DOI: https://doi.org/10.24425/amm.2025.152500

ALI O. ER[1*], E. ASLAN[1]

A COMPARATIVE STUDY ON CUTTING TOOL PERFORMANCE IN HIGH-SPEED FACE-MILLING OF HARDENED TOOL STEELS

In this study cutting speeds and tool life constants for seven different cutting tools are investigated while high-speed face milling of four different much used hardened tool steels.1.2379 and 1.2080 cold-work tool steels, 1.2344 hot-work tool steel and 1.2738 plastic mold steel were machined with PVD TiN coated ceramic, PCBN, PVD TiN coated carbide, PVD TiAlN coated carbide cermet, CVD TiN-TiCN-Al_2O_3 coated carbide, uncoated carbide and uncoated cermet cutting tools. Wear of cutting tools measured for all species after every pass. Also, the tool life constants for each tool materials are calculated and are given for convenient tool material. Generally, PCBN tool gave the best results in high-speed face milling of all hardened tool steels. Unexpectedly uncoated carbide and uncoated cermet gave useful results while high-speed face milling of hardened 1.2344 hot-work tool steel.

Keywords: Tool life; high-speed machining; face milling; hardened tool steels; machinability; smart manufacturing

1. Introduction

In metal cutting operations most important decision to be taken is the selection of the appropriate cutting tool. Two different methods for appropriate cutting tool selection are used according to a metal cutting methods such as turning, milling, and workpiece material. One of these methods is selecting the appropriate cutting tool after experimental study. The other method is selecting the appropriate cutting tool according to Taylor Equation tool life constants which will give the convenient tool life and cutting speed [1]. The first method is an expensive and time-consuming method. In the other method, Taylor Equation, determining tool life constants is an important matter. The reference tables for the constants are mostly created for low and moderate cutting speeds for machining processes.

High-speed machining of hardened steel is an important subject for industrial applications. Using the cutting tool efficiently is one of the most important subjects for all machining operations. Considering the tool life of the cutting tool right obtains lower tool cost, dimensional accuracy, and desired surface roughness. Hence determining the suitable tool and correct tool life constant is very important. Especially parallel to the developments in cutting tool materials high-speed machining become more important as can be seen from the literature because of its advantages. These advantages are high metal removal rates, low cutting forces, good surface quality and integrity, reduction in cutting tool variety [2], dissipation of heat with chip removal resulting in a decrease in workpiece distortion [3]. Thus, final finishing operations are usually decreased or sometimes eliminated resulting in lower manufacturing costs [4]. In contrast the advantages, there are some disadvantages of high-speed machining which will have to be taken precautions about. These disadvantages are high tool wear, requirement of expensive tool materials, advanced coatings, precision tool holder tapers, costly machine tools and control systems [2].

Because of the disadvantages, tool wear measurement or prediction is an important matter for high-speed machining applications. Literature investigation about high-speed machining of hardened tool steels shows that especially tool performances of the different tools comparison are made while machining hardened tool steels such as AISI D2 cold-work tool steel [5-13], AISI H13 hot-work tool steel [3,6,14-21], AISI H11 tool steel [22], AISI A2 tool steel [23] and AISI P20 [24], AISI D3 [25-27]. Most of the studies on high-speed machining made for end milling application [3-27]. There is a review on the processing of hardened steels. In this review, it was stated that there is not enough study about tool wear and tool life [28]. There are some studies about wear mechanisms in high-speed machining [29], temperature

1 KIRIKKALE UNIVERSITY, MECHANICAL ENGINEERING DEPARTMENT, 71450, YAHŞIHAN-KIRIKKALE / TURKEY

* Corresponding author: er@kku.edu.tr

measurement when high-speed machining of hardened tool steel [30], chip formation in high-speed milling [31], performance evaluation of different coating materials while high-speed machining [32] and high-speed five-axis milling of hardened tool steel. There is a deficiency for face milling applications. There are only a few studies about face milling operations [33-39]. For smart manufacturing prediction of cutting tool wear during milling process are made using artificial intelligence techniques [40]. There is a short review about future trends in high speed milling of metal alloys [41].

The aim of this research is making a comparative evaluation about the high speed machining performances of different cutting tools, determining the right cutting speed and tool life constants while high-speed face milling of hardened tool steels. In this study, seven different cutting tool materials were tested for four different hardened tool steels till finding the appropriate cutting tool and cutting speeds. Then tool life constants are determined for each cutting tool material. Tool life constants tables which will be created for high-speed machining will obtain time possession for academicians and industry. Especially automatic tool changing systems with smart features will be held in the machine tools industry. Because in unmanned digital factories the decisions will be taken according to datas from the smart manufacturing systems. And determining the tool life of cutting tools will become more important in the coming years for machine learning applications.

2. Materials and method

2.1. Materials

Hardened tool steels, most commonly used by manufacturers in industrial operations are chosen for this research. These materials are 1.2379 (AISI D12/DIN X155CrVMo12-1) and 1.2080 (AISI D3/DIN X210Cr12) cold-work tool steel, 1.2344 (AISI H13/DIN X40CrMoV5-1) hot-work tool steel and 1.2738 (AISI P20/DIN 40CrMnNiMo8-6) plastic mold steel. Chemical composition and hardness of the materials are given in TABLE 1. Materials with the dimensions of 100×200×300 mm are hardened to 55, 56 and 58 HRC.

TABLE 1

Chemical composition and hardness of the materials

	1.2379 ***(AISI D12)***	**1.2080** ***(AISI D3)***	**1.2344** ***(AISI H13)***	**1.2738** ***(AISI P20)***
Hardness	*56 HRC*	*55 HRC*	*58 HRC*	*55 HRC*
% C	1.55	2.00	0.38	0.38
% Si	0.25	0.25	1.10	0.30
% Mn	0.35	0.30	0.40	1.50
% V	0.95	—	0.95	—
% Cr	11.80	11.50	5.20	2.00
% Mo	0.80	—	1.40	0.20
% Ni	—	—	—	1.10

2.2. Cutting Tools

The cutting tool is determined according to ISO 8688-1: “Tool life testing in milling-Part1: Face milling” [42]. Face mill has 125 mm diameter and inserts coded as SPAN 1203 EDR. The axial rake angle is 0°, radial rake angle is 8° and approach angle of the tool is 75°. Insert geometry of cutting tool is also designated in ISO 8688-1: SPAN 1203 EDR.

In this research eligible cutting tool for machining hardened tool steels is determined. For determining appropriate cutting tool material seven different tool materials have been tested. These cutting tool materials and their coatings are given in TABLE 2.

Dry face milling tests were carried out on a Mazak VTC-20B vertical machining center. After every cutting pass wear of insert was examined with Scherr Tumico 98/0001 toolmaker’s microscope and surface roughnesses were measured with Hommel Tester T1000.

TABLE 2

Cutting tool materials and their coatings

Tool Number	**Cutting Tool Materials**	**Coating**	
		Method	**Material**
Tool 1	Coated Ceramic	*PVD*	TiN
Tool 2	PCBN	Uncoated	—
Tool 3	Coated Carbide	*CVD*	TiN-TiCN-Al_2O_3
Tool 4	Coated Cermet	*PVD*	TiAlN
Tool 5	Coated Carbide	*PVD*	TiN
Tool 6	Carbide	Uncoated	—
Tool 7	Cermet	Uncoated	—

2.3. Experimental design

Cutting parameters controlled according to the tool-workpiece couple is determined as mentioned in the standard. In the standard, there are two relationships between the parameters. Axial depth of cut (a_a) must be 8 times feed rate (f_z) and radial depth of cut (a_r) must be 0.6 times diameter of the face mill (D).

According to the tool manufacturer catalog and relationships between the parameters at ISO 8688-1, axial depth of cut is determined as 0.25 mm, radial depth of cut as 75 mm and feed rate as 0.032 mm. The cutting parameters for experimental design are given in TABLE 3.

TABLE 3

Cutting parameters

Cutting parameters	**Values**
Feed rate (mm/rev)	0.032
Radial depth of cut (mm)	75
Axial depth of cut (mm)	0.25
Cutting speeds (m/min)	Variable

Experiments are taken place for determining appropriate cutting tool and cutting speed while machining hardened tool steels.

To obtain this purpose, the experiments are realized for each cutting tool with at least five different cutting speeds. Tool life criteria are taken according to flank wear mechanism. When mean flank wear reaches at 0.3 mm or maximum flank wear reaches at 0.6 mm it is assumed that the tool has lost its sharpness and could not work properly. Maximum cutting speed is decided according to obtain at least five-minute tool life. Then the cutting speed is reduced degree by degree until obtaining maximum twenty-five minute tool life as explained in ISO 8688-1 [42]. Experiments were repeated until reaching satisfactory results about the cutting speed range and to form the required graphics for calculating the tool life constants. Afterward with the tool lives ($T_1 - T_k$), matching the cutting speeds ($v_{c1} - v_{ck}$) tool life constants are calculated according to Taylor Equation given by Eq. 1:

$$vc \times T^n = c \qquad (1)$$

$$v_{c1} \times T_1^{\,n} = v_{c2} \times T_2^{\,n} = c$$

$$\log v_{c1} + n.\log T_1 = \log v_{c2} + n.\log T_2$$

$$n_{1,2} = (\log v_{c2} - \log v_{c1})/(\log T_1 - \log T_2)$$

$$n_{2,3} = (\log v_{c3} - \log v_{c2})/(\log T_2 - \log T_3)$$

$$\vdots$$

$$n_{k-1,k} = (\log v_{ck} - \log v_{ck-1})/(\log T_{k-1} - \log T_k)$$

$$\boldsymbol{n = (n_{1,2} + n_{2,3} + n_{3,4} + n_{4,5} + \ldots\ldots + n_{k-1,k})/k-1}$$

Then c is calculated from Eq. 1.

In the Tool and Manufacturing Handbook [43] as the application of the economic model, the tool life is given for $T = 30$ min and $T = 90$ min for the cutting tool materials. In this article, the economic cutting speed for $T = 30$ min and $T = 90$ min are calculated with the use of "n" and "c" values which are found after the experimental work from Eq. 2.

$$v_c = \frac{c}{T^n} \qquad (2)$$

$$T = 30 \rightarrow v_c = \frac{c}{30^n}$$

$$T = 90 \rightarrow v_c = \frac{c}{90^n}$$

3. Results and discussion

After the experimental work performed with seven different cutting tools, the results are evaluated in terms of surface roughness, tool life, appropriate cutting speeds and tool life constants for each tool. These results are discussed for each material.

3.1. Hardened 1.2379 cold work tool steel

While machining hardened 1.2379 cold work tool steel only PCBN gave best results. In terms of tool life, other six tools worn at the beginning of the first pass. The tool lives which are measured against different cutting speeds and the tool life constants which are calculated according to are given in Fig. 1. After the pre-experiments for this material couples, five convenient cutting speeds are chosen as can be seen in Fig. 1. The range is varying between 100 and 500 m/min. Tool life of the PCBN has decreased 50% with the increasing cutting speeds. The cutting speed that is calculated for one minute tool life "c" is 2617 m/min and tool life constant "n" is 0.986. Tool life graphics for this material couple are given in Fig. 1.

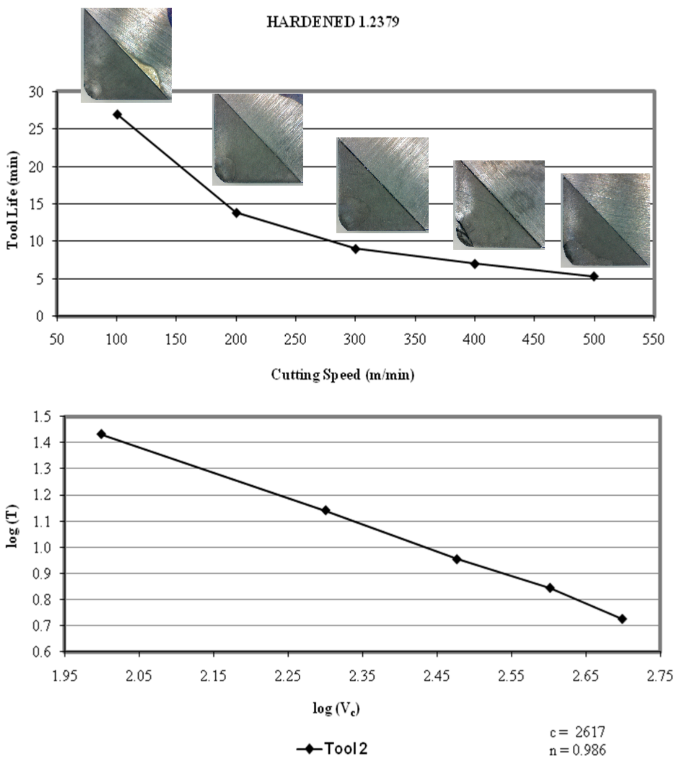


Fig. 1. Tool life vs cutting speed. (Tool 2 – PCBN for hardened 1.2379 cold-work tool steel)

3.2. Hardened 1.2080 cold work tool steel

Investigating the appropriate cutting tool for hardened 1.2080 cold work tool steel, the same results which were found for 1.2379 cold work steel have been obtained. Except PCBN, other six tools failed at the beginning of the first pass. The tool life which is measured against different cutting speeds and tool life constants which are calculated according to Eq. 1 are given in Fig. 2.

After the preliminary study, five convenient cutting speeds are determined as can be seen in Fig. 2. The cutting speed range is varying between 100 and 900 m/min. In the milling of 1.2379 cold work steel, the upper value was 500 m/min with 5.33 min tool life. Also in the milling of 1.2080, the convenient cutting speed is ascending to 900 m/min with 4 min tool life. Tool life of the PCBN has decreased dramatically with the increasing cutting speeds. Tool life of the PCBN for 100 m/min cutting speed is 32 min, whilst for 900 m/min cutting speed, tool life is only 4 min. The tool life constants, that is calculated for one-minute tool life "*c*" is 3855 m/min and "*n*" is 1.077. The tool life-cutting speed and logarithmic tool life-cutting speed graphics are given according to results that were taken from the experiments in Fig. 2.

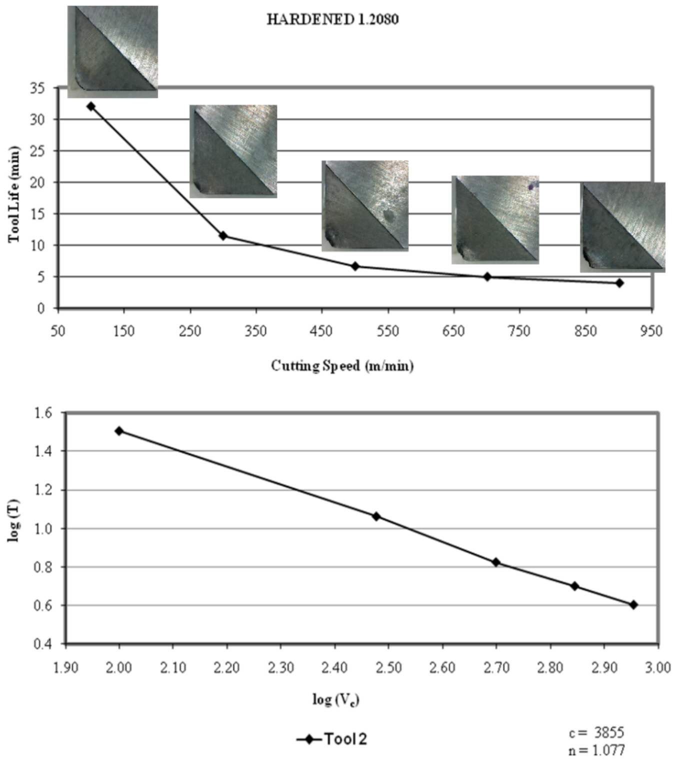
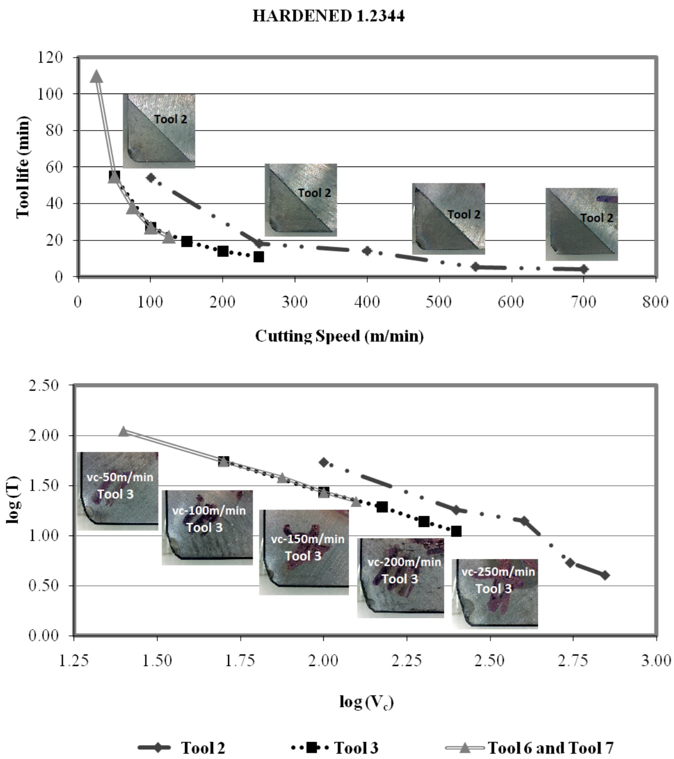


Fig. 2. Tool life vs cutting speed. (Tool 2 – PCBN for hardened 1.2080 cold-work tool steel)

3.3. Hardened 1.2344 hot work tool steel

Four different cutting tools gave satisfactory results for investigating of the appropriate cutting tool for hardened 1.2344 hot work tool steel. Other three tools failed on the first pass. The tool lives which are measured against different cutting speeds and tool life constants which are calculated for each cutting tool according to Eq. 1 are given in Fig. 3. Firstly, the cutting tool performance of PCBN is explained. After the experimental work for this material couples, five convenient cutting speeds defined between 100 and 700 m/min as can be seen in Fig. 3. In the milling of 1.2080 cold work steel, the lower value was 100 m/min with 32 min tool life. Also in the milling of 1.2344 hot work tool, steel tool life that is measured for 100 m/min cutting speed is ascending to 54 min. Tool life of PCBN has decreased dramatically with the increasing cutting speeds. Tool life of the PCBN for 100 m/min cutting speed is 54 min whilst for 700 m/min cutting speed tool life is only 4 min. The tool life constants, that is calculated for one-minute tool life "*c*" is 5154 m/min and "*n*" is 0.969. The upper value of tool life of PCBN is 13.5 times greater than the lower range while the cutting speed is only 7 times greater than the other. It is seen from the Fig. 3. that five convenient cutting speeds between 50 and 250 m/min are chosen after the experiments with CVD coated carbide. Tool life of the CVD coated carbide has decreased well-proportionally with the increasing cutting speeds. Tool life of the CVD coated carbide for 50 m/min cutting speed is 55 min whilst for 250 m/min cutting speed tool life is only 11 min.



P.S. Values of Tool 6 and Tool 7 are the same.

Fig. 3. Tool life vs cutting speed. (PCBN, CVD coated carbide, uncoated carbide and uncoated cermet for hardened 1.2344 hot-work tool steel)

The tool life constants, that is calculated for one minute tool life "*c*" is 2946 m/min and "*n*" is 1.005. Cutting tool performance of uncoated carbide has the same attitude as uncoated cermet. The experimental results from the cutting tests for this material couples, five convenient cutting speeds between 25 and 125 m/min are chosen as can be seen in Fig. 3. Tool life of the uncoated carbide and uncoated cermet has decreased well-proportionally with the increasing cutting speeds. Tool life of the uncoated carbide and uncoated cermet for 25 m/min cutting speed is 110 min whilst for 125 m/min cutting speed tool life is only 22 min. The tool life constants, that is calculated for one minute tool life "*c*" is 2923 m/min and "*n*" is 1.007. The tool life-cutting speed and logarithmic tool life-cutting speed graphics of all cutting tools appropriate for machining hardened 1.2344 hot-work tool steel are given in Fig. 3.

In the face-milling of 1.2344 hot work steel, the highest cutting speed was used with PCBN, 700 m/min of cutting speed with 4 min tool life. The highest cutting speed that was reached with PCBN is approximate 3 times greater than CVD coated carbide and 5 times greater than uncoated carbide and uncoated cermet. The highest tool life, 110 min, was obtained with uncoated carbide and uncoated cermet while machining with 50 m/min of cutting speed. The comparison made at the same speed, 100 m/min, the highest tool life was obtained with PCBN, 54 m/min while other cutting tools have the half of PCBN's tool life of 27 m/min.

3.4. Hardened 1.2738 plastic mold steel

The experimental results from the cutting tests for hardened 1.2738 plastic mold steel, two different cutting tools, PVD TiN coated ceramic and PCBN, gave useful results. Other five tools failed. The tool lives which are measured for different cutting speeds, the cutting parameters used for machining and tool life constants which are calculated according to Eq. 1 are given for each cutting tool in Fig. 4. First, the cutting tool performance of PVD TiN coated ceramic is given in Fig. 4. After the experiments, five convenient cutting speeds between 200 and 1000 m/min are defined as can be seen in Fig. 4. Tool life of PVD TiN coated ceramic cutting tool has decreased well-proportionally with the increasing cutting speeds. Tool life of this cutting tool for 200 m/min of cutting speed is 70 min, whilst for 1000 m/min of cutting speed, tool life is only 2.66 min. The tool life constants, that is calculated for one minute tool life "c" is 2204 m/min and "n" is 0.493. Five convenient cutting speeds for PCBN are defined as can be seen in Fig. 4. The range is varying between 100 and 500 m/min. Tool life of the PCBN has decreased well-proportionally with the increasing cutting speeds. Tool life of PCBN for 100 m/min of cutting speed is 108 min, whilst for 500 m/min of cutting speed, tool life is only 5.33 min. The tool life constants, that is calculated for one minute tool life "*c*" is 2250 m/min and "*n*" is 0.697. The tool life-cutting speed and logarithmic tool life-cutting speed graphics of all cutting tools are drawn according to results that were taken from the experiments and are given in Fig. 4.

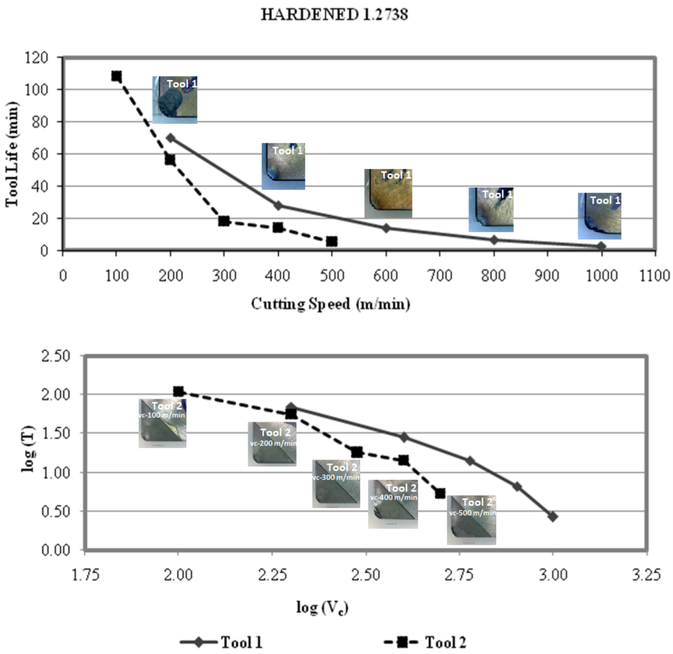


Fig. 4. Tool life vs cutting speed. (PVD TiN coated ceramic and PCBN cutting tools for hardened 1.2738 plastic-mold steel)

In the milling of 1.2738 plastic mold steel, the highest cutting speed can be used with PVD TiN coated ceramic cutting tool, 1000 m/min with 2.66 min tool life. Maximum speed used for PVD TiN coated ceramic cutting tool is approximate 2 times greater than PCBN's. The highest tool life, 108 min, was obtained with PCBN while machining at 100 m/min of cutting speed. The comparison made at the same speed, 200 m/min, the highest tool life was obtained with PVD TiN coated ceramic cutting tool, 70 min tool life while PCBN has 56 min of tool life.

3.5. Overall results

After the experimental works, which are taken with seven different cutting tools, first of all, the appropriate cutting tools for each hardened tool steel were found. Appropriate cutting tool for machining hardened cold-work tool steels, 1.2379 and 1.2080, is PCBN. While machining 1.2344 hot-work tool steel four different cutting tools can be used. These are PCBN, CVD coated carbide, uncoated carbide and uncoated cermet. Two different cutting tools, PVD TiN coated ceramic and PCBN can be used for machining of hardened 1.2738 plastic mold steel. These overall results are given in TABLE 4.

TABLE 4

Appropriate cutting tools for each hardened tool steel

Hardened 1.2379 (AISI D12) 56 HRC	Hardened 1.2080 (AISI D3) 55 HRC	Hardened 1.2344 (AISI H13) 58 HRC	Hardened 1.2738 (AISI P20) 55 HRC
• PCBN	• PCBN	• PCBN • TiN-TiCN-Al_2O_3 coated carbide • Uncoated carbide • Uncoated cermet	• PCBN • TiN coated ceramic

TABLE 5

Tool life constants

Material	Cutting Tool	Tool Life Constants						Cutting Speeds	
		Calculated		Taken from graphic		% deviation		For 30 min tool life	For 90 min tool life
		n	*c*	*n*	*c*	*n*	*c*	$v_c^{(30\ min)}$	$v_c^{(90\ min)}$
Hardened 1.2379	PCBN	0.986	2617	0.993	2636	–1	–1	91	31
Hardened 1.2080	PCBN	1.077	3855	1.056	3884	2	–1	99	30
	PCBN	0.969	5154	0.739	1964	24	62	191	66
Hardened	CVD TiN+TiCN+Al_2O_3 coated WC	1.005	2946	1.000	2747	0	7	97	32
1.2344	Uncoated WC	1.007	2923	1.000	2747	1	6	95	31
	Uncoated Cermet	1.007	2923	1.000	2747	1	6	95	31
Hardened	PVD TiN coated Ceramic Ceramic (Al_2O_3/TiCN) based Ceramic	0.493	2204	0.538	2100	–9	5	412	240
1.2738	PCBN	0.697	2250	0.538	1348	23	40	210	98

Then the calculations are held to find the tool life constants according to Eq. 3. Verifying the results, vt^n graphics are drawn with the aim of experimental data. From the graphics, another *n* and *c* constants are found and the deviations between them are calculated and are given in TABLE 5. According to these results, PCBN is not an appropraite cutting tool for high-speed face milling of hardened 1.2344 hot-work tool steel and 1.2738 plastic mold steel.

4. Conclusion

Tool life estimation is a very important matter for smart changing cutting tool systems in the unmanned digital factories. Appropriate cutting tools for high-speed face milling of hardened tool steels, for cold-work tool steels, is PCBN with the speed of 91 m/min for 1.2379 and 99 m/min for 1.2080. Uncoated carbide is an appropraite cutting tool for 1.2344 hot-work tool steel with the speed of 95 m/min. PVD TiN coated ceramic cutting tool can be used for 1.2738 plastic mold steel is with the speed of 412 m/min. This speed is extremely high speed for machining of hardened tool steels and is extremely high from the catalog value of the cutting tool.

Generally, PCBN tool gives satisfactory results in high-speed face milling of hardened cold-work tool steels for which were tested.

In the machining of hardened tool steels, uncoated carbide and cermet cutting tools are not suggested. Unexpectedly uncoated carbide and uncoated cermet gave useful results while high-speed face milling of hardened 1.2344 hot-work tool steel with lower cutting speeds such as 50 or 100 m/min. Tool life for suggested cutting speed, 50 m/min is 55 min. and cutting speed for one minute tool life is 2923 m/min. Another interesting result is usage of uncoated carbide and cermet cutting tools for 1.2344 hot-work tool steel. These tools gave same results as CVD coated carbide while machining of 1.2344 hot-work tool steel. Tool life with both coated and uncoated cutting tool is 27 min for 100 m/min of cutting speed. According to this result for a lower price, uncoated cutting tools are more useful than the coated carbide while high-speed face milling of hardened 1.2344 hot-work tool steel. The suggested cutting tool for machining of hardened tool steels, PCBN gave lower tool life values than expected. Tool life with PCBN cutting tool is 54 min for 100 m/min of cutting speed, while tool life for both coated and uncoated carbide is 27 min. Comparing the price of PCBN and uncoated cutting tool, the price of PCBN cutting tool is 10 times greater than the price of uncoated cermet and carbide cutting tools. Also, tool life of PCBN cutting tool is 2 times greater than the tool lives of uncoated cutting tools. Looking at the price-tool life equilibrium uncoated carbide and cermet cutting tools are more convenient than the PCBN and coated carbide cutting tools.

In contrast to the workpiece hardness, the hardest tool steel, 1.2344 hot work tool steel, could be machined with a larger number of cutting tool materials. It is thought to be related to the chemical composition given in TABLE 1. The hardened material 1.2344 has the largest Si %. It is seen that % Si has a positive contribution to machinability in the milling of hardened tool steels.

In general 1.2738 plastic mold steels has the best machinability among this materials. In milling operations ceramic cutting tools is not preferred because of its brittleness in intermittent stock removal. In high speeds operations, as intermittent stock removal at high speeds approaches continuity, ceramic cutting tool gave good results.

Funding

This work was supported by the State Planning Organization (Turkish: Devlet Planlama Teşkilatı, DPT) with the grant number DPT 2003K 120770-3.

REFERENCES

[1] F.W. Taylor, On the art of cutting metals. ASME Publication, (1907).

[2] R.C. Dewes, D.K. Aspinwall, A review of high-speed milling of hardened steels. Journal of Materials Processing Technology **69**, 1-17 (1997).
DOI: https://doi.org/10.1016/S0924-0136(96)00042-8

[3] P. Fallböhmer, C.A. Rodríguez, T. Özel, T. Altan, High-speed machining of cast iron and alloy steels for die and mold manufacturing. Journal of Materials Processing Technology **98**, 104-115 (2000).
DOI: https://doi.org/10.1016/S0924-0136(99)00311-8

[4] P. Fallböhmer, T. Altan, H.K. Tönshoff, T. Nakagawa, Survey of the die and mold manufacturing industry. Journal of Materials Processing Technology **59**, 158-168 (1996).
DOI: https://doi.org/10.1016/0924-0136(96)02297-2

[5] P. Koshy, R.C. Dewes, D.K. Aspinwall, High-speed end milling of hardened AISI D2 tool steel (~58 HRC). Journal of Materials Processing Technology **127**, 266-273 (2002).
DOI: https://doi.org/10.1016/S0924-0136(02)00155-3

[6] H. Coldwell, R. Woods, M. Paul, P. Koshy, R. Dewes, D. Aspinwall, Rapid machining of hardened AISI H13 and D2 moulds, dies and press tools. Journal of Materials Processing Technology **135**, 301-311 (2003).
DOI: https://doi.org/10.1016/S0924-0136(02)00861-0

[7] V.N. Gaitonde, S.R. Karnik, C.H.A. Maciel, J.C.C. Rubio, A.M. Abrão, Machinability Evaluation in Hard Milling of AISI D2 Steel. Materials Research **19** (2), 360-369 (2016).
DOI: https://doi.org/10.1590/1980-5373-MR-2015-0263

[8] J.A. Arsecularatne, L.C. Zhang, C. Montross, P. Mathew, On machining of hardened AISI D2 steel with PCBN tools. Journal of Materials Processing Technology **171**, 244-252 (2006).
DOI: https://doi.org/10.1016/j.jmatprotec.2005.06.079

[9] J.B. Saedon, S.L. Soo, D.K. Aspinwall, A. Barnacle, N.H. Saad, Prediction and Optimization of Tool Life in Micromilling AISI D2 (~62 HRC) Hardened Steel. Procedia Engineering **41**, 674-1683 (2012).
DOI: https://doi.org/10.1016/j.proeng.2012.07.367

[10] C. Wang, Y. Xie, L. Zheng, Z. Qin, D. Tang, Y. Song, Research on the Chip Formation Mechanism during the high-speed milling of hardened steel. International Journal of Machine Tools & Manufacture **79**, 31-48 (2014).
DOI: https://doi.org/10.1016/j.ijmachtools.2014.01.002

[11] S. Wojciechowski, P. Twardowski, The influence of tool wear on the vibrations during ball end milling of hardened steel. Procedia CIRP **14**, 587-592 (2014).
DOI: https://doi.org/10.1016/j.procir.2014.03.108

[12] S. Wojciechowski, P. Twardowski, Tool life and process dynamics in high-speed ball end milling of hardened steel. Procedia CIRP **1**, 289-294 (2012).

[13] C.Y. Wang, Y.X. Xie, Z. Qin, H.S. Lin, Y.H. Yuan, Q.M. Wang, Wear and breakage of TiAlN and TiSiN coated carbide tools during high-speed milling of hardened steel. Wear **336-337**, 29-42 (2015).
DOI: https://doi.org/10.1016/j.wear.2015.04.018

[14] M.M. Aguiar, A.E. Diniz, R. Pederiva, Correlating surface roughness, tool wear and tool vibration in the milling process of hardened steel using long slender tools. International Journal of Machine Tools & Manufacture **68**, 1-10 (2013).
DOI: https://doi.org/10.1016/j.ijmachtools.2013.01.002

[15] J.P. Urbanski, P. Koshy, R.C. Dewes, D.K. Aspinwall, High-speed machining of moulds and dies for net shape manufacture. Materials & Design **21** (4), 395-402 (2000).
DOI: https://doi.org/10.1016/S0261-3069(99)00092-8

[16] A. Çiçek, F. Kara, T. Kivak, E. Ekici, Evaluation of machinability of hardened and cryo-treated AISI H13 hot work tool steel with ceramic inserts. Int. Journal of Refractory Metals and Hard Materials **41**, 461-469 (2013).
DOI: https://doi.org/10.1016/j.ijrmhm.2013.06.004

[17] S. Ravi, M.P. Kumar, Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel. Cryogenics **51**, 509-515 (2011).
DOI: https://doi.org/10.1016/j.cryogenics.2011.06.006

[18] M.N. Durakbasa, A. Akdogan, A.S. Vanli, A.G. Bulutsuz, Optimization of end milling parameters and determination of the effects of edge profile for high surface quality of AISI H13 steel by using precise and fast measurements. Measurement **68**, 92-99 (2015).
DOI: https://doi.org/10.1016/j.measurement.2015.02.042

[19] J.L. Endrino, G.S. Fox-Rabinovich, R. Escobar Galindo, W. Kalss, S. Veldhuis, L. Soriano, J. Andersson, A. Gutiérrez, Oxidation post-treatment of hard AlTiN coating for machining of hardened steels. Surface & Coatings Technology **204**, 256-262 (2009).
DOI: https://doi.org/10.1016/j.surfcoat.2009.07.010

[20] X. Cui, D. Wang, J. Guo, Performance optimization for cemented carbide tool in high-speed milling of hardened steel with initial microstructure considered. International Journal of Mechanical Sciences **114**, 52-59 (2016).
DOI: https://doi.org/10.1016/j.ijmecsci.2016.05.017

[21] B.D. Beake, L. Ning, C. Gey, S.C. Veldhuis, A. Komarov, A. Weaver, M. Khanna, G.S. Fox-Rabinovich, Wear performance of different PVD coatings during hard wet end milling of H13 tool steel. Surface & Coatings Technology **279**, 118-125 (2015).
DOI: https://doi.org/10.1016/j.surfcoat.2015.08.038

[22] D. Begic-Hajdarevic, A. Cekic, M. Kulenovic, Experimental Study on the High-Speed Machining of Hardened Steel. Procedia Engineering **69**, 291-295 (2014).
DOI: https://doi.org/10.1016/j.proeng.2014.02.234

[23] Z. Pu, A. Singh, High-speed ball nose end milling of hardened AISI A2 tool steel with PCBN and coated carbide tools. Journal of Manufacturing Processes **15**, 467-473 (2013).
DOI: https://doi.org/10.1016/j.jmapro.2013.05.005

[24] L. Lu, Q.M. Wang, B.Z. Chen, Y.C. Ao, D.H. Yu, C.Y. Wang, S.H. Wu, K.H. Kim, Microstructure and cutting performance of CrTiAlN coating for high-speed dry milling. Trans. Nonferrous Met. Soc. China **24**, 1800-1806 (2014).
DOI: https://doi.org/10.1016/S1003-6326(14)63256-8

[25] E. Aslan, Experimental investigation of cutting tool performance in high-speed cutting of hardened X210Cr12 cold work tool steel (62 HRC). Materials and Design **26**, 21-27 (2005).
DOI: https://doi.org/10.1016/j.matdes.2004.04.004

[26] N. Camuşcu, E. Aslan, A comparative study on cutting tool performance in end milling of AISI D3 tool steel. Journal of Materials Processing Technology **170**, 121-126 (2005).
DOI: https://doi.org/10.1016/j.jmatprotec.2005.04.111

[27] E. Aslan, N. Camuşcu, High-speed end milling of hardened AISI D3 cold-work tool steel with CBN cutting tool. G.U. Journal of Science **18** (3), 453-458 (2005).

[28] S. Chinchanikar, S.K. Choudhury, Machining of hardened steel – Experimental investigations, performance modeling and cooling techniques: A review. International Journal of Machine Tools & Manufacture **89**, 95-109 (2015).
DOI: https://doi.org/10.1016/j.ijmachtools.2014.11.002

[29] S. Dolinsek, B. Sustarsic, J. Kopac, Wear mechanisms of cutting tools in high-speed cutting of processes. Wear **250**, 349-356 (2001).
DOI: https://doi.org/10.1016/S0043-1648(01)00620-2

[30] R.C. Dewes, E. Ng, K.S. Chua, P.G. Newton, D.K. Aspinwall, Temperature measurement when high-speed machining hardened moulds/dies steel. Journal of Materials Processing Technology **92-93**, 293-301 (1999).
DOI: https://doi.org/10.1016/S0924-0136(99)00116-8

[31] Y. Ning, M. Rahman, Y.S. Wong, Investigation of chip formation in high-speed end milling. Journal of Materials Processing Technology **113**, 360-367 (2001).
DOI: https://doi.org/10.1016/S0924-0136(01)00628-8

[32] M.C. Kang, I.W. Park, K.H. Kim, Performance evaluation of AlP-TiAlN coated tool for high-speed machining. Surface and Coatings Technology **163-164**, 734-738 (2003).
DOI: https://doi.org/10.1016/S0257-8972(02)00696-5

[33] C.E. Becze, P. Clayton, L. Chen, T.I. El-Wardany, M.A. Elbestawi, High-speed five-axis milling of hardened tool steel. International Journal of Machine Tools and Manufacture **40** (6), 869-885 (2000).
DOI: https://doi.org/10.1016/S0890-6955(99)00092-9

[34] C. Vila, H.R. Siller, C.A. Rodriguez, G.M. Bruscas, J. Serrano, Economical and technological study of surface grinding versus face milling in hardened AISI D3 steel machining operations. Int. J. Production Economics **138**, 273-283 (2012).
DOI: https://doi.org/10.1016/j.ijpe.2012.03.028

[35] H. Calıskan, C. Kurbanoglu, P. Panjan, M. Cekada, D. Kramar, Wear behavior and cutting performance of nanostructured hard coatings on cemented carbide cutting tools in hard milling. Tribology International **62**, 215-222 (2013).
DOI: https://doi.org/10.1016/j.triboint.2013.02.035

[36] Q. Niu, Q. An, M. Chen, W. Ming, Wear Mechanisms and Performance of Coated Inserts During Face Milling Of TC11 And TC17 Alloys. Machining Science and Technology **17**, 483-495 (2013).
DOI: https://doi.org/10.1080/10910344.2013.806184

[37] A. Li, J. Zhao, Y. Dong,D. Wang, X. Chen, Surface Integrity of High-Speed Face Milled Ti-6Al-4V Alloy With Pcd Tools. Machining Science and Technology **17**, 464-482 (2013).
DOI: https://doi.org/10.1080/10910344.2013.806180

[38] L.C. Silva, P.R. Mota, M.B. Silva, E.O. Ezugwu, A.R. Machado, Study of burr behavior in face milling of PH 13-8 Mo stainless steel. CIRP Journal of Manufacturing Science and Technology **8**, 34-42 (2015). DOI: https://doi.org/10.1016/j.cirpj.2014.10.003

[39] Z.Q. Liu, X. Ai, H. Zhang, Z.T. Wang, Y. Wan,Wear patterns and mechanisms of cutting tools in high-speed face milling. Journal of Materials Processing Technology **129**, 222-226 (2002).
DOI: https://doi.org/10.1016/S0924-0136(02)00605-2

[40] S. Shankar, T. Mohanrajand R. Rajasekar, Prediction of cutting tool wear during milling process using artificial intelligence techniques. International Journal Of Computer Integrated Manufacturing **32**, 2, 174-182(2019).
DOI: https://doi.org/10.1080/0951192X.2018.1550681

[41] B. C. Kar, A. Panda, R. Kumar, A. K. Sahoo, R. R. Mishra, Research trends in high speed milling of metal alloys: A short review. Materials Today: Proceedings **26**, part 2, 2657-2662 (2020).
DOI: https://doi.org/10.3390/ma15207261

[42] ISO 8688-1, Tool life testing in milling- Part 1: Face milling, 1989.

[42] Tool and Manufacture Engineering Handbook 1, Machining, 1-61.