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METHODOLOGY FOR DETERMINING THE CUTTING CONDITIONS IN DRILLING OF AUTOMATED MANUFACTURING

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Abstract

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Hole machining is quite common in engineering technology. It follows from the requirements of the specific holes used not only for arranging various types of shafts and axis but also for jointing parts and other purposes. This paper illustrates methodology and experiments for determination of optimal cutting conditions and appropriate cutting tools based on an example of drilling. The choice of drilling technology is based on the design requirements for the shape and dimensions, namely the nature of semi-finished product, with regards to the requirements of quality, reliability and economic efficiency.

Keywords: optimal cutting conditions, hole drilling, tool wear criteria, quality, economics efficiency

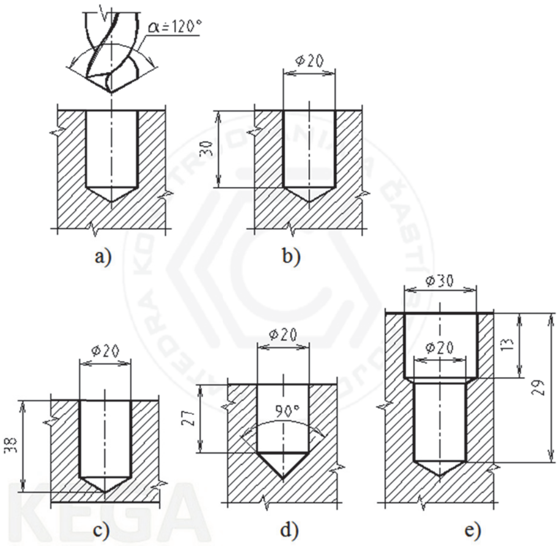
INTRODUCTION

Development and practice gradually defines the use of different methods of machining holes. To calculate diameters ranging from a few tenths to one millimeter are used micro drills. Some unconventional methods are increasingly being used, e.g. electron beam, laser. Holes with a diameter up to 10 mm are usually drilled with twist drills. High price of NC machines and centers of machine time require applying of a new approach to the determination of cutting conditions that indicate the economy machining. Based on an example of drilling, there is a presentation of methodology for selecting optimal cutting conditions which is suitable also for other types of instruments when it is revised. One of important factors of cutting operation is roughness of the machined surface Ra. If cutting conditions are badly selected, not only the roughness Ra increases, but also the cutting tool is being extesively blunted (Votava, 2013).

Work piece on which the experiments were performed is grey cast iron. Gray (graphite) cast iron is the most common casting material. Its mechanical properties are mostly influenced by the shape, amount and distribution of graphite, which can be lamellar, spiderlike, flake, compacted, and granular. By means of cast iron inoculation with magnesium, cerium and titanium can be achieved a rounding of sharp flakes of graphite and cast iron with a tensile strength of 300 MPa. Their characteristic feature is a very good damping capacity, which is used in the manufacture of heavy machine tool stands, pump bodies et al.

Another type of cast iron, which can be mentioned in this experiment, is ductile iron characterized by regularly grained spherical graphite that may be obtained by treating with magnesium or cerium. It is characterized by relatively high strength of 400–700 MPa. It is used for highly loaded parts such as gearboxes, parts of brakes and so on (Vasilko *et al.*, 1991a).

This cast iron can be also used as an initial material for production of soil-processing tools; however, it is necessary to process an appropriate heat-treatment. The material fits into loamy-sandy soil (Votava, 2007).



1: *Scheme of a hole drilling into material (different types of holes)*

We introduce composition, mechanical and physical properties as well as the price of ductile iron (Fürbacher, 2006).

Composition of Ductile Iron

Fe / 3.4–3.8 % C / 2.0–3.0%Si / 0.1–0.6%Mn / max 0.05% P / max 0.1%Cr

Mechanical properties:

Yield strength	250–680 MPa
Tensile strength	410–830 MPa
Tensibility	3–18 %
Hardness HB max.	115–320

Physical properties:

Density	7010÷7250 $kg.m^{-3}$
Specific heat capacity	473 J.kg.K
Thermal expansion coefficient	10.10^{-6} K^{-1}
Thermal conductivity	29–44 W.m.K
Linear shrinkage during solidification	1.2%
Price	19–22 €.kg

Examples of the Use of Gray Cast Iron

- 42 2410 Gray cast iron (GI) for the thin-walled castings from 4 to 15 mm, parts of stoves,
- 42 2425 GI for casting thick from 15 to 50 mm, engine rollers, cog wheels,
- 42 2435 GI castings thick from 40 to 100 mm, machine tool stands,
- 42 2303 Ductile iron (DI) for the castings 5 to 100 mm thick, parts of vehicles and agricultural machineries,
- 42 2306 DI for crankshafts and camshafts, cog wheels, pistons, piston rings,
- 42 2309 DI for highly stressed castings with wear resistance.

MATERIALS AND METHODS

At the beginning we realized the tests on the drilling machine by drilling the holes to the casting of gray cast iron with crust from the run-out side of the instrument with the wall thickness of 40 mm.

In the experiment we tested twist drills made of high speed steel tr. (19830) and cemented carbide K 1 with the same geometry (γ_0 = 12°, α_0 = 8°, 2ϕ = 118°, D = 16 mm).

Drilling of the hole L/D = 2.5 was carried out without cooling. In terms of criterion for the wear resistance it was chosen VB = 0.8 mm for the drill back wear for high speed steel drills (HSS) and 0.4–0.5 mm for cemented carbide drills (SCD) (Balog *et al.*, 2005).

Requirements used when drilling in operating conditions:

- For HSS bits:
  f_m = 100 $mm.min^{-1}$,
  n = 300 min^{-1},
  v_c =16.5 $m.min^{-1}$.
- For SCD bits:
  f_m = 130 $mm.min^{-1}$,
  n = 480 min^{-1},
  v_c = 26 $m.min^{-1}$.

Detected durability in tests:
T_{HSS} = 34 min,
T_{SCD} = 100 min.

The overall length of the run time of the drill bit l in its durability was:
l_{HSS} = 3 400 mm,
l_{SCD} = 13 000 mm.

Number of machined holes x until the drill bit wears off:
x_{HSS} = 100,
x_{SCD} = 325.

and a number of holes, resp. boreholes drilled in a minute:
x_{mHSS} = 2.5 boreholes,
x_{mSCD} = 3.25 boreholes.

Tests were repeated 10 times with each type of the instrument and the results were statistically evaluated.

The cutting conditions were used according to modes applied to the universal drills. These conditions are obviously not optimal for the use in automated production systems. Therefore, the analytical calculation method was used according to the following procedure:

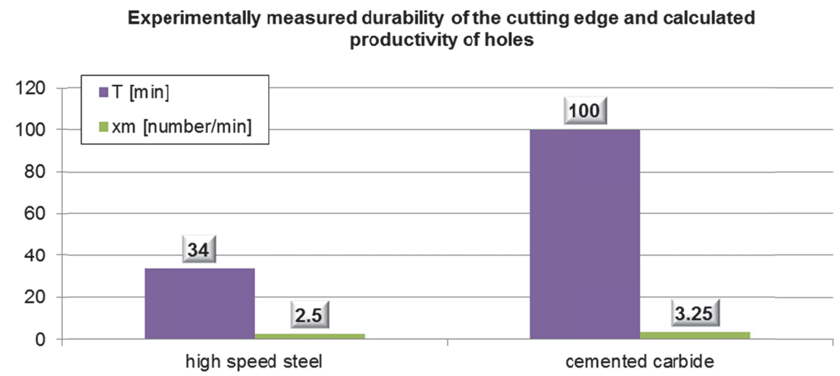
Economically efficient durability of the drill bit can be determined from the known formula:

$$T_{opt} = (m-1) \times \left(\tau \upsilon + \frac{N_T}{N_m} \right), \quad (1)$$

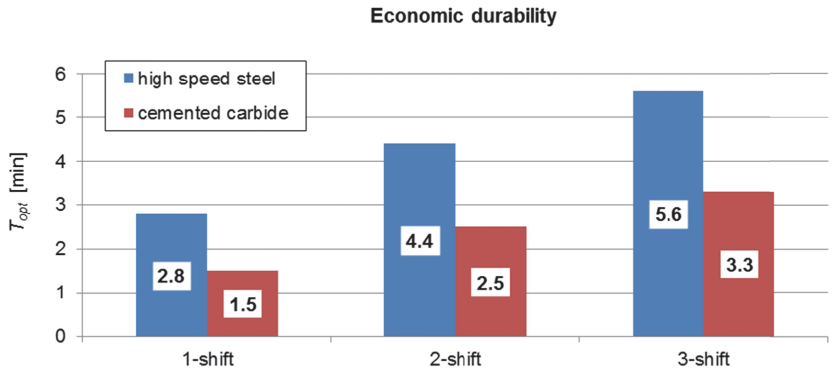
where

m........is an exponent in the dependence T-v (for HSS–8, SCD–2.5),

τ_v ......time for the tool change (in the machining centers of newer structures 4.8 s = 0.08 min is achieved),



2: *The ratio of experimentally measured durability (purple) and calculated durability according to productivity (green)*



3: *Economic durability*

N_m ....the costs within one minute run time of the machine. It is determined from the price of machine, energy, service, repair…

In this case:

- during one shift operation: $N_m = 0.116$ €,
- during two shift operation: $N_m = 0.07$ €,
- during three shift operation: $N_m = 0.05$ €.

N_T..... costs of the tool during its lifetime.

$$N_T = N_n + N_p, \tag{2}$$

where

N_n..... are costs of installation, removal and adjustment of the tool ($N_n = 0.007$ €),

N_p..... are costs of the tool runtime until the tool wears off.

In accordance with calculation:

$$N_{THSS} = 0.0365 \text{ € a } N_{TSCD} = 0.106 \text{ €}.$$

Fig. 3 represents the economic durability.

The cutting conditions were used according to modes applied to the universal drills. These conditions are obviously not optimal for the use in automated production systems. Therefore, the analytical calculation method was used according to the following procedure:

Economically efficient durability of the drill bit can be determined from the known formula:

$$V_c = \frac{C_v}{T^{\frac{1}{m}}}, \tag{3}$$

where

C_v (T = 1 min) for HSS = 25 m.min^{-1} and for SCD = 165 m.min^{-1}.

Consequently, the optimum durability of the drill bit cutting edge is represented in Fig. 4.

Feed per minute may be determined in a similar way (Fig. 5).

This corresponds to the path travelled by the drill bit of this wear intensity (Fig. 6).

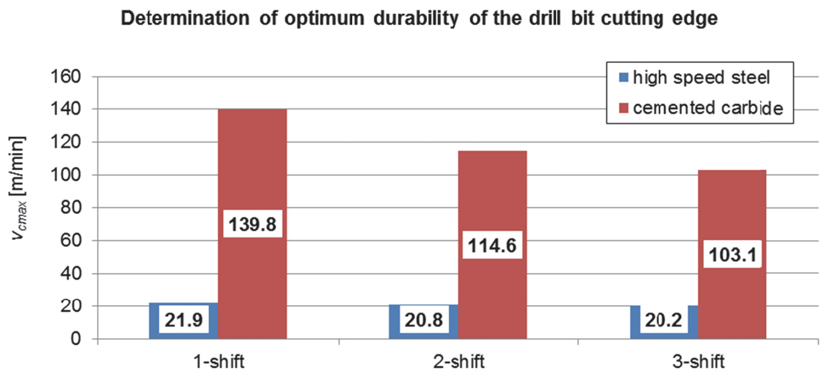
The number of machined holes during tool life is presented in Fig. 7.

The following is the number of holes drilled in a minute (Fig. 8).

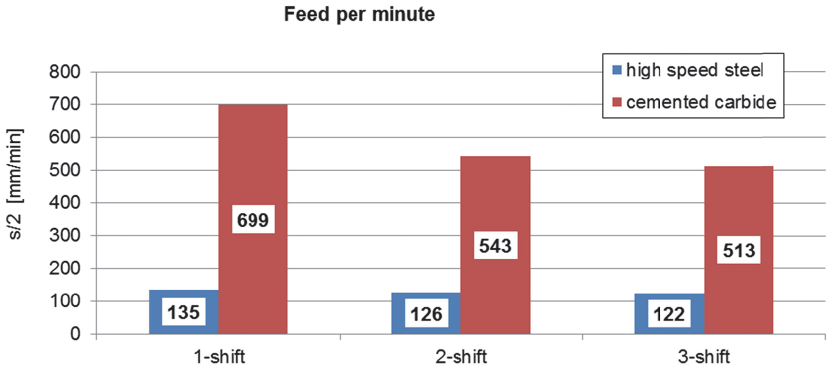
Comparing with experimental data, we obtain an increase in productivity (Fig. 9).

RESULTS AND DISCUSSION

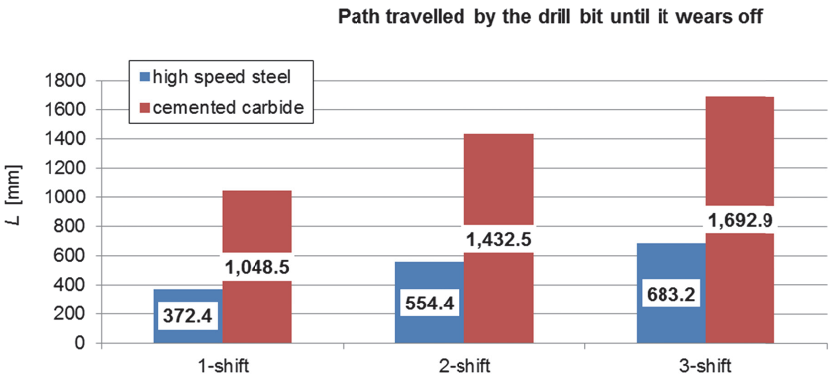
The results show that within the application to the expensive NC and CNC machines and centres, cemented carbide drills are more effective and more durable (Fig. 2). Cutting tips made of sintered carbide



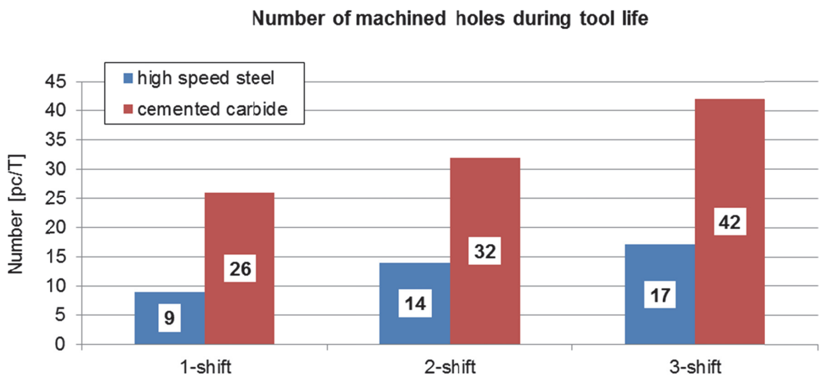
4: *Determination of optimum durability of the drill bit cutting edge*



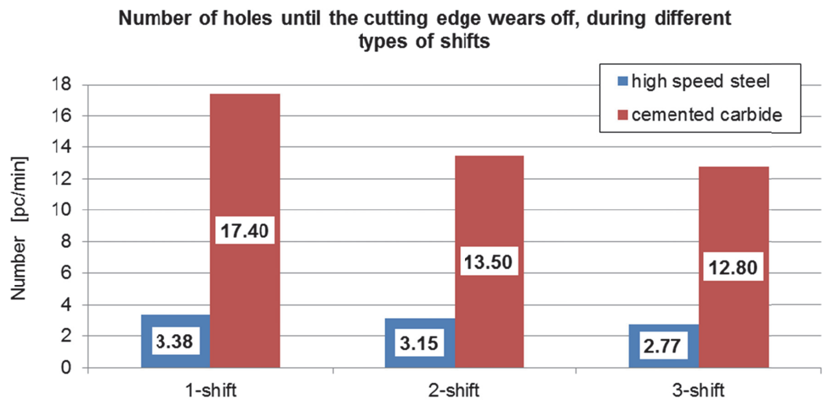
5: *Determination of feed per minute*



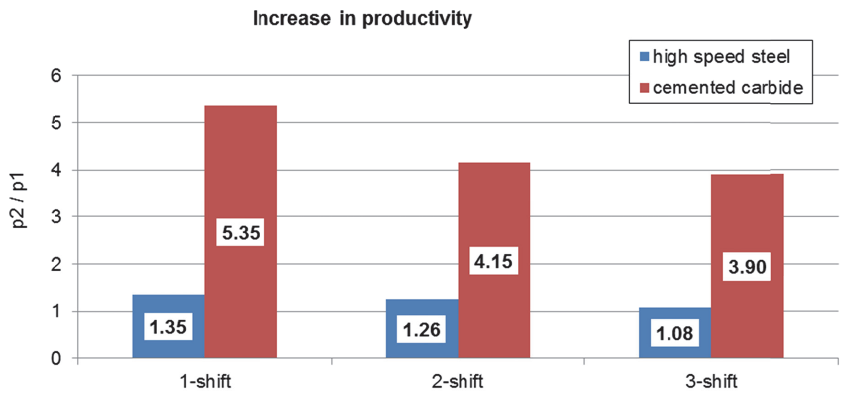
6: *Path travelled by the drill bit till the end of tool life*



7: *Machined holes during tool life*



8: *Number of machined holes until the cutting edge of the tool wears off, during different types of shifts*



9: *Increase in productivity during different types of shifts*

have a lower R_a value, which results in a lower adhesion of anticorrosion coatings. (Votava, 2011)

The existence of bark on a semi-product near the drill outlet from the material leads to the reduction of durability. To reduce the impact of casting crust on wear rate, we reduced cutting speed of the tool of HSS by 25% (from 16.5 m.min^{-1}).

Durability tests of drilling in operating conditions revealed that durability of HSS drills increases by 30–40% and SCD drills by 10–15%.

When using cemented carbide, probability of a failure of a cutting edge decreases.

It is necessary to involve an anticorrosion protection to the technological process of machine part production (Votava, 2013). When using metal coating, mostly zinc coating, the base material has to fulfill given chemical composition and surface roughness R_a.

It is known that durability of drills depends on the length of the bore. Therefore, it is necessary to know this dependence. Hence, we carried out tests of drilling different length of bores to steel 12 050.1 and gray cast iron.

Holes of diameter 8–10 mm were machined by HSS drills. As a wear criterion it was chosen dulling of a tool back VB_k = 0.7 mm. When machining cast iron, cutting fluid was used (5% emulsion, 3% technical soda, water).

For lengths L = 4D and more drilling was carried out with the drill outlet for chip removal.

From measured values we evaluated mathematical dependence of durability on cutting length:

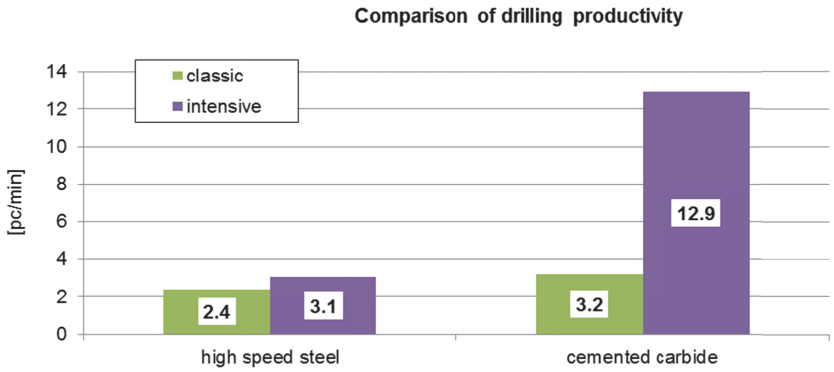
For steel:

$$T(L) = 0.5\left(\frac{L}{D}\right)^5 + 10\left(\frac{L}{D}\right)^4 - 84.6\left(\frac{L}{D}\right)^3 + +356\left(\frac{L}{D}\right)^2 - 760.9\left(\frac{L}{D}\right) + 720. \quad (4)$$

And for cast iron:

$$T(L) = -0.8\left(\frac{L}{D}\right)^5 + 15.5\left(\frac{L}{D}\right)^4 - 113.8\left(\frac{L}{D}\right)^3 + +401.5\left(\frac{L}{D}\right)^2 - 689.4\left(\frac{L}{D}\right) + 487. \quad (5)$$

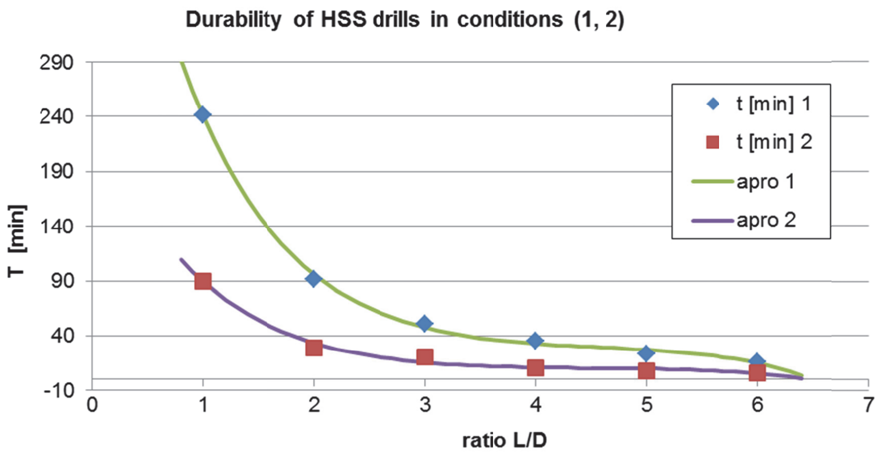
Functional dependence of tool durability can be determined as a multi-parameter, non-linear regression (Tab. I). The coefficients b, m_1, m_2, m_3 are calculated from the practical measurements of the application RO1, RO2. The closeness of calculated and measured of tool wear is confirmed by the correlation index I_k for both applications RO1, RO2 at a high level of reliability,



10: *Comparison of drilling productivity (number of holes drilled per minute) in classic drilling until a tool wears off and in intensive conditions in accordance with criterion of maximum productivity*

I: *Closeness of calculated and measured tool wear*

	m_3	m_2	m_1	b	I_k
apro 1	655.2549343	−0.0705	8.571102	−9.57031	0.998178
apro 2	258.8532369	−0.03055	4.671863	−10.8367	0.989012



11: *Durability of HSS drills in conditions (1, 2)*

where:
T........time,
L.......length,
D......diameter,
b........absolute polynomial factorization,
m_1, m_2, m_3.....coefficients of linear and exponential components,
I_k.......correlation index.

Mathematical dependence of durability on a cutting length of steel, for conditions (1, 2):

$$T\left(\frac{L}{D}\right) = b + m_1 \times \frac{L}{D} + m_2 \times e^{\frac{L}{D}} + m_3 \times e^{-\frac{L}{D}} \qquad (6)$$

The dependence of durability of HSS drills in conditions (1, 2) is presented in Fig. 11. In the same way it is possible to process the dependences for the drilling with the tool of SCD.

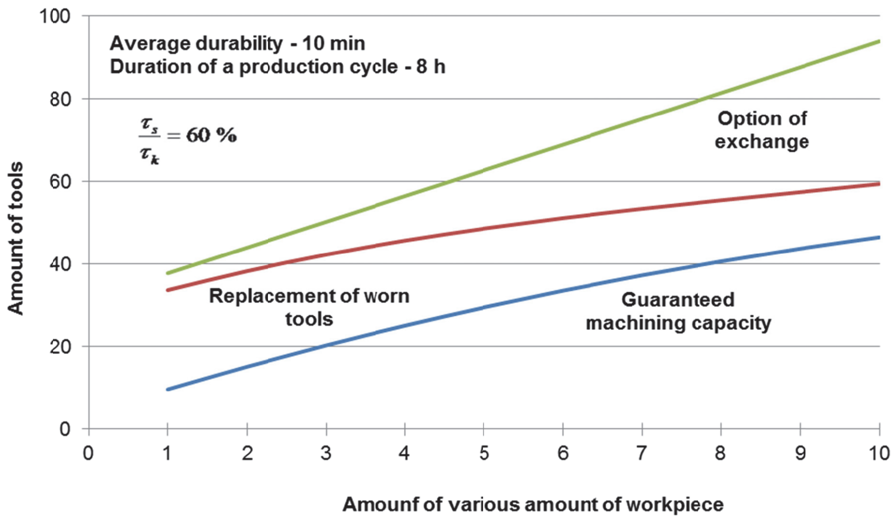
The dependence of HSS drills is determined within the drilling in conditions 1, 2:

- Condition 1 – steel C45
  $n = 710–800\ min^{-1}$,
  $v_c = 18–20\ m.min^{-1}$,
  $f = 0.12\ mm$,
  $f_m = 100\ mm.min^{-1}$.
- Condition 2 – gray cast iron
  $n = 800–1\,000\ min^{-1}$,
  $v_c = 20–25\ m.min^{-1}$,
  $f = 0.15\ mm$,
  $f_m = 135\ mm.min^{-1}$.

where
f........feed per revolution,
f_m......feed per minute.

This dependence can be used to calculate the relative durability of tools for their applications in various types of drilling.

When machining in automated manufacturing systems it is interesting to investigate the causes



12: *Dependence of amount of tools on amount of various amount of workpiece*

of tool consumption (Vasilko *et al.*, 1991b; Panda *et al.*, 2011).

Monitoring of real operations shows that the need for a tool depends on the following parameters:

- duration of production cycle,
- amount of different parts,
- proportion of machining time to total time,
- medium tool life,

Basically, the need for tools is derived from the following factors:

- the amount of tools limited by machining capacity,
- the amount of tools as a replacement of worn tools,
- the amount of tools limited by possibility of exchange (alternative tools).

Structure of dependence of amount of tools concerning previously mentioned factors, is depicted in Fig. 12.

Concerning Fig. 12 it can be seen that increasing amount of parts is connected with:

1) nonlinear growth of amount of tools is connected with machining capacity. It is due to the fact that some tools will be used more than once,
2) amount of worn tools will decrease absolutely as well as relatively because the frequency of use of each tool decreases,
3) amount of tools with possibility of exchange increases progressively.

High price of numerically controlled machines requires increasing cutting conditions, especially cutting speed (Modrák *et al.*, 2012). Use of cutting conditions corresponding to the classical work of machine tools negatively affects the economy of machining. We have shown that on the example of drilling a hole in the cast iron workpiece with two instruments made from different materials.

CONCLUSION

In drilling as well as boring, the optimal cutting conditions are influenced by types of machining processes.

Cutting environment is very important in machining process. There are usually used different types of oils and emulsions. It involves a mixture of water and mineral oils, active emulsifiers, such as organic acids, plant oils additives and high-pressure additives, e.g. sulphur-based and acid-based. For deep hole drilling we used cutting fluids. It concerns mineral oils enriched with additives, especially high-pressure ones, which not only reinforce lubrication system but have also other effect.

SUMMARY

This paper illustrates methodology and experiments for determination of optimal cutting conditions and appropriate cutting tools based on an example of drilling. The choice of drilling technology is based on the design requirements for the shape and dimensions, namely the nature of semi-finished product, with regards to the requirements of quality, reliability and economic efficiency.

To calculate diameters ranging from a few tenths to one millimeter are used micro drills. Some unconventional methods are increasingly being used, e.g. electron beam, laser. Holes with a diameter up to 10 mm are usually drilled with twist drills. High price of NC machines and centers of machine time require applying of a new approach to the determination of cutting conditions that indicate the economy machining. Based on an example of drilling, there is a presentation of methodology for selecting optimal cutting conditions which is suitable also for other types of instruments when it is revised.

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The results show that within the application to the expensive NC and CNC machines and centres, cemented carbide drills are more eff ective and more durable.

The existence of bark on a semi-product near the drill outlet from the material leads to the reduction of durability. To reduce the impact of casting crust on wear rate, we reduced cutting speed of the tool of HSS by 25% (from 16.5 $m.min^{-1}$). Durability tests of drilling in operating conditions revealed that durability of HSS drills increases by 30–40% and SCD drills by 10–15%. When using cemented carbide, probability of a failure of a cutting edge decreases. This dependence can be used to calculate the relative durability of tools for their applications in various types of drilling.

When machining in automated manufacturing systems it is interesting to investigate the causes of tool consumption. Monitoring of real operations shows that the need for a tool depends on the various parameters mentioned in the text.

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