graphic expression of minimum machining costs criterion (for HSS Co + TiN coated drill)

From figure 1 it follows that any kind of deviation from the optimum cutting speed to lower or higher values results in an increase in the machining costs of a given overlay length. From the form of the total costs line it is possible to conclude on the costs grow when the optimum cutting speed is not achieved. The most common reason for deviation is the use of machine-tool with a speed that changes in steps, when it is not possible to set the exact spindle revolutions according to the calculated optimum cutting speed. If possible, therefore we use machine-tools with more revolution steps or modern machine-tools with stepless speed variation.

The minimum machining costs criterion during the single-shift operation, the single-machine operation and using the solid sharpened tools can be expressed mathematically with the equation (1).

$$N = \frac{K1}{n} + \frac{K2}{n.T} + K = \min \tag{1}$$

where: n = f (v_c), T = f (v_c).

The single costs are calculated from following equations:

$$K1 = \frac{L}{f}.NsCm \tag{2}$$

$$K2 = \frac{L}{f}.\left(t_{102}.N102Cm + NnT\right) \tag{3}$$

$$N102Cm = NsCm = kc.\frac{Tfo}{60}.\left(1 + \frac{Rd}{100}\right) + \frac{Nhs}{60} \tag{4}$$

$$Nhs = Os.kus \tag{5}$$

$$Os = \frac{Cs}{Zs.Cf} \tag{6}$$

$$NnT = \frac{Cn}{zo + 1} + tos.kc.\frac{Tfos}{60}.\left(1 + \frac{Ros}{60}\right) \tag{7}$$

where the symbol signification is following (table 1).

Table 1. Economic base material for optimalizing calculation

L	section turned length, mm
n	revolutions, min^{-1}
f	feed, $mm.rev^{-1}$
v_c	cutting speed, $m.min^{-1}$
k_c	addition to shift time
T	tool life, min
T_{fo}	workman´s wages tariff, $CZK.h^{-1}$
T_{fos}	tool sharpener's tariff, $CZK.h^{-1}$
R_d	shop overhead, %
R_{os}	tool shop overhead, %
Z_s	machine service life, year
t_{os}	sharpening time, min
t_{102}	insert changing time, min
k_{us}	machine maintenance and repair coefficient
C_n	tool price (inclusive of repeated coating costs), CZK
C_s	machine price, CZK
C_f	time fund, $h.year^{-1}$
z_o	feasible sharpening number

The graphical result of this calculation is in figure 1 and figure 4. The PC program enables the rapid calculation of changed optimum cutting conditions for any change of the above-mentioned inputs.

Workpiece and tool materials

For tests the drills of foreign manufacturer of 6.0 mm diameter were used according to DIN 338 RN from improved high speed steel. Tested HSS drills were provided without PVD coating, tested HSS Co drills were provided with PVD coating of TiN. Coatings were made by cooperative firm, which makes them like profession.

Long term tests of drill cutting life were carried out in our department's machining laboratory by standard procedure. Drilling without the cutting fluid ("dry machining") was made using beam drilling machine VS 20, feed f = 0.12 $mm.rev^{-1}$ and revolutions n_1 = 1800 min^{-1} and n_2 = 2800 min^{-1}. Holes of L = 3.D = 18 mm were drilled in the steel 11 373 (according to ČSN 41 1373, STN 41 1373) of 25 mm thickness. The nominal percentage chemical composition is 0.17 C_{max}, 0.045 P_{max}, 0.045 S_{max} and 0.007 N_{max}, the composition according to the analysis is 0.167 C, 0.19 Si, 0.47 Mn, 0.04 Cr, 0.02 Ni, 0.009 Mo, 0.004 V, 0.096 Cu, 0.028 Co, 0.009 Sn, 0.046 Al, 0.001 Zr, 0.000 Sb, 0.010 P and 0.016 S. The steel approximates, for example, to the steel Fe360B (ISO 630-80, BS 4360-86), S235JRG1 (EN 10025-94), Fe37B1FN (EN 30-69), USt37-2 (DIN 17100-80) or Gr. C (ASTM A283-78). The mechanical properties of tested steel was as follows: strength of rupture R_m = 399 MPa, yield point R_c = 296 MPa, elongation at rupture A = 41.7 %, reduction of area Z = 67.0 %, hardness HB = 122.

The flank wear (parameter VB) was measured using the toolmaker's microscope. Measured wear values at two cutting speeds (v_{c1} = 33.9 $m.min^{-1}$, v_{c2} = 52.8 $m.min^{-1}$) related to the time were plotted as wear - time dependence VB = f (t) (figure 2).

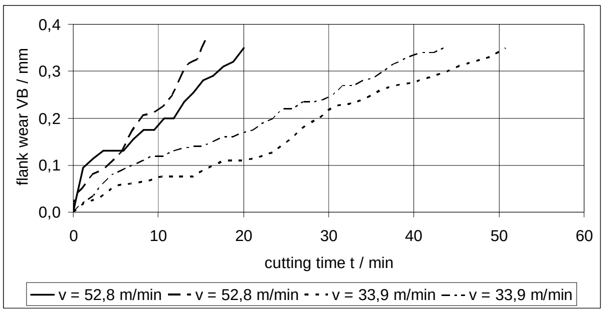

Figure 2. Illustration of flank wear related to the time (for HSS Co + TiN coated drill)

From the flank wear course related to the time the values of the tool life (T) were read for the in advance determined limit value (VC = 0.35 mm). Using that values the equations of the relationship tool-life - cutting speed T = f(v_c) were calculated, shown in table 2. The graphic expression of test results from table 2 is in figure 3.

Table 2. Economic base material for optimalizing calculation

	drill	
parameter	HSS	HSS-Co + TiN
equation of relationship T - v_c	T = $8,59.10^4.v_c^{2,58}$	T = $1,26.10^5.v_c^{1,95}$
tool price, CZK	24	842 *)

*) repeated coating costs after each drill regrinding included

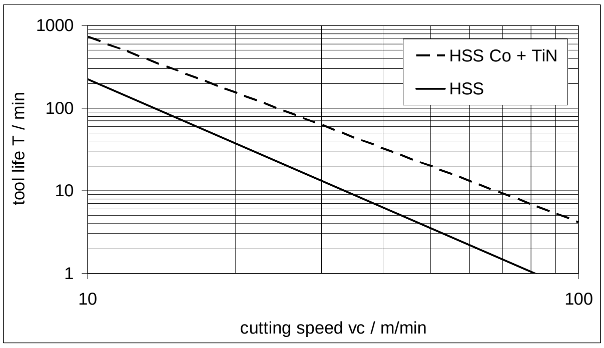

Figure 3. T – v_c relationship

Optimization of the cutting conditions

Optimization of the cutting conditions for the minimum production costs criterion was calculated using the relations mentioned in the theoretical part of this article. The calculation was made using a personal computer. We used the real economic indexes of a workshop and the prices valid in the present time in the Czech Republic. The PC program enables a rapid calculation of the optimum cutting conditions for any change of the input parameters.

In the calculation, using the own autor´s program, there were put following values: L = 18 mm, f = 0.12 $mm.rev^{-1}$, n = 1 800 and 2 800 min^{-1}, v_c = 33.9 and 52.8 $m.min^{-1}$, T = (2) and (3) in table 2, k_c = 1.1, T_{fo} = 60 $CZK.h^{-1}$, R_d = 300 %, T_{fos} = 80 $CZK.h^{-1}$, R_{os} = 400 %, t_{os} = 1.5 min, k_{us} = 1.1, C_s = 50000 CZK (incl. 19 % VAT), Z_s = 6 years, C_f = 2 008 $h.year^{-1}$, t_{102} = 0,33 min, C_n = see table 2 (incl. 19 % VAT), z_o = 20 (for information: 1 € = 28.50 CZK, in July 2007).

The result of the calculation for tested drills is graphically represented in figure 4.

Numeric expression of minimum machining costs criterion is in table 3.

From figure 4 is evident, that any kind of deviation from the optimum cutting speed $v_{c\ opt}$ results in the increase of machining costs. But it is possible to set the machine at optimum cutting speed (optimum r.p.m.) exactly only at machines with stepless speed variation. At machines with speed variation in steps (what was the case of for tests used drilling machine) it is necessary to include the machine costs increase. The increase of machining costs depends not only on the difference between settled and optimum revolutions, but on the curve form of the relationship costs - cutting speed, too. At the flat curve-form the increase will be minor and contrariwise.

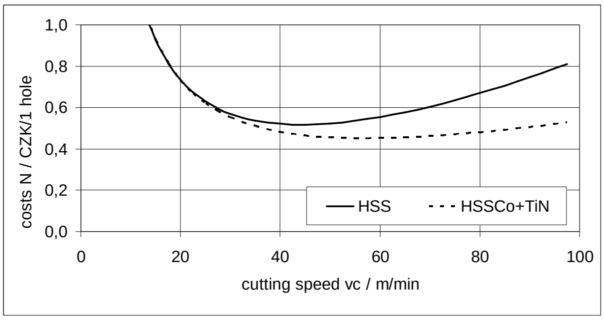

Figure 4. Graphic illustration of minimum machining costs criterion

Table 3. Numeric expression of minimum machining costs criterion

drill	$v_{c\ opt}$ /m.min^{-1}	n_{opt} / min^{-1}	T_{opt} / min	N_{min} / CZK/1hole
HSS	44.25	2350	4.8	0.517
HSS-Co +TiN	57.25	3040	14.5	0,450

4. Conclusions

By detailed study of results we come to quite essential determination. From the tests results given in summary in figure 4 and table 3 it follows that at all costs included the use of more expensive tool with TiN coating (new coating after every sharpening is included in calculation) is more advantageous. Its use decreases costs, and at the same time we are able to use higher cutting speed at higher cutting life.

From the economic-technical tests evaluation it follows, that the use of only one criterion – the purchase cost of the tool - is for optimum tool choice impossible. By tests and calculations there were demonstrated, that the use of more expensive coated tool of longer cutting life makes possible to decrease the total drilling costs in comparison with the use of cheaper uncoated tool of shorter cutting life.

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