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RESEARCH

Influence of Workpiece Hardness on Tool Wear in Profile Micro-milling of Hardened Tool Steel

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A B S T R A C T

Machining of engineering metallic materials on micro-level is very complicated. Micro-milling with solid tools, as one of microengineering technologies, is an acceptable process to machining of complex metallic micro-parts. The main problem in micro-milling is sensitivity of cutting tool, due its suppleness and short tool life, and its influences to workpiece accuracy and quality. In this paper is experimentally investigated tool wear of micro-milling tool. During machining tests, influence of workpiece hardness and process parameters is evaluated. Workpiece was cold work alloyed tool steel X155CrVMo12, hardened to different hardness 45, 54 and 63 HRc. Cutting tool was carbide ball-end micro-mill with TiAlN coating, and diameter of 0.6 mm. For different combination of input parameters, tool wear curves is presented, and signification of input parameters on tool wear is evaluated and discussed.

1. INTRODUCTION

Nowadays, production technologies such as cutting, deforming, casting and alternative processes are employed partially in production of micro-parts and components. According to the definition, micro-machining is a production process which allows the production of parts with at least two dimensions, measured in the two perpendicular directional directions, that less than 1000 μm [1]. These production technologies are grouped together in, so called, microengineering technologies (MET). Also, in addition to this group, there are group of micro-system technologies (MST) that oriented to production of micro-electro-mechanical system components (MEMS). Both mentioned groups are unified under micro-technologies [2]. In addition to these processing technologies, in micro-parts production process are included many others systems, such as special tool machine, special tools and fixtures, assembling systems, manipulation systems, measuring and control systems, etc. The intense development of automotive industry, aerospace industry, space industry, medicine and energy has conditioned the need for the production of parts with relatively small dimensions. Mentioned micro-parts must be functionally and constructively optimized, with high quality, accuracy, and reliability. In these systems, there is a wide range of different construction materials.

A special problem in these technologies is the machining of the micro-parts with complex geometry, and made of hard-to-machining materials. These problems are encountered in machining of functional parts and mould tools and die, made of high-alloyed hardened tool steels. In industry practice, common technologies in machining of mentioned materials are laser beam machining (LBM) and electro-discharge machining (EDM) [3]. The main disadvantage of LBM is the impossibility of efficient three-dimensional machining due to the inability to control of beam penetration. Also, generated heat can damage the machined surface. The main disadvantage of EDM is lack of machined surface quality. EDM is very technology with very low production rate.

Acceptable solution is use of micro-milling as mechanical solid tool based technology [4]. Due to tool machine kinematics, it enables three-dimensional machining, with relatively high production rate. Main disadvantage of micro-milling is sensitivity of cutting tool, especially in milling of hardened steels. Materials of this type occupy a large percentage in the total sum of construction materials (Fig. 1).

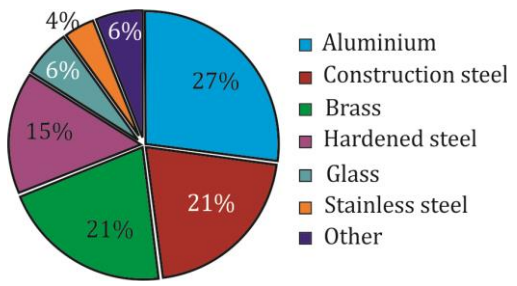

Fig. 1. Percentages of materials in micro-milling [4].

The sensitivity of micro-milling tools is reflected through low tool life and the presence of large tool deflections. Mentioned disadvantage of micro-milling process directly influences to accuracy and quality of micro-parts. The high hardness of the workpiece material leads to intensive tool wear, and thus the increase in machining inaccuracies and machining costs.

1.1 Previous researches

The aim of this paper is to characterisation and investigation the influence of workpiece material hardness and process parameter on the tool wear. In next, are given and analysed some research by other researcher.

Experimental investigations of alloyed steel micromilling were performed by Tansel et al. [5]. Analysis of the results comes to conclusions about the relationship of increasing resistance to cutting, wear and roughness by influence of cutting parameters. Bissacco et al. [6,7] analysed micromilling of powder mould steel with 54 HRc hardness. They evaluated influence of cutting parameters, machining condition, and size effect on the output process parameters. Armachareon and Mativenga [8] concluded that the tool is the most sensitive element of the machining system in micromilling of AISI H13, hardened to 45 HRc. The same authors [9], performed analysis of the influence of tool coating on the surface quality and the tool wear. Klocke et al. [10] analysed influence of cutting parameters on the output process parameters in micromilling of tool steel X38CrMoV5 with cubic boron nitride tools. Analysis of the surface quality, through the analysis of influence of cutting speed and feed on surface roughness and built on edges, were conducted by Cristofaro et al. [11]. Gilbin et al. [12] investigated the influence of different coatings on the tool, coating thickness and cutting parameters on the machinability of tool steel 42NiCrMo16, hardened 54 HRc. They noted that the TiAlCrN coating, gives the best results when processing. Kerbs and Kersting [13] investigated the influence of the tool inclination in micromilling of tool steel. Analysis of micromilling of 40NiCrMo16 tool steel, carried out Escolle et al. [14]. They focused on the study of the influence of different coatings on tools and cutting parameters on tool wear and surface roughness. They concluded that the AlCrN coating gives better results than the TiAlN coating in terms of tool life. Oliaei and Karpat [15] investigated the influence of tool wear on cutting resistances and tool deflection in micromilling of stainless steel AISI 420. Li and Chou [16] analysed the minimizing lubrication (MQL) lubricant application techniques when machining AISI H13 tool steel, 38 HRc hardness. The analysis showed that the use of MQL technique reduces the tool wear of 60%. Saedon et al. [17] modelled and optimised of tool life in micromilling of AISI D2 steel, hardened to 62 HRc. Kuram and Ozcelik [18] modelled the surface roughness, the cutting resistances and the tool wear in micromilling of stainless steel AISI 304L. The experiment was performed using Taguchi's method.

2. EXPERIMENTAL SETUP

Experimental research was performed at the precision high-speed *Sodick MC430L* micro-milling centre (Fig. 2). The experiments were performed in MQL lubrication condition.

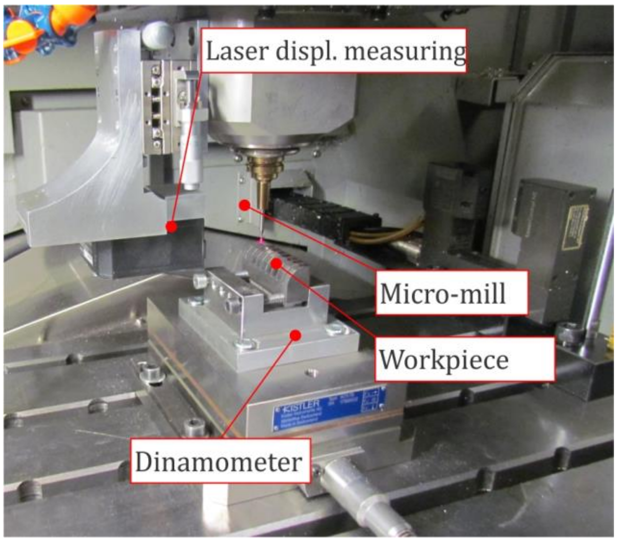

Fig. 2. Experimental setup.

The SECO carbide two flute ball-end micro-mills with TiAlN coating a long neck were used. The diameter of this mills is d_c = 0.6 mm, neck length l_3 = 5 mm, helix angle of this mills ω = 20°, and rake angle γ = 4°. The mean value of the measured radius of cutting wedge is r_c = 8 µm.

As a workpiece material, cold work alloyed tool steel X155CrVMo12 was used. In this, chrome-molybdenum based steel, percentages of alloy elements was as follow: 1.55 % of C, 0.32 % of Si, 0.35 % of Mn, 11.8 % of Cr, 0.90 % of Mo, 0.80 % of V and 0.30 % of Ni. It has excellence mechanical properties and heat conductivity, tensile strength of R_m = 1800 - 2300 MPa, good cross volume hardening ability, and very low machinability in cutting. In hardening, a martensitic structure with alloying elements carbides is found, that gives it exceptional hardness and wear resistance.

Table 1. Values of workpiece physical properties.

Hardness HRc	Yield strenght MPa
45	1500
54	1900
63	2200

For experimental investigation were used three different workpiece hardness *WPH* = 45, 54 and 63 HRc. For mentioned hardness, frame and mean values of mechanical and structural properties, guaranteed by steel producer is given in Table 1.

Workpiece had inclination of machining surface, with angle of 20°. It is prepared by ball milling cutter, with Ø6 mm, and manually polished. As cutting parameters in experiments were: depth of cut a_p = 15 µm, cutting width a_e = 16 µm, feed per tooth f_z = 10 µm/tooth, and following cutting speeds v_c = 40, 55, and 70 m/min. This recommendations were adopted based on own preliminary and research by other researcher. Based on this, in Table 2 are shown 9 different parameters combinations of experimental runs.

Table 2. Experimental combination.

Exp no.	WPH [HRc]	v_c [m/min]
1	63	70
2	63	55
3	63	40
4	54	70
5	54	55
6	54	40
7	45	70
8	45	55
9	45	40

2.1 Measuring device and procedure

Tool wear was measured by the measuring of radius of cutting tool edge (Fig. 3). Radius of cutting tool edge is ability parameter which defining of tool edge geometry variation in machining time due the tool wear.

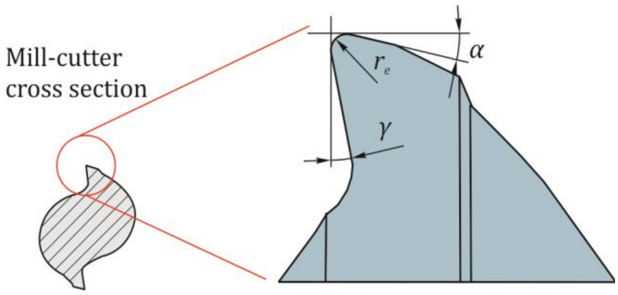

Fig. 3. Cutting edge radius.

Measuring of tool wear, over cutting edge radius were carried out on optical scanner ALICONA InfiniteFocus SL (Fig. 4). Scanning is performed by continuously vertically optical lens moving, and automatically taking of successive array of sample surface images, by so called variation of the focus technique [19].

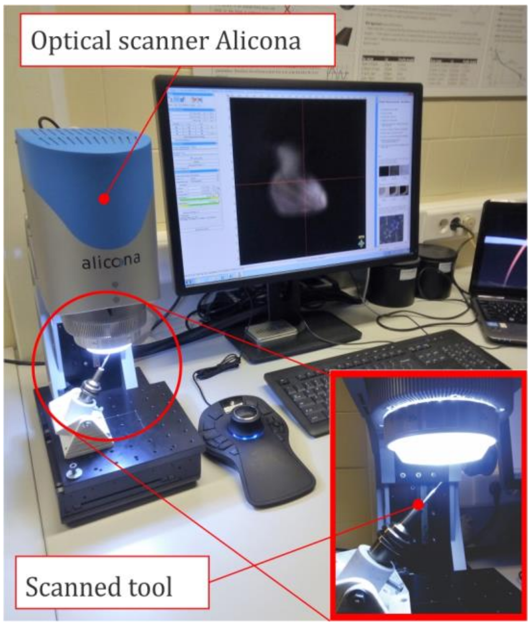

Fig. 4. Alicona InfiniteFocus SL device.

Mentioned technique can be interpreted by schema on Fig. 5. From the currently obtained image, only the sharpest parts are distinguished, their colour is captured, and noted the current position of the lens. After analysing the images, the information obtained is integrated into the topographic view of the scanned surface.

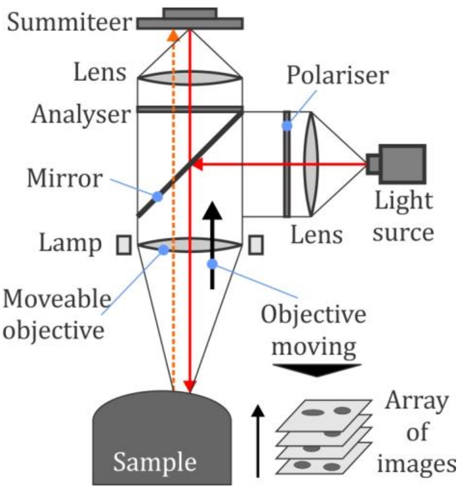

Fig. 5. Focus variation on InfiniteFocus SL [19].

On Fig. 6 is shown the user interface of Alicona software. This interface allows measuring of cross section of topographic scan of cutting tool tip. Based on the selected area, the cutting edge contour can be obtained and measured.

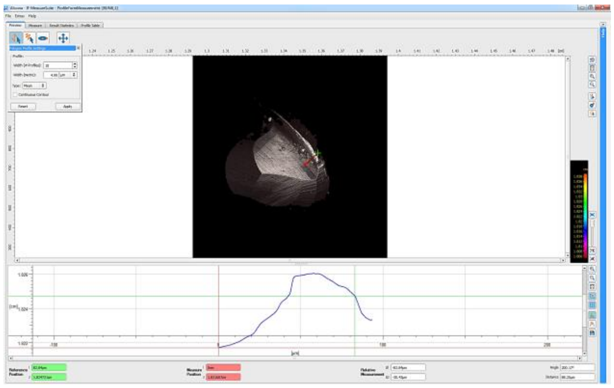

Fig. 6. Alicona measuring software.

3. RESULTS AND DISCUSSIONS

Increase of cutting edge radius is measured for different input parameter combination. This procedure was included milling of workpiece, stopping of machine and very quickly scanning of micro-mill tip. Run stopping is performed for each 30 seconds. On Fig. 7 is shown cutting tool edge radius increasing during machining.

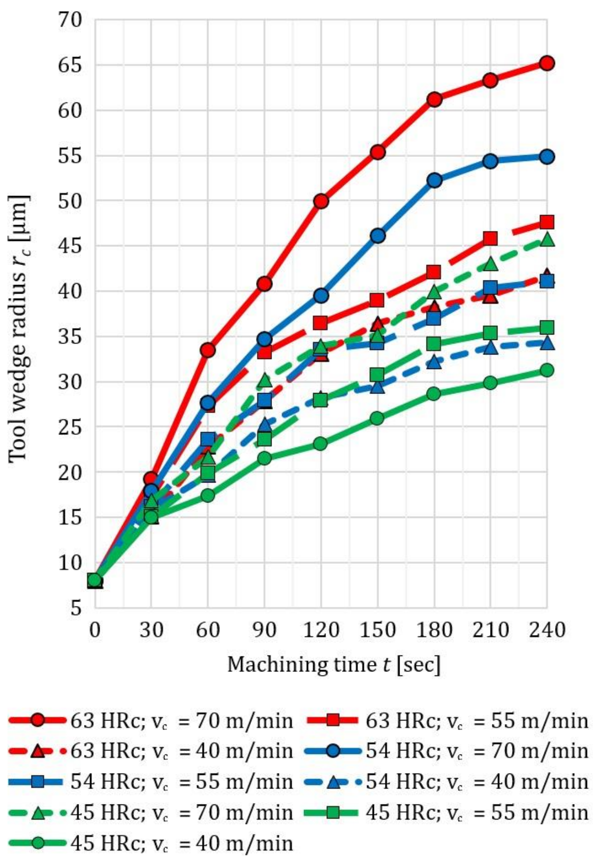

Fig. 7. Cutting tool edge radius changing.

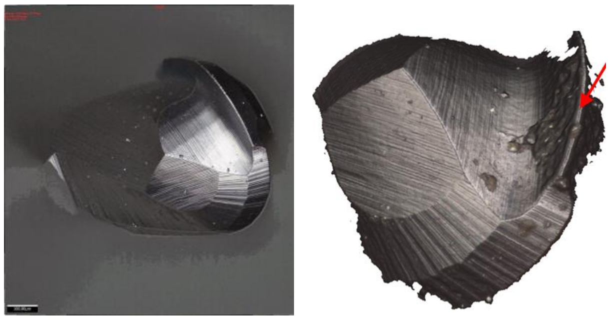

Fig. 8. Image and scan of new tool.

Image and scan of new cutting tool are shown on Fig. 8. On scan can be noticed tool tip and cutting edge geometry, and traces of tool brushing during its manufacturing. Measuring of tool wear was stopped after 240 seconds. Based on curve shapes on diagraph from Fig. 7, can be concluded that tool wear but cutting edge radius in fact, progressive and nonlinear, increases during machining time. Can be concluded that combinations with higher workpiece hardness and cutting speed give intensive tool wear. On end of measuring runs, cutting edge radius had maximum value of 65 μm for hardness of 63 HRc and cutting speed of 70 m/min. Minimum value can be noticed in experimental combination 45 HRc and 40 m/min, and its values is 32 μm.

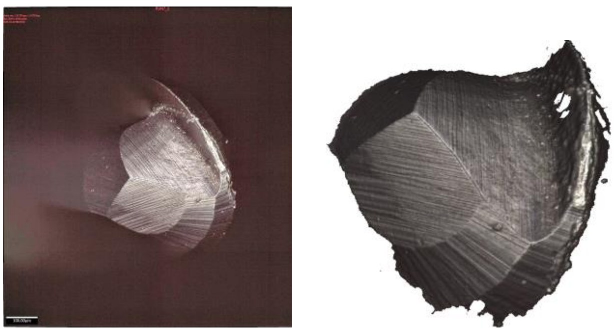

Fig. 9. Image and scan of tool in experimental run 8.

On Figs. 9 and 10 are shown scans of cutting edge on end of measuring run. Based on it can be concluded cutting edge destruction.

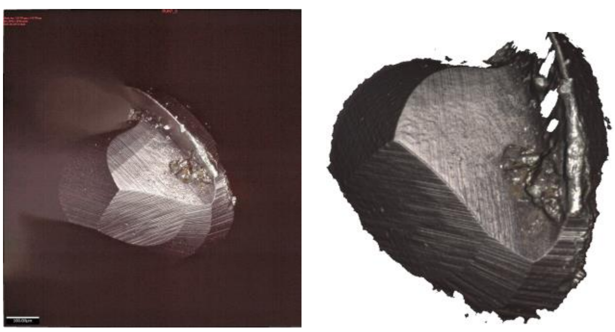

Fig. 10. Image and scan of tool in experimental run 1.

In both cases can be noticed intensive destruction of coating layer on cutting edges. This destruction is caused by intensive abrasive wear that effected by very hard carbides particle in workpiece material structure. Built-on-edge on cutting tool (BUE) is noted at higher tool wear stages. BUE was higher at higher workpiece material hardness. Also, can be concluded some of BUE significantly changing cutting edge geometry. In first, built-on-edge decreases the rake angle of tool wedge. Base on measuring, it is concluded that maximum tool wear or cutting edge radius is greatest on touching point between tool and workpiece, where chip cross section area is maximum. Furthermore, it decreases with chip cross section area decreasing, in the direction of a greater equivalent cutting tool radius. In this direction, there is increasing of effective cutting speed in some percentage, but it do not has influence on tool wear.

Definition of tool life for micro ball-end mills, as economical criterion of machinability, is not precisely defining and standardized in literature. Some authors are defined it over criterion of tool diameter decreasing of in flat-end mill machining. Also, some researcher is evaluated the flank wear on clearance surface on cutting tool wedge, as criterion of tool life. However, in research that presented in this paper, tool life criterion is defined as machining time when cutting edge radius reaches value of 30 μm. Increasing the cutting edge radius causes phenomenon of the size effect. The size effect is caused by same value rang between cutting parameters, cutting tool geometrical parameters, and mechanical and structural properties of workpiece material [1-4]. Presence of size effect can be noticed in machining with low values of cutting depth and feed per tooth, and also in later stages of cutting tool wear. In this cases, there are mechanism of material plugging during chip forming, mechanism of machined surface brushing, sudden rise of cutting tool deflection, and etc. (Fig. 11).

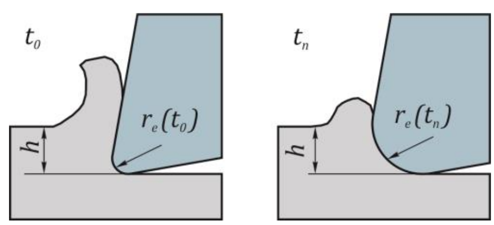

Fig. 11. Alicona measuring software

Table 3. Calculated economical and productivity parameters of micro-milling.

Exp no.	*T* [min]	*MRR* [mm³/min]	*MRV* [mm³]
1	0.88	0.186	0.164
2	1.23	0.146	0.180
3	1.75	0.106	0.186
4	1.17	0.186	0.217
5	1.78	0.146	0.260
6	2.63	0.106	0.280
7	1.48	0.186	0.276
8	2.37	0.146	0.345
9	3.58	0.106	0.380

For this criterion is evaluated tool life *T* [min], which values for different input parameters are given in Table 3. Graphically, dependence of tool life on workpiece hardness and cutting speed is shown on Fig. 12.

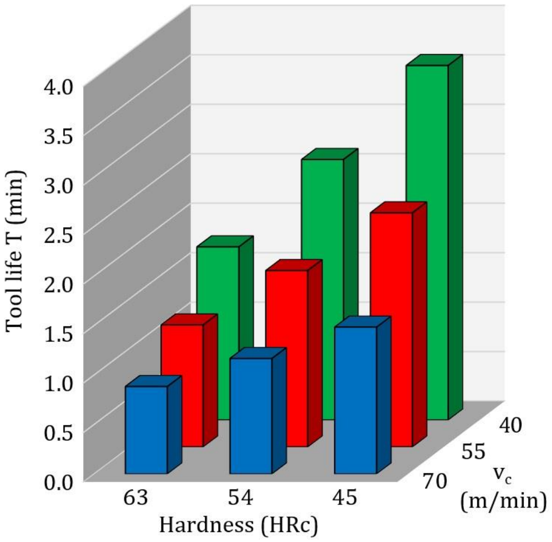

Fig. 12. Comparison of tool life for different inputs.

Maximum tool life, with values of *T* = 3.58 min, is obtained in experimental combination of hardness 45 HRc and cutting speed of 40 m/min. According previous conclusions, minimum tool life, with values of *T* = 0.88 min, is obtained for hardness of 63 HRc and speed of 70 m/min. Based on cutting parameters, area of chip cross section and length of machining, there is calculated material removal rate *MRR* [mm³/min], as productivity criterion. As product of *MRR* and *T*, there is calculated material removed volume *MRV* [mm³]. Comparison of tool life versus material removed value is shown on Fig. 13.

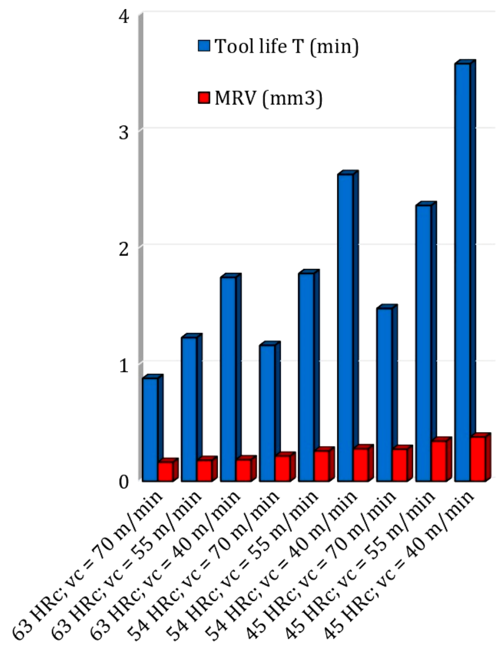

Fig. 13. Tool life and material removed volume.

Differences of MRV for machining with same workpiece hardness and different cutting speeds are not great. In other hand, machining with different workpiece harnesses and cutting speed shows low differences of *MRV*. This observations lead to conclusion that workpiece with higher hardness must be machined on lower cutting speeds.

Modelling of tool life was based on ANOVA, which performed in software *DesignExpert®*. According to it, mathematical model is presented as formula (1):

$$T = 14.92 - 0.19 \cdot WPH - 1.17 \cdot v_c + 0.002 \cdot WPH \cdot v_c \,. \quad (1)$$

Signification of input parameters and model of tool life is presented in Table 4.

Table 4. Results of ANOVA

	Sum of squares	Mean square	F value	p value
Model	5.77319	1.9244	294.87	< 0.0001
A-HRc	2.12415	2.1241	325.48	< 0.0001
B-vc	3.27082	3.2708	501.18	< 0.0001
AB	0.37823	0.3782	57.95	0.0006
Residual	0.03263	0.0063		
Cor Total	5.80582			

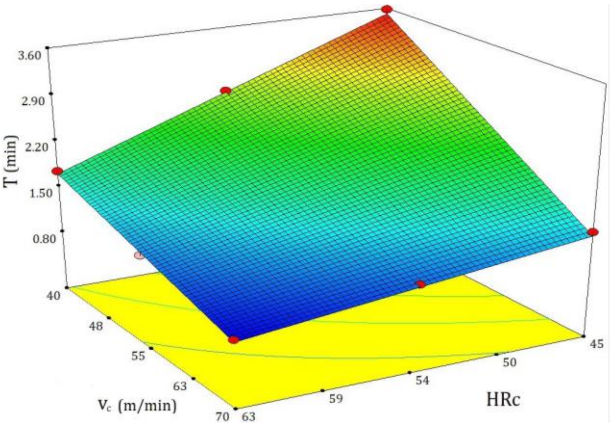

Fig. 14. Modelled values of tool life.

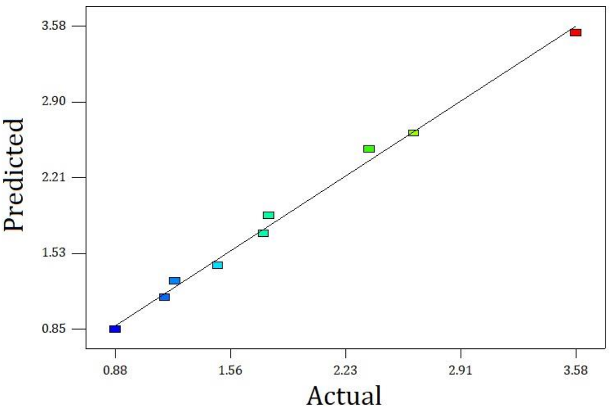

Fig. 15. Measured versus predicted values of tool life.

On Fig. 14 is shown graph of influences of workpieces hardness and cutting speed on tool life, obtained on mentioned mathematical model. Also, on same graph are shown measured values. Based on it, can be concluded high matching of measured and predicted values of tool life. It is also noted on graph that shown on Fig. 15. Based on ANOVA, there are concluded the predicted values standard deviation of 0.081. Also, predicted R-squared value is 0.975 and mean error is 1.87 %.

4. CONCLUSIONS

In this paper, of influence of workpiece hardness and cutting speed on tool wear in ball-end micro-milling of tool steel, in MQL lubrication condition, is investigated. Tool wear is evaluated by increasing of cutting edge radius, which measured by fast focus variation scanner. Based on literature sources, mentioned cutting edge radius is very significant factor. Increase of mentioned radius causes phenomena of size effect and related negative phenomena which is not found in machining on macro level [20].

According of experimental results, there was evaluated economical criterion – the tool life of ball-mills, and productivity parameters of machining, such is *MRR* and *MRV*. Main mechanism of tool wear was abrasive wear which destroyed tool coating layer very fast. Also, there noted adhesive wear mechanism, which caused BUE and changed cutting wedge geometry. In paper is concluded that higher workpiece hardness and higher cutting speed causes intensive tool wear and low tool life. Can be concluded that workpieces with hardness, traditionally, must be machined on low cutting speeds. However, tool life has low value in any case. Maximum tool life, *T* = 3.58 min, is milling of workpiece with hardness of 45 HRc, on cutting speed 40 m/min. Based on measured and calculated values, modelling was performed, based on ANOVA. Modelling process is resulted with very accurate model, with R-squared value of 0.975.

Results of research in this paper are part of extensive research on profile micro-milling of hardened tool steel. As future research, influence of other cutting parameters and machining condition will be performed. Based on this researches, optimisation will be used with aim get appropriate cutting parameters. This will lead to higher productivity and economy, and quality and accuracy of micro-parts, in micro-milling of tool steels and difficult-to-machine materials.

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