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PREDICTING THE TOOL LIFE IN THE DRY MACHINING OF DUPLEX STAINLESS STEEL

PROGNOZOWANIE OKRESU TRWAŁOŚCI OSTRZA W OBRÓBCE NA SUCHO STALI NIERDZEWNEJ DUPLEX*

This paper examines the influence of cutting parameters, namely cutting speed, feed and depth of cut onto tool life in DSS turning process. The study included developing a mathematical model to determine the tool life. Verification research has been carried out on CNC lathe, hence the test plan has been adjusted to the possibility of programmable machines controlling GE Fanuc series 0 - T. The comparison of results obtained by given experimental plan was performed in industrial company.

***Keywords**: Duplex Stainless Steel, machining, turning, tool life, Responce Surface Method.*

W artykule przedstawiono wpływ parametrów obróbki, a mianowicie prędkości skrawania, posuwu i głębokości skrawania na okres trwałości ostrza w procesie toczenia stali duplex. Badania obejmowały opracowanie modelu matematycznego dla określenia okresu trwałości ostrza skrawającego. Badania weryfikacyjne wykonywano na tokarce sterowanej numerycznie, stąd plan badań dostosowany został do możliwości programowych maszyny ze sterowaniem GE Fanuc seria 0 – T. Porównanie wyników przeprowadzono w warunkach produkcyjnych.

***Słowa kluczowe**: stal nierdzewna, obróbka skrawaniem, toczenie, okres trwałości ostrza, metoda powierzchni odpowiedzi.*

Nomenclature

a_p	depth of cut in mm
f	feed rate in mm/rev
v_c	cutting speed in m/min
T	tool life in min
DSS	Duplex Stainless Steel

1. Introduction

According to companies producing construction materials duplex stainless steel is gaining importance, which is reflected in the wide range of these products available in the market. One limitation of the efficiency of the turning of this steel is the consumption of cutting tool indexable tool inserts. According Olszak [10] DSS is classified as difficult-to-cut. In recent years, machinability of austenitic steels has been dealt by researchers such as Abou-El-Hossein K. A. et al., Akasawa T. et al., Charles J. et al., Ciftci I., Cunat P. J., Kosmač A., and Paro J. et al. [1, 2, 4, 5, 6, 7, 8, 11], while machining of DSS has been described by Bouzid Saï W. and Lebrun J. L. [3]. The wearing process of a tool point, which is largely dependent on cutting parameters, is an important factor. The wear of a tool point leads to deterioration in quality of machined surface. The basic requirement in the application of indexable tool inserts in industrial conditions is the total increase in production; not the precision performance of its particular machine parts. According to Smith [14], where the equipment stocks are consolidated and the materials used in cutting tools are more universal, we can, in industrial conditions, use a smaller number of types and geometry of the cutting tool. Smaller stocks of indexable tool inserts allow us to more effectively optimize the production process. The above-mentioned aspects, combined with the optimization of the cutting speed, feed and depth of cut, allow the desired production targets to be met. Due to an optimization of the cutting parameters, it is possible to take full advantage of the basic equipment; as a result you can expect a large increase in overall production efficiency. In order to know surface quality and dimensional properties is necessary to employ theoretical models making it feasible to do predictions in function of operation conditions. The response surface method (RSM) is practical, economical and relatively easy for use [13].

2. Experimental techniques

2.1. Workpiece and cutting tool materials

Machined material was 1.4462 (DIN EN 10088-1) steel with a ferritic-austenitic structure containing about 50% of austenite. The ultimate tensile strength UTS=700 MPa, Brinell hardness - 293 HB. The elemental composition of the machined material and technical details of the cutting tools are given in tables 1 and 2 respectively.

Cutting tool inserts of TNMG 160408 designation clamped in the tool shank of ISO-MTGNL 2020-16 type were employed. Based on the industry recommendations a range of cutting parameters T1: v_c = 50 ÷ 150 m/min, f = 0,2 ÷ 0,4 mm/rev, a_p = 1 ÷ 3 mm was selected. The study was conducted within a production facility. The research program was carried out on a lathe CNC 400 Famot – Pleszew.

2.2. Research plan

As the method of optimization for DSS cutting parameters a static determined selective-multivariate uniform static - rotatable PS/

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Table 1. Chemical composition of 1.4462 duplex stainless steel

Element	%C max	%Si max	%Mn max	%P max	%S max	%Cr	%Ni	%Mo	%N	Others
[%] at.	0,03	1,00	2,00	0,030	0,020	21,0 23,0	4,50 6,50	2,50 3,50	0,10 0,22	-

Table 2. Cutting tool specification

Tool	Substrate	Others
T1	Hardness: 1350 HV3 Grade: M25, P35	Coatings: Ti(C,N)-(2 μm) (Top layer) Al_2O_3-(1.5 μm) (Middle layer) TiN-(2 μm) (Bottom layer) Coating technique: CVD

Table 3. Coded indication of the study plan

Test No.	Coded factors			Decoded real value		
	x_1	x_2	x_3	v_C [m/min]	f [mm/rev]	a_p [mm]
1	-1	-1	-1	70	0,24	1,4
2	-1	-1	+1	70	0,24	2,6
3	-1	+1	-1	70	0,36	1,4
4	-1	+1	+1	70	0,36	2,6
5	+1	-1	-1	130	0,24	1,4
6	+1	-1	+1	130	0,24	2,6
7	+1	+1	-1	130	0,36	1,4
8	+1	+1	+1	130	0,36	2,6
9	-1,682	0	0	50	0,3	2
10	1,682	0	0	150	0,3	2
11	0	-1,682	0	100	0,2	2
12	0	1,682	0	100	0,4	2
13	0	0	-1,682	100	0,3	1
14	0	0	1,682	100	0,3	3
15	0	0	0	100	0,3	2
16	0	0	0	100	0,3	2
17	0	0	0	100	0,3	2
18	0	0	0	100	0,3	2
19	0	0	0	100	0,3	2
20	0	0	0	100	0,3	2

DS-P:λ program has been selected [12]. A choice of the PS/DS-P:λ program was dictated with the assumption that the second-degree polynomial function model will be a nonlinear model which can be reduced to a linear model. The second-degree polynomial function has been chosen because there are no restrictions in research related to the measurement technique. The required number of experimental points is $N = 2^3 + 6 + 6 = 20$ (Table 3).

There are eight factorial experiments (3 factors on two levels, 2^3) with added 6 star points and centre point (average level) repeated 6 times to calculate the pure error [9].

3. Modeling tool life and its application

3.1. Tool life model

The aim of this study was an attempt to verify, in industrial conditions, the calculated value of the function describing tool life during turning DSS. Based on the PS/DS-P:λ program and the modeled experimental data of the polynomial function of tool life:

$$T = f(v_c;\ f;\ a_p) = 118{,}438 - 0{,}88687 \cdot v_c - 89{,}9855 \cdot f - 14{,}439 \cdot a_p + 0{,}0053856 \cdot v_c^2 + 400{,}4555 \cdot f^2 + 6{,}0762 \cdot a_p^2 - 1{,}3131 \cdot v_c \cdot f + 0{,}0029556 \cdot v_c \cdot a_p - 47{,}6564 \cdot f \cdot a_p, \quad (1)$$

Chosen results for maximum and minimum values of v_c and f and for average value of a_p are presented in Table 4. It is evident that the results obtained on the basis of the model are consistent with the results obtained during the experiment.

Table 4. Verified research parameters of the model of tool life

Cutting parameters			*T* - average value of research	*T* - calculation results
v_c [m/min]	*f* [mm/rev]	a_p [mm]		
150	0,2	2	40 min 19,4 s	42 min 27,9 s
150	0,4	2	16 min 24,4 s	14 min 04,0 s
50	0,2	2	46 min 01,4 s	49 min 06,5 s
50	0,4	2	39 min 08,5 s	46 min 58,4 s

It is evident that the results obtained on the basis of the model are consistent with the results obtained during the experiment.

3.2. Verification study of the model

The evaluation of the mathematical model was performed using the Student's t test to compare two mean values of populations with normal distributions and homogeneous variances. Statistical calculations were performed with the Statistica 9.0 [15] program.

The assumptions of normality were examined using the Shapiro-Wilk test for the model of tool life (Table 5).

Table 5. Tests of normality for the model of tool life

Variable	n	W	p
Average value of research	4	0,8251	0,1555
Calculation results	4	0,7741	0,0633

As the level of significance of p is greater than 0,05 for the test case, there is no reason to reject the hypothesis of normal distribution.

Two general populations are examined with normal distributions $N(m_1, \sigma_1)$ and $N(m_2, \sigma_2)$, where the parameters of these distributions are unknown. There are two sample sizes $n_1 = 4$ and $n_2 = 4$. On the basis of test results the hypothesis is tested H_0: $\sigma_1^2 = \sigma_2^2$, against the alternative hypothesis H_1: $\sigma_1^2 \neq \sigma_2^2$. The results of the calculations for the model of tool life are presented in Table 6.

Table 6. The results of F-statistic model calculations for tool life

F	1,5563
p	0,7251

Because p is greater than 0,05, there is no reason to reject the hypothesis of homogeneity of variance for each of the cases.

The two populations having normal distributions are being studied now $N(m_1, \sigma_1)$ and $N(m_2, \sigma_2)$, standard deviations are unknown, but equal, i.e. there is $\sigma_1 = \sigma_2$. Based on two sample sizes $n_1 = 4$ and $n_2 = 4$, the hypothesis is verified H_0: $m_1 = m_2$ against the alternative hypothesis H_1: $m_1 \neq m_2$. The average values from both samples are verified $\overline{x_1}$ and $\overline{x_2}$ and variances s_1^2 and s_2^2, then the value of t statistics according to the following formula:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} . \tag{2}$$

The calculation results are presented in Table 7.

Table 7. The results of t-statistic model calculations for tool life

t	-0,2566
p	0,8060

The significance level of p for the tested models is greater than 0,05 which means there is no reason to reject the hypothesis of equal averages. Therefore, it is shown on the significance level of 0,05, that the average value of research and the model are not significantly different. It can therefore be concluded that the designated model reflects changes in tool life represented by the empirical values.

4. Tool life as the function of cutting parameters

Table 8–10 shows results (values) of the tool life of *T*, depending on the particular technological cutting parameters in the turning process of duplex stainless steel. It was calculated on the basis of equation (1).

Table 8. Values of tool life according to T for T = f(a_p) for v_c = 50 ÷ 150 m/min and f = 0,2 ÷ 0,4 mm/rev obtained for the depths of cutting a_p = 1 mm, a_p = 2 mm, a_p = 3 mm

No	v_c [m/min]	f [mm/rev]	$T_{(ap=1)}$ [min]	$T_{(ap=2)}$ [min]	$T_{(ap=3)}$ [min]
1	50	0,2	54,702	49,108	55,667
2		0,3	54,395	44,036	45,829
3		0,4	62,098	46,972	44,000
4	100	0,2	37,768	32,321	39,028
5		0,3	30,895	20,683	22,624
6		0,4	32,032	17,054	14,229
7	150	0,2	47,761	42,463	49,317
8		0,3	34,323	24,259	26,347
9		0,4	28,894	14,065	11,387

Table 9. Values of tool life according to T for T = f(v_c) for f = 0,2 ÷ 0,4 mm/rev and a_p = 1 ÷ 3 mm obtained for the cutting speed v_c = 50 m/min, v_c = 100 m/min, v_c = 150 m/min

No	f [mm/rev]	a_p [mm]	$T_{(vc=50)}$ [min]	$T_{(vc=100)}$ [min]	$T_{(vc=150)}$ [min]
1	0,2	1	54,702	37,768	47,761
2	0,3		54,395	30,895	34,323
3	0,4		62,098	32,032	28,894
4	0,2	2	49,108	32,321	42,463
5	0,3		44,036	20,683	24,259
6	0,4		46,972	17,054	14,065
7	0,2	3	55,667	39,028	49,317
8	0,3		45,829	22,624	26,347
9	0,4		44,000	14,229	11,387

Table 10. Values of tool life according to T for T = f(f) for v_c = 50 ÷ 150 m/min and a_p = 1 ÷ 3 mm obtained for the feed f = 0,2 mm/rev, f = 0,3 mm/rev, f = 0,4 mm/rev

No	v_c [m/min]	a_p [mm]	$T_{(f=0,2)}$ [min]	$T_{(f=0,3)}$ [min]	$T_{(f=0,4)}$ [min]
1	50	1	54,702	54,395	62,098
2		2	49,108	44,036	46,972
3		3	55,667	45,829	44,000
4	100	1	37,768	30,895	32,032
5		2	32,321	20,683	17,054
6		3	39,028	22,624	14,229
7	150	1	47,761	34,323	28,894
8		2	42,463	24,259	14,065
9		3	49,317	26,347	11,387

Those data can be useful for both technologist and the CNC machine tool operator.

5. Conclusions

The purpose of this article was to develop a methodology which can offer the possibility of predicting the tool life in the turning process of duplex stainless steel. Predicting the required parameter of tool life *T* in the process of dry machining is an important part of the process and impact of such conditions on the technological properties of the surface layer.

Factorial design of an experiment can be successfully employed using coated carbide cutting tools in turning DSS. The following conclusions have been drawn:

1. Second-order model predicting equations for tool life have been developed using response surface methodology for turning the DSS with coated tools.
2. The established equations clearly show that the cutting speed was main influencing factor on the tool life.
3. The predicted values and measured values are fairly close which indicates that the developed tool life prediction model can be effectively used to predict the tool life for the turning process. Using such models, a remarkable time and cost savings can be obtained.

References

1. Abou-El-Hossein KA, Yahya Z. High-Speed End-Milling of AISI 304 Stainless Steels Using New Geometrically Developed Carbide Inserts. Journal of Materials Processing Technology, 2005, 162–163, 596–602.
2. Akasawa T. et al. Effects of Free-Cutting Additives on the Machinability of Austenitic Stainless Steels. Journal of Materials Processing Technology, 2003, 143–144, 66–71.
3. Bouzid Saï W, Lebrun JL. Influence of Finishing by Burnishing on Surface Characteristics. Journal of Materials Engineering and Performance, 2003, volume 12(1), 37.
4. Charles J. et al. Austenitis Chromium – Manganese Stainless Steel – A European Approach. Materials and Applications Series, 2010,volume 12, Euro Inox.
5. Ciftci I. Machining of Austenitic Stainless Steels using CVD Multi-Layer Coated Cemented Carbide Tools. Tribology International, 2006, 39, 565–569.
6. Cunat PJ. The Euro Inox Handbook of Stainless Steel. Materials and Applications Series, 2002,volume 1, Euro Inox.
7. Cunat PJ. Working with Stainless Steel. Materials and Applications Series, 2009,volume 2, EDP Sciences and Euro Inox.
8. Kosmač A. Electropolishing Stainless Steel. Materials and Applications Series, 2010, volume 11, Euro Inox.
9. Montgomery D. Design and Analysis of Experiments, 5th Edition, New York: John Wiley & Sons, Inc., 2003.
10. Olszak W. Obróbka skrawaniem. Warszawa: WNT, 2008.
11. Paro J. et al. Tool Wear and Machinability of X5 CrMnN 18 18 Stainless Steels. Journal of Materials Processing Technology, 2001, 119, 14-20.
12. Polański Z. Metody optymalizacji w technologii maszyn. Warszawa: PWN, 1977.
13. Sahin Y, Riza Motorcu A. Surface Roughness Model for Machining Mild Steel with Coated Carbide Tool. Materials & Design, 2005, 26, 321–326.
14. Smith GT. Cutting Tool Technology, Industrial Handbook. London: Springer-Verlag, 2008.
15. StatSoft, Inc. (2009). STATISTICA (data analysis software system), version 9.0. www.statsoft.com

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