Optimization of the cutting regims and estimation of possibilities of efficiency rise at the face milling

A Mikhailov, T Ivchenko, I Petryaeva and R Grubka
Donetsk National Technical University, 58 Artioma Street, Donetsk, Ukraine
E-mail: irina_petryaeva@mail.ru

Abstract. There are presented the results of the cutting regimes optimization on the criteria of the prime price, the productivity and multiplicative association of these criteria at the face milling. The coefficients of intercommunication between of the cutting regimes, expected on the different criteria of optimization, are grounded. Analytical dependences of optimum values of feed and cutting speed are allowing to calculate the optimum cutting regims for any machining terms. Got dependences provide the quantitative estimation of the cutting regimes intensification at the use of the hard-alloy cutting tool with wearproof coverages. The efficiency estimation is executed on basis of the productivity rise and of the prime price decline at the face milling by the hard-alloy cutting tool with wearproof coverages. There are presented the results of experimental and theoretical researches of the cutting tool life, cutting temperature and work surface roughness at the face milling by the cutting tool with wearproof coverages. The comparative analysis of the possibilities of the productivity rise and of the prime price decline is executed due to the cutting tool life increase, the cutting temperature and the work surface roughness lowering at the use of the cutting tool with different wearproof coverages.

1. Introduction
The rise of the manufacturing efficiency is the major problem of the modern engineer. This problem successfully decides based on the application of the hard-alloy cutting tool with wearproof coverages including the face milling cutters [1] and ground of optimum terms it exploitation. It is known the method of the optimization of the cutting regimes at the face milling on the criteria of the productivity and the prime price [2, 3]. There is of interest the use for the face milling of multiplicative association of these criteria, applied before at the turning [4].

It is known the method of the cutting regimes optimization on the different criteria and estimation of efficiency of the cutting tools with wearproof coverage’s at the turning [5]. The method is based on the estimation of the possibilities of intensification of the optimum cutting regimes due to the increase of the tool with wearproof coverages life, declines of cutting temperature and roughness of the treated surface. There is of interest further development of this method as it applies to other types of the machining and foremost to the face milling, which is the most widespread method of the flat surfaces treatment.

The purpose of the presented work is the optimization on the different criteria of the cutting regimes at the face milling and analysis of possibilities of it efficiency rise due to the use the hard-alloy cutting tool with wearproof coverages.
2. General information
In presented work the there are used followings generally accepted criteria of the optimization: productivity \( P \), prime price \( C \), association of these criteria \( C_M = P/C \) [4]. The objective functions expresses dependence of the optimization criteria on the cutting speed \( V \) and the feed \( S \) [4]:

\[
P(V,S) = VS \to \max; C(V,S) = V^{-1}S^{-1} + MK_{\text{max}}^{\text{max}}V^{kV}S^{kS} \quad ; \quad C_M(V,S) = V^{-2}S^{-2} + MK_{\text{max}}^{\text{max}}V^{kV-1}S^{kS-1}, \tag{1}
\]

where \( M = (t_c + A_u/A)(t + V^\omega B^\eta z^\phi /C_v K_v D^\theta \phi)^{1/m} \); \( k_v = 1/m - 1 \); \( k_s = y_v/m - 1 \); \( t_c \) - the restoration time of the tool; \( T \) - the cutting tool life period; \( A \) - the expenses for 1 minute of the equipment work; \( A_u \) - the expenses for 1 the cutting tool life period; \( t \) - the cutting depth; \( B \) - the milling width; \( z \) - the number of the milling cutter tooth; \( D \) - the diameter of milling cutter; \( C_v, K_v \) - factors and \( x_v, u_v, y_v, y_s, y_m \) - the indexes characterizing degree of influence of the depth \( t \), milling width \( B \), feed \( S \) and cutting tool life \( T \) for cutting speed \( V \); \( K_\theta = \phi /\Theta \) - coefficient of the necessary decline of the cutting temperature \( \Theta \) at exceeding by it possible level \( \Theta \), [4].

For providing of possibility of comparative analysis the indicated objective functions (1) it is expedient to present in a relative kind, where as a base for comparison their values are accepted the optimum feed \( S_o \) and cutting speeds \( V_o \): \( Pr = P(V,S)/P(V_o,S_o) \); \( Cr = C(V,S)/C(V_o,S_o) \); \( Cr_M = C_M(V,S)/C_M(V_o,S_o) \).

Two-parameter graphs of the relative objective functions of the productivity \( P_r \), prime price \( Cr \) and association of these criteria \( Cr_M \) depending on the cutting speed \( V \) and the feed \( S \), which are presented on the figure 1 testify to the presence of extremums of objective functions.

![Figure 1](image)

**Figure 1.** Two-parameter graphs of the relative objective functions of the productivity \( P_r \), prime price \( Cr \) and association of these criteria \( Cr_M \) depending on the cutting speed \( V \) and the feed \( S \).

There are set analytical dependences of the optimum feed \( S_o \) and cutting speed \( V_o \) from the face milling parameters, which allow for any terms treatments to expect the optimum cutting regimes.

At the rough milling optimum feed \( S_{11} \) regardless of the optimization criterion is determined coming from the limitations on the cutting plate strength, at the finish milling the optimum feed is determined coming from the limitations on the work surface roughness:

\[
S_{11} = \left[ 34c^{1.35} K_{\phi o}^{0.8} D^{\eta_p} / C_p K_p \right]^{(x_p-0.77)} B^{\eta_p} z^{\phi_p} \quad ; \quad S_{o2} = (R_o / C_R)^{\eta_p}, \tag{2}
\]

where \( C_p, K_p \) - factors and \( x_p, y_p, n_p \) - the indexes characterizing degree of influence of cutting depth \( t \), feed \( S \) and cutting speed \( V \) for cutting force \( P_z; K_\phi = (\sin 60^\circ / \sin \phi) \) - factors taking into account the tool
cutting edge angle \( \varphi \); \( c \) – the width of the cutting plate; \( C_R \) – factor; \( y_r \) – index characterizing degree of influence feed \( S \) for the work surface roughness.

The calculations of the optimum cutting regimes are resulted for two variants of the machining (the rough face milling and the finish face milling) of the construction steel by the sintered hard alloy cutting tool. The geometrical parameters are: major cutting edge angle \( \varphi = 67^\circ \), rake angle \( \gamma = -11^\circ \); diameter of milling cutter \( D = 125\text{mm} \); milling width \( B = 85\text{mm} \); cutting tool life period \( T = 180\text{min} \).

Definition of the optimum cutting regimes at the rough milling is executed for following terms: cutting depth \( t = 3\text{mm} \); width of the cutting plate \( c = 4.76\text{mm} \). Definition of the optimum cutting regimes at the finish milling is executed for following terms: cutting depth \( t = 1\text{mm} \); work surface roughness \( R_a = 2.5\text{mkm} \). The dependences of the work surface roughness \( R_a \) from the cutting process parameters at the face milling \( R_a = 11.6S^{1.62} \) [2].

Graphs of the change of the optimum feed \( S_o \) depending on the cutting depth \( t \) for the different milling cutter diameter \( D \) at the rough milling are presented on the figure 2. Graphs of change of the optimum feed \( S_o \) depending on the work surface roughness \( R_a \) for the different tip radius \( r \) of the milling cutter tooth are presented on the figure 3.

![Figure 2. Graphs of dependence of the optimum feed \( S_o \) on the cutting depth \( t \) for the different milling cutter diameter \( D \) at the rough milling.](image1)

![Figure 3. Graphs of dependence of the optimum feed \( S_o \) on the work surface roughness \( R_a \) for the different tip radius \( r \) at the finish milling.](image2)

At the face rough milling the optimum cutting speeds are determined taking into account the optimization criterion: \( V_{oM} \) – for criterion of the maximum productivity, \( V_{oC} \) – for criterion of the minimum prime price, \( V_{oMI} \) – for criterion of the multiplicative association of these criteria.

\[
V_{oM} = \frac{C_V K_V D^{q_v}}{T^{m} t^{v_x} S_{o1}^{Y_v} B_{u_x - p_v}}; \quad V_{oC2} = (m/(1 - m)M)^m S_{o1}^{-y_v}; \quad V_{oM1} = (2m/(1 - 2m)M)^m S_{o1}^{-y_v}
\]

(3)

As a result of the comparison of these optimum cutting speeds it is set that optimum at productivity cutting speed is on 30% higher, than optimum on the prime price speed and on 9% higher, than optimum on criterion of the association. In general case, the indicated coefficients can be expected: \( K_{VC} = V_{oC}/V_{oM}; \quad K_{VM} = V_{oM}/V_{oP} \).

\[
K_{VC} = [mT/(1 - m)(t_c + A_u/A)]^m; \quad K_{VM} = [2mT/(1 - 2m)(t_c + A_u/A)]^m.
\]

(4)

At the face finish milling it is necessary to take into account the temperature limitations in case that cutting temperature exceed a possible level \( \Theta = 800^\circ\text{C} \). The necessity of account of the temperature limitations is determined on the basis of the border value of coefficient of decline of the cutting temperature \( K_{a0} = \Theta/\Theta(V_{oC}, S_{o}) \leq 1 \). The optimum cutting speed \( V_{o\Theta} \) is determined take into account the temperature limitations. In default of the temperature limitations, the optimum cutting speeds are
determined taking into account the optimization criterion: \( V_{oP} \) – for the productivity criterion, \( V_{oC} \) – for prime price criterion, \( V_{oM} \) – for the association of these criteria:

\[
V_{oP} = \left( \Theta / \left( C_\Theta t_{\Theta}^{x_\Theta} S_{o2}^{x_{\Theta}} \right) \right)^{1/n_{\Theta}}, \text{ if } K_{\Theta oP} \leq 1; \quad K_{\Theta oP} = \left( \Theta / \left( C_\Theta t_{\Theta}^{x_\Theta} S_{o2}^{x_{\Theta}} V_{oP}^{n_{\Theta}} \right) \right);
\]

\[
V_{oC} = \left( m/(1-m)M \right)^{n_{\Theta}} S_{o2}^{n_{\Theta}}, \text{ if } K_{\Theta oC} \geq 1; \quad K_{\Theta oC} = \left( \Theta / \left( C_\Theta t_{\Theta}^{x_\Theta} S_{o2}^{x_{\Theta}} V_{oC}^{n_{\Theta}} \right) \right);
\]

\[
V_{oM} = \left( 2m/(1-2m)M \right)^{n_{\Theta}} S_{o2}^{n_{\Theta}}, \text{ if } K_{\Theta oM} \geq 1; \quad K_{\Theta oM} = \left( \Theta / \left( C_\Theta t_{\Theta}^{x_\Theta} S_{o2}^{x_{\Theta}} V_{oM}^{n_{\Theta}} \right) \right),
\]  

where \( C_{\Theta} \) - factors and \( n_{\Theta}, y_{\Theta}, x_{\Theta} \) – the indexes characterizing degree of influence of cutting speed \( V \), feed \( S \) and depth \( t \) for the cutting temperature \( \Theta \); \( K_{\Theta oP}, K_{\Theta oC}, K_{\Theta oM} \) – the border value of coefficient of cutting temperature decline for different optimization criterion: for criterion of the maximum productivity, for criterion of the minimum prime price, for criterion of the multiplicative association of these criteria accordingly.

Graphs of change of coefficients \( K_{\Theta C} \) and \( K_{\Theta M} \) depending on the cutting tool life \( T \) are presented on the figure 4. Graphs of change of the border value of coefficient of the cutting temperature decline \( K_{\Theta o} \) depending on the optimum feed \( S_{o} \) for the different optimization criterion at the finish milling are presented on the figure 5.

**Figure 4.** Graphs of dependence of the coefficients \( K_{\Theta C} \) and \( K_{\Theta M} \) on the cutting tool life period \( T \) at the face milling.

**Figure 5.** Graphs of change of the border value of coefficient of the cutting temperature decline \( K_{\Theta o} \) depending on optimum feed \( S_{o} \) for the different optimization criterion at the face finish milling.

Graphs of change of the optimum cutting speeds \( V_{o} \) depending on the optimum feed \( S_{o} \) for the different optimization criterion at the rough milling are presented on the figure 6. Graphs of change of the border value of coefficient of the cutting temperature decline \( K_{\Theta o} \) depending on the optimum feed \( S_{o} \) for the different optimization criterion at the finish milling are presented on the figure 7. The dependences of the cutting temperature \( \Theta \) from the cutting process parameters at the face milling of construction steel \( \Theta = 302 V_{0.2}^{0.21} S_{0.21}^{0.21} \) [2].

The presented graphs illustrate conformities to law of changeoptimium on the different criteria cutting regimes and present recommendations on a choice optimum feed \( S_{o} \) and cutting speeds \( V_{o} \) under various conditions of the rough and face finish milling. Analytical dependences of optimum values of feed (3) and cutting speed (4) are allowing to calculate the optimum cutting regimes for any machining terms.

For the before indicated machining terms following optimum cutting regimes at the rough milling are defined: optimum feed \( S_{o} = 0.12 \text{mm/t}; \) optimum cutting speed \( V_{oP} = 160 \text{m/min}; \) \( V_{oC} = 121 \text{m/min}; \) \( V_{oM} = 147 \text{m/min}; \) at the finish milling are defined: optimum feed \( S_{o} = 0.06 \text{mm/t}; \) optimum cutting
speed $V_{o\theta}$ = 126m/min. At the removal of temperature limitations can be got optimum cutting speed $V_{oP2}$ = 200m/min; $V_{oC2}$ = 146m/min; $V_{oM2}$ = 178m/min. The account of the temperature limitations results the decline of the optimum cutting speed $V_{o\theta}$.

Get analytical dependences of optimum cutting regimes provide the quantitative estimation of the cutting regimes intensification at the use of the hard-alloy cutting tool with wearproof coverages. Efficiency of the face milling at the use of the cutting tool with different wearproof coverages is arrived at an account the cutting tool life increase $T_{cov}$, the cutting temperature $\Theta_{cov}$ and the work surface roughness lowering $R_{acov}$ by comparison to them indexes for cutting tool without coverages:

$$T_{cov} = K_T\left(C_v K_V D^{q_v} / T^{m_T} S^{n_{oT}} B^{m_B} z^{n_z}\right)^{1/m_v}; \ \Theta_{cov} = K_\Theta C_\Theta V^{r_v} S^{n_{oS}} T^{n_T}; \ \ R_{acov} = K_R C_R S^{r_s}$$

(6)

where $K_T$, $K_\Theta$, $K_R$ – coefficients of the cutting tool life $T$ increase, the cutting temperature $\Theta$ and the work surface roughness $R_a$ decline.

The quantitative estimation of the cutting regimes intensification at the use of the hard-alloy cutting tool with wearproof coverages is provided based on coefficients change of the feed $K_S$ and cutting speed $K_V$, which are presented on the figure 8 and figure 9:

$$K_S = K_R^{-1/y_r}; \ \ K_V = K_T^{m_T} Kaday^{1/n_T} K_{R}\gamma_{r}^{y_{r}/y_{m_{TS}}}, \ \ \text{if} \ K_{\Theta_{oT}} \leq 1; \ \ K_V = K_T^{m_T} K_{R}^{y_{r}/y_{m_{TS}}}, \ \ \text{if} \ K_{\Theta_{oT}} \geq 1.$$  

(7)
The quantitative estimation of increase of the machining efficiency at the face milling at the use of the cutting tool with different wearproof coverages is executed based on coefficients of the productivity rise $K_P$ and of the prime price decline $K_C$:

$$K_P = \begin{cases} \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > T} \leq 1; \\ \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > C} \leq 1; \\ \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > C} \geq 1. \end{cases}$$

Graphs of change of coefficients of the productivity increase $K_P$ and of the prime price decline $K_C$ depending on the coefficients of the cutting tool life $K_T$ increase and the cutting temperature $K_{\Theta}$ decline are presented on the figure 9 and figure 10 ($K_R = 1$).

$$K_P = \begin{cases} \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > T} \leq 1; \\ \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > C} \leq 1; \\ \frac{1}{K_T^{(m)} K_R^{(y)}} & \text{if } K_{\Theta > C} \geq 1. \end{cases}$$

Figure 10. Graphs of dependence of the coefficient of the productivity increase $K_P$ on the coefficients of the cutting tool life $K_T$ increase and the cutting temperature $K_{\Theta}$ decline at the face milling.

Figure 11. Graphs of dependence of the coefficients of the prime price decline $K_C$ on the coefficients of the cutting tool life $K_T$ increase and the cutting temperature $K_{\Theta}$ decline at the face milling.

Coefficients of the cutting tool life increase $K_T$, the cutting temperature $K_{\Theta}$ and the work surface roughness decline $K_R$ of the face milling at the use of the cutting tool with different wearproof coverages are determined based on experimental researches.

Experiments were executed for next terms: the face milling of the construction steel by sintered hard alloy cutting tool with two variants of the wearproof coverages - titanium carbid TiC and titanium nitrid TiN (cutting depth $t = 2mm$; feed $S = 0.3mm/rev$).

It is set that at the face milling for the indicated machining terms a cutting temperature does not exceed a possible level $\Theta = 800^\circ$. Consequently coefficients of the cutting temperature $K_{\Theta} < 1$ and optimum cutting regimes can be determined without account of the temperature limitations.

As a result of experiment there are set coefficients of the cutting tool life increase $K_T$ at the face milling of the cutting tool with coverages TiC - $K_{T, TiC} = 2.2$; with coverages TiN - $K_{T, TiN} = 3.3$.

As a result of experiment there are set coefficients of the work surface roughness decline $K_R$ at the face milling of the cutting tool with coverages TiC - $K_{R, TiC} = 0.95$; with coverages TiN - $K_{R, TiN} = 0.9$.

Results of efficiency estimation of face milling cutters with wearproof coverages based on experimental researches are presenting in the table 1.
Table 1. Factors of efficiency estimation of face milling cutters with wearproof coverages.

| Wearproof coverage on hard-alloy cutting tool | Factors of efficiency estimation of face milling cutters with coverages |
|---------------------------------------------|-------------------------------------------------------------------------|
|                                             | Coefficients                                                          |
|                                             | cutting tool life increase $K_I$ | surface roughness decline $K_R$ | productivity increase $K_P$ | prime price decline $K_C$ |
| without coverage                           | 1                                                                       | 1                            | 1                           | 1                           |
| titanium carbid TiC                        | 2.2                                                                    | 0.95                         | 1.24                        | 0.79                        |
| titanium nitrid TiN                        | 3.3                                                                    | 0.9                          | 1.4                         | 0.71                        |

The results of researches testify that more effective is the use of coverages from of titanium nitrid TiN. Productivity is in 1.4 times higher and prime price is in 1.4 times below, than tools without coverages. Results of efficiency estimation of face milling cutters with wearproof coverages on the basis of known literary data [1] are presenting in the table 2.

Table 2. Factors of efficiency estimation of face milling cutters with multi-layered coverages.

| Multi-layered wearproof coverage on hard-alloy cutting tool | Factors of efficiency estimation of face milling cutters with multi-layered coverages |
|------------------------------------------------------------|--------------------------------------------------------------------------------------|
|                                                            | Coefficients                                                                 |
|                                                            | cutting tool life increase $K_I$ | productivity increase $K_P$ | prime price decline $K_C$ |
| without coverage                                          | 1                                                                         | 1                             | 1                         |
| duplex-layered (Ti,Zr)CN-(Ti,Zr)N                        | 4.7 – 6.2                                                                  | 1.5 – 1.6                     | 0.65 – 0.6                |
| three-layered TiN-TiCN-TiN                               | 2.4 – 3.9                                                                  | 1.3 – 1.5                     | 0.75 – 0.7                |
| three-layered TiCN-TiZrN-TiN                             | 4.9 – 7.2                                                                  | 1.5 – 1.7                     | 0.65 – 0.6                |

3. Conclusion

Multi-layered coverages have substantial advantage before one-layered coverages and cutting tools without coverages. Productivity of the face milling cutters with three-layered wearproof coverages TiCN-TiZrN-TiN is in 1.7 times higher and prime price is in 1.7 times below, than without coverages. Thus the comparative analysis of the possibilities of the productivity increase and of the prime price decline is executed due to the cutting tool life increase, the cutting temperature and the work surface roughness lowering at the use of the cutting tool with different wearproof coverages.

4. References

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