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Experimental research of flank wear process of carbide cutting inserts during hard milling of Armox 500 steel

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Abstract:

The authors' article deals with the research or implementation of long-term testing of the process of wear of the flank surface of indexable carbide cutting inserts with PVD coating. The mentioned wear process is realized through the technological process of milling high-strength steel Armox 500. The material Armox 500 is used in practice in the special engineering industry and in the production of external ballistic protection of combat vehicles. In practice, there is a demand for ever higher parameters, such as increased mechanical properties of such steels. This increases the ballistic resistance of Armox armor sheets, which in practice presents new problems associated with mechanical processing to the desired state. Therefore, the authors' research for this reason is focused on monitoring the technological milling process of Armox 500 steel in terms of the wear process, which is important for the achieved dimensional accuracy and quality of machined surfaces. The face milling experiment was performed on a FA3V vertical milling machine with SNHF 1204EN-SR-M1 geometry cutting inserts with tool material type 8230 (P30) from DormerPramet. The cutting inserts were clamped in a 50 mm diameter Narex face milling cutter. The experiment consisted of monitoring the process of wear of the flank surface VB with the set criterion of flank wear VB = 0.2 mm.

1 Introduction

Steel armor is used for its ability to withstand more impacts in a small area. Hardness of 400 to 450 HBW are mainly used for vehicle chassis that are prone to explosions from mines and improvised explosive devices. Armor with a hardness of around 400 HBW is hard and tough at the same time and can therefore withstand an immediate explosion. Armor with a hardness of over 500 HBW is used as a base material for construction because it has high hardness and ballistic resistance and can be processed relatively well. Armor with a hardness of over 600 HBW has the best ballistic properties, but due to their high hardness they cannot be bent. They are used for additional cladding of places prone to impact.

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Armox type armor steels are characterized by high density in combination with excellent mechanical properties, e. g. ultra-high strength and high hardness thus the ability to resist penetration against fired projectiles [1]. Under these circumstances, said high-strength steels experience large plastic deformations of the order of 10^2 to 10^3 s^{-1} and the deformation process is affected by the effects of strain hardening and thermal softening. [2].
The authors [3, 4, 11] used a wide range of machined and cutting materials to investigate the face milling process. In this paper, the mathematical least squares method was used as an experimental method, as well as the use of SEM (Scanning Electron Microscopy). Direct heat generation at the tool-machined material interface has a significant effect on dimensional changes due to thermal deformation in the machining process or a surface defect caused by oxidation, as reported in the literature [5]. During the performed experiments, several machining parameters were entered. It can be said that Armox was machined using cemented carbide cutting inserts and PVD coated. The research was performed to analyze the performance in terms of cutting conditions, wear on the flank surface and tool life in order to evaluate the efficiency of used cemented carbide cutting inserts. This was recorded and documented using a Tescan Vega TS 5135 SEM microscope. The same observation, which was made by Pokorný et al. [6], An et al. [7] and Li et al. [8], reported experimental studies and researches of the technological process of hard milling of high-strength steels using cemented carbide cutting inserts. All the following articles were devoted to the investigated surface integrity factor including all investigated characteristics [7, 8]. Gopalsamy et al. [9] reported an investigation into the hard machining of hard tool steels. Experiments were performed to analyze the performance of cutting conditions existing in hard milling technology with respect to material removal rate (MRR), wear, tool life and surface quality to determine the effectiveness of the sintered carbide cutting inserts used for the milling used cutters. The results were confirmed by SEM microscopy. Cui et al. [10] published research on the mechanisms of the flank wear process in particular and confirming that with increased cutting speed, the effect of oxidative wear on the side becomes more pronounced, while the effect of adhesive wear is subsequently reduced. All these studies investigate the possibility of machinability and the achieved results visibly improve the face milling process.

2 Experimental details

2.1 Basic Information

The chemical composition and mechanical properties of tested Armox steel, which is determined by the supplier Winfa Ltd., was realized in the CEDITEK (Center of diagnostics and testing of materials) Laboratories.

2.2 Additional Information

The authors of the article used Armox 500 armor plate as a test material in the process of experiments. It is an armor made in Sweden and is used in practice as a ballistic protection of the outer parts of combat vehicles and weapon systems. The authors of the article also performed their own measurement of chemical composition by the method of spectral analysis of chemical elements on the Spectrolab JrCCD device in the laboratory of spectral analysis at the Faculty of Special Technology TnUAD in Trencin. The measured percentage results of the content of chemical elements in Armox 500 steel can be seen in Table 1. Results of chemical composition was obtained by spectral analysis method measured in the Spectrolab JrCCD measuring device. The hardness of the experimental material was also measured in the laboratory of mechanical tests at the Faculty of Special Technology by the Rockwell method. The resulting hardness of the base material reached the value HRC = 48 ÷ 52. The summary results of the chemical composition and measured mechanical properties of the tested steel Armox 500 can be seen in Table 1 as was mentioned above.

Table 1 Chemical composition and mechanical properties of high-strength steel Armox 500 where: Mn, Cr, Ni, Mo, B - alloying elements C, Si, P, S - admixtures (accompanying elements)

Chemical composition [wt. %]	C	Si	Mn	P	S	Cr	Ni	Mo	B
	0.27	0.23	1.10	0.014	0.009	0,81	1,58	0.7	0.004
Mechanical properties	Tensile strength R_m [MPa]		Limit of proportionality $R_{p0.2}$ [MPa]			Toughness KU [J]	Hardness [HBW]		Elongation A_5 [%]
	1638		1422			25	516		9

From a microstructural point of view, Armox 500 is a structural medium-alloyed high-strength steel (with a higher Ni content), which has a fine-grained martensitic structure obtained by low-temperature tempering. In Fig. 1, a hard, low-tempered martensitic structure is observable with some small amount of retained austenite expected. From the microstructure it is also possible to observe the occurrence of carbides (small white polygonal-shaped particles) as a product of the transformation of tetragonal martensite (dark color) to cubic tempered martensite (dark color) during tempering.

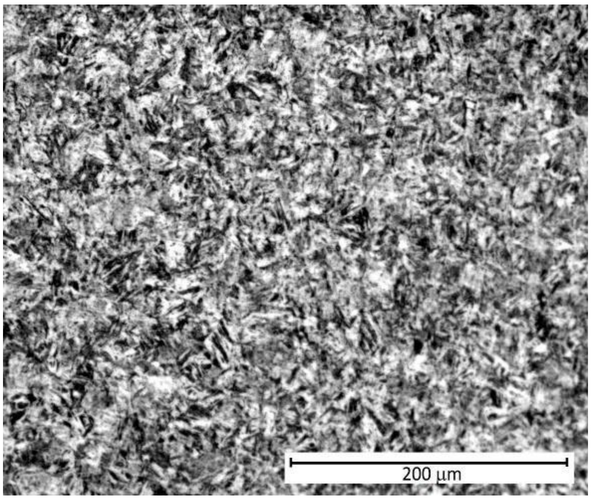

Fig. 1 Microstructure of Armox 500 steel base material obtained by light microscopy

2.3 Experimental methods

The authors of the article in their experiment focused on the so-called long-term testing of carbide interchangeable cutting inserts of SNHF 1204EN-SR-M1 geometry (see in Fig. 2) with cemented carbide type 8230 from DORMERPRAMET Ltd. (type P30 according to ISO standard) with PVD coating TiAlCN + TiN. Changeable cutting inserts were mechanically clamped in a NAREX type face milling cutter (see in Fig. 4) with a diameter of Ø50 mm with the designation PN222460.12 according to the ISO standard and with the number of teeth $z = 4$. The inserts were supplied with the following cutting edge geometry: cutting edge setting angle $\chi_r = 75^o$; orthogonal rake angle $\gamma_o = -7^o$; cutting edge inclination angle $\lambda_S = -4^o$; and with clearance angle $\alpha = 7^o$. The experiment was carried out on a machine tool of the FA3V type using two pieces of machine vices for clamping 2 pieces of Armox 500 armor sheets with thicknesses of 2x 20 mm and a height of 160 mm, as can be seen in Fig. 3. To determine the dependence of tool life as a function of cutting speed $T = f(v_c)$ in face milling process of Armox 500 armor sheet, the authors followed the principles valid for long-term tool life test depending on cutting speed according to ISO 3685. The prepared material has dimensions 20 x 160 x 500 mm. The face milling method was proposed by the authors using the face milling method, which satisfies the condition that the milling width $a_e = B$ is (0.6 to 0.8). *D*. The dependence $T = f(v_c)$ was monitored at the following constant cutting parameters: depth of cut $a_p = 2$ mm; width of cut $a_e = B = 40$ mm; feed per tooth $f_z = 0.056$ mm; at the specified wear criterion valid for high-strength materials $VB_K = 0.2$ mm. The face milling process was carried out without the use of cutting or cooling medium.

Fig. 2 Geometry of tested cutting inserts used in the face milling process

Fig. 3 A look at the method of clamping 2 pieces of ARMOX 500 sheets, using two machine vices on a FA 3V machine tool

To determine the graphical dependence of tool life $T = f(v_c)$, the authors will monitor the impact of cutting speeds in the process of research, as follows:

$v_{c1} = 55.7$ m.min^{-1} at $n_1 = 355$ min^{-1}
$v_{f1} = 80$ mm.min-1
$v_{c2} = 78.5$ m.min-1 at $n_2 = 500$ min^{-1}
$v_{f2} = 112$ mm.min^{-1}
$v_{c3} = 111$ m.min-1 at $n_3 = 710$ min^{-1}

v_{f3} = 160 mm.min^{-1}

Ensures a constant feed rate per tooth is f_z = 0.056 mm, feed per revolution f_o = 0.224 mm at number of teeth of the milling cutter is z = 4. Each experiment was performed twice by the authors of the article at the same cutting parameters and after rotating the cutting inserts in the milling cutter, which meets the recommendations of the literature [3].

The results of flank wear and achieved tool life were recorded by the authors in the table and in graphical form (see in Fig. 8) *VB* = f (time). It was clean at the stated cutting parameters machine time of face milling as follows:

$$t_{AS1} = \frac{1+1_v}{f_z.zn} = \frac{505}{0{,}0563.4.355} = 6.31\text{min}$$

$$t_{AS2} = \frac{1+1_v}{f_z.zn} = \frac{505}{0{,}0563.4.500} = 4.48\text{min}$$

$$t_{AS2} = \frac{1+1_v}{f_z.zn} = \frac{505}{0{,}0563.4.710} = 3.15\text{min}$$

Fig. 4 View of the face milling process at a cutting speed v_c = 111 m.min^{-1} (machine spindle speed n = 710 min^{-1}), depth of cut a_p = 2 mm, and feed rate per tooth f_z = 0.056 mm

The circumferential throw of the clamped cutting inserts in the face milling cutter was measured by the authors indicator watch and the maximum throw was 0.02 to 0.03 mm. Measurement wear of the cutting inserts was continuously ensured with a Brinel magnifying glass with magnification 10x, after removing the milling cutter from the machine tool and inserting it into the rotary clamp. Subsequently, the flank wear of the most extended cutting insert, which was marked for this reason. The cutting insert that was extended by 0.02 to 0.03 mm at circuit to other cutting inserts also had maximum wear VB_{max} and after exceeding VB_K = 0.2 mm, this carbide cutting insert was also cut at the spindle speed of the machine n = 710 min^{-1}, as evidenced by the departure of glowing chips (as can be seen in Fig. 4). The resulting wear of the flank surface of the tested cutting inserts was observed by means of a scanning electron microscope (see in Fig. 5) of the Tescan VEGA 5135 type with X-Ray microanalyzer Noran Six / 300.

Fig. 5 View of a scanning electron microscope type Tescan VEGA 5135 with X-Ray microanalyzer Noran Six / 300, which was used in the experimental process to monitor the final wear of tested cutting plates type SNHF1204ENSR-M during face milling process of Armox 500 steel

3 Results and discussion

Long-term tool life testing of cemented carbide cutting inserts during machining with a defined cutting edge geometry is defined by the international standard ISO3685-E-77-05-15. Tool life values are derived from the characteristic wear curves of the tested cutting inserts for a given wear criterion on the flank surface *VB*, or for the rake face of the cutting insert according to the *KT* criterion (groove depth on the face). It is recommended to perform the long-term testing process from three to five times. The long-term test is repeated using one variable two to four times. Then the credibility of the achieved results is statistically guaranteed and correctly determined. The tool wear criterion VB_k = 0.6 mm is for roughing operations or VB_k = 0.3 mm for finishing the machining method. When machining high-strength materials, it is necessary to determine the VB_k criterion for at least half values. The results of the tool wear of the flank surface of the tested carbide cutting inserts and the achieved tool life of the cutting tool are given in Tab. 2 and in the resulting graph (shown in Fig. 8), according to a predetermined criterion *VB* = f (time).

Table 2 Measured values to determine the durability of the tested cutting tool T (min) with the values of the logarithm v_{ci} (m • min $^{-1}$) and Ti (min)

N	v_{ci}	T_i	log T_i	log v_i	log T_i. log v_i	$\log^2 v_i$
1	55,7	166	2,22011	1,74586	3,87600	3,04803
2	78,5	93	1,96848	1,89487	3,73001	3,59053
3	111	29	1,46240	2,04532	2,99678	4,1993
1	55,7	185	2,26717	1,74586	3,95816	3,04803
2	78,5	113	2,05308	1,89487	3,89032	3,59053
3	111	30,5	1,48430	2,04532	3,04165	4,1993
Σ	-	-	11,455	11,3721	21,4930	21,6757

Note: where N is the number of measurements (individual selected cutting speeds)

$\sum \log^2 v_{ci} = 21.6757$

$(\sum \log v_{ci})^2 = (11.3721)^2 = 129.325$

Substituting the appropriate values from Tab. 2 into the equation for (*m*) we get the following form:

$$m = \frac{N.(\sum \log T_i . \log v_i) - \sum \log T_i . \sum \log v_i}{N. \sum \log^2 v_{ci} - (\sum \log v_{ci})^2}$$

$$= \frac{6.(11{,}455.11{,}3721) - 11{,}455.11{,}3721}{6.21{,}6757 - (11{,}3721)^2} = -1{,}7956 = -b$$

Determine the constant C_T by substituting the calculated value for the exponent m into equation (26) and obtain the following form:

$$\log C_T = \frac{\sum \log T_i + m. \sum \log v_i}{N}$$

$$= \frac{11{,}455 + 1{,}7956.11{,}3721}{6} = 5{,}3126$$

Then

$$C_T = 10^{\log C_T} = 10^{5{,}3126} = 205400 = 2{,}05.10^5$$

The resulting dependence T = f (v_c), obtained from the graphs and processed by the least squares method, is in Fig. 9, in a logarithmic coordinate system. Final shape for calculating cutting life edges depending on the cutting speed for face milling of high-strength Armox material 500 has the following final shape:

$m = 1.7956 = \text{tg}\ \alpha$

$\alpha = \text{arctg}\ 1.7956 = 60.88^{\circ} = 60^{\circ}\ 53'$

$$T = \frac{C_T}{v_c^m} = \frac{2{,}05.10^5}{v_c^{1{,}7956}}$$

After performing long-term tests on Armox 500 face milling, the appearance of the back surface of the worn cutting inserts is shown in Fig. 6a, b and in Fig. 7a.b obtained by observation on an SEM microscope of Tescan Vega.

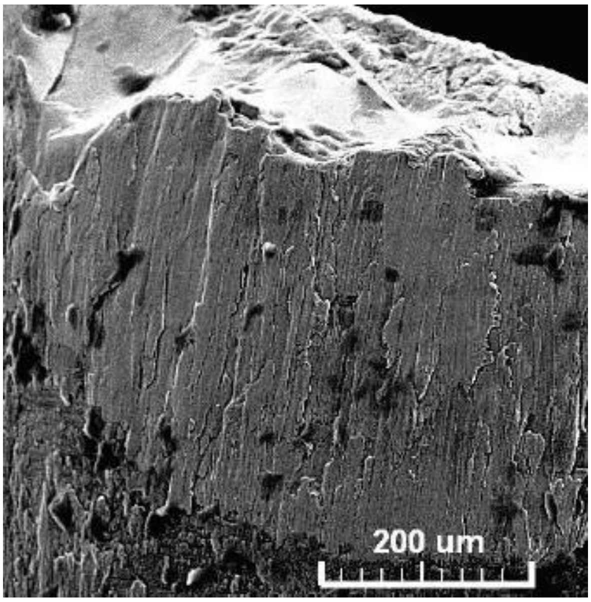

Fig. 6a SEM display of VB wear (250 ×), cutting speed v_c = 55.7 m • min $^{-1}$

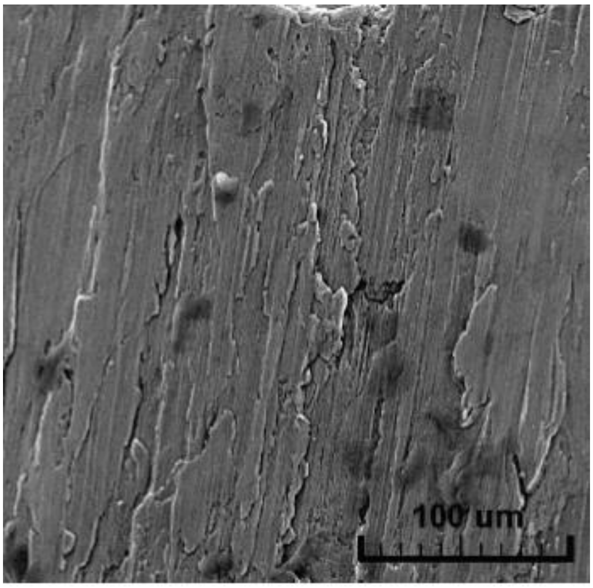

Fig. 6b SEM display of VB wear (500 ×), cutting speed v_c = 55.7 m • min $^{-1}$

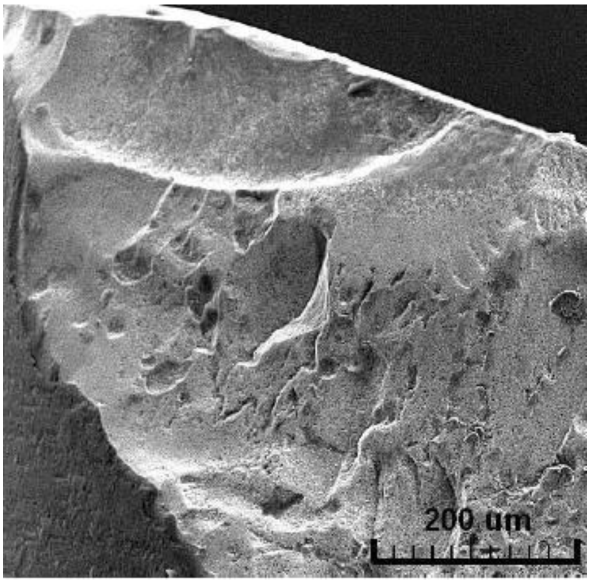

Fig. 7a SEM display of VB wear (250 ×), cutting speed v_c = 78.5 m • min^{-1}

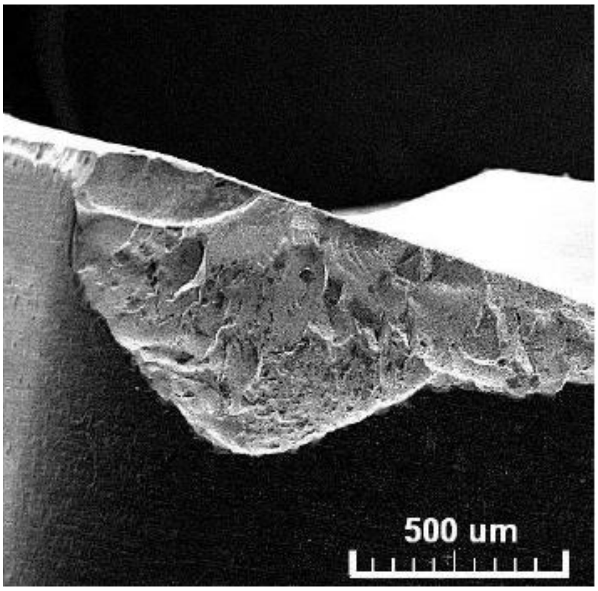

Fig. 7b SEM display of VB wear (100 ×), cutting speed v_c = 78.5 m • min^{-1}

4 Conclusion

Implemented long-term tests of face milling of high-strength steel ARMOX 500 with milling cutter of type NAREX Ø50 mm PN222460.12; with number of teeth $z = 4$; $\chi_r = 75^o$; $\gamma_o = -7^o$; $\lambda_S = -4^o$; $\alpha = 7^o$; MK -50 and using carbide cutting inserts type 8230 (P30) and geometry SNHF 1204EN-SR-M1 at depth of cut $a_p = 2$ mm, and milling width of cut $a_e = 40$ mm showed that hard face milling can be realized even with increased cutting parameters in the range of cutting speeds v_c = 55.7; 78.5 to 111 m.min^{-1} with the specified wear criterion VB_K = 0.2 mm. Experimental tests of hard face milling of high-strength steel Armox 500 showed lower values of achieved tool life at the value of reported values of cutting speeds in the range v_c = 55.7 to 111 m.min^{-1}. Throwing of face milling teeth was ensured in both cases in the range 0.015 ÷ 0.02 mm. A throw value of 0.05 mm is no longer permitted. Experimental tests of hard face milling of Armox 500 armor plates with a milling cutter with interchangeable inserts have also shown that the use of emulsion cooling is not necessary. Due to the higher hardness of Armox 500 high-strength steel, for example, compared to the abrasion-resistant Hardox 500 material with the same DORMERPRAMET type 8230 cutting material, tool life at the same cutting speeds was 18 to 38% lower, on average 28%.

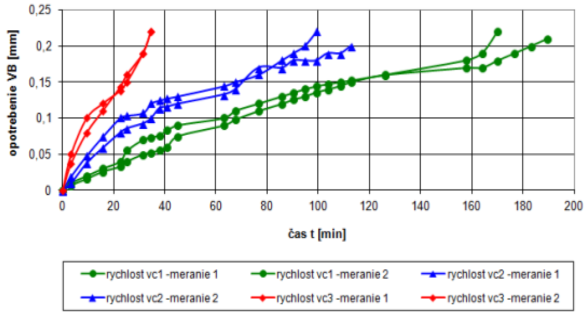

Fig. 8 Graphical dependence of the wear course on time for milling high-strength steel ARMOX 500 with interchangeable inserts type SNHF 1204ENSR-M1: 8230 from DORMERPRAMET to determine the dependence T = f (vc)

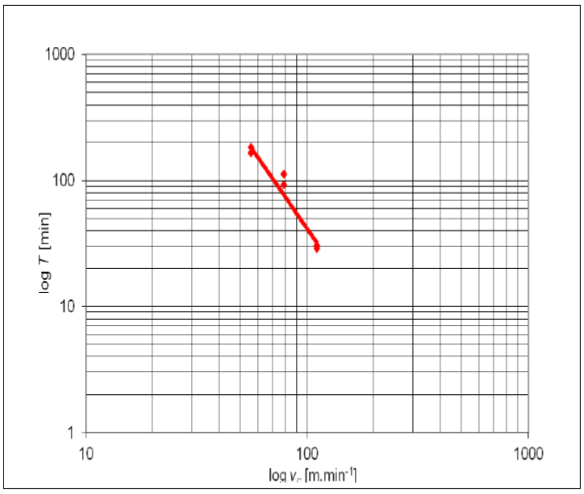

Fig. 9 Dependence T = f (vc) obtained during milling of ARMOX 500 high-strength steel

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