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Operation Safety and Performance of Milling Cutters with Shank Style Holders of Tool Inserts

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Abstract

Paper introduces results related to the application of advanced milling cutters provided with shank style of tool insert holder. Design of prototypes of tool bodies is based on calculations of theoretical number of tool edges. Bodies of milling cutter include holes to mount tool insert holder while two types of insert shape as round and octagonal are used in milling cutter design. Based on measuring of cutting forces when milling planar surfaces, critical cutting conditions leading to the tool damage are identified and they are compared with commercial milling cutters. Applying cutting force data, operation safety is being studied concerning outer appearance of tool failure. Application of Finite Element Method is used to assess the critical spots leading to the insert holder failure. Maximum stress which brings about ductile fracture of shank style's insert holder has been found out by FEM modelling. Operation capability of tool inserts is compared with tool performance data. Surface roughness and short term tool wear testing was used as tool performance criteria to asses capability of new cutting tools in face milling operations. Surface quality produced by that kind of milling cutter is referred to as semi finishing and finishing cut. Advantages and limitations of that milling cutter innovation are discussed.

Keywords: milling cutters innovation, face milling, insert holders, tool edge loading, principal stress, tool edge wear, surface quality

Nomenclature

a_e	radial depth of cut (mm)
a_p	axial depth of cut (mm)
C_{Fc}	specific cutting force (N/mm^2)
D_e	effective radius of milling cutter (mm)
F_c	cutting force (N)
F_f	feed force (N)
F_p	passive force (N)
f_z	feed per tooth (mm)
h_{max}	maximum uncut chip thickness (mm)
$h_{c,max}$	maximum chip thickness (mm)

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K	chip ratio
mHV	chip microhardness (N/mm^2)
Ra	arithmetic mean deviation (µm)
Rz	maximum height of surface profile (µm)
TRS	transverse rupture strength (N/mm^2)
VB	tool flank wear (mm)
v_c	cutting speed (m/min)
v_f	feed rate (mm/min)
z	number of tool inserts
Greek symbols	
α_n	clearance angle (deg)
γ_n	tool rake angle (deg)
τ_{sh}	shear stress (N/mm^2)

1. Introduction

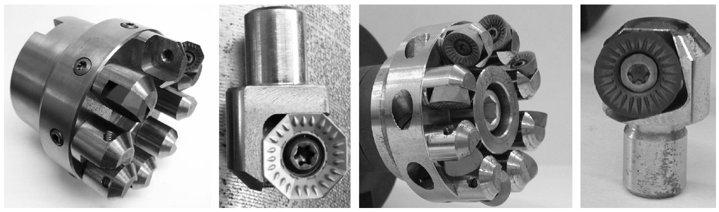
Milling is one of the most employed processes of machining for producing wide variety of surfaces in machinery. Because of more variations in the kinds of machines and milling cutters used, milling applies various innovations of tooling. Basically, milling operations use three kinds of tool design as solid milling cutters (e.g., plain and side mills, end mills, etc.), inserted–blade cutters as well as indexable insert cutters as given by Drozda and Wick [1]. Classifying of the milling tools by [1] shows wide design variety as nonadjustable/adjustable pocket design, open slot and rail design as well as cartridge style of holding indexable inserts. On the other hand, data concerning cutter design are very rare. According to Řasa [2], calculation of cutter's effective diameter D_e is based on empirical data. Methodology to model the geometry of end mill was developed by Tandon et al. [3] and expression of tool geometry for CAD design was shown by Novoselov [4] and Lin [5]. Various modelling techniques to design cutters were proposed by Chen et al. [6] and Nand and Hornik [7], including implementation of Finite Element Method (FEM). Results from Budak [8] demonstrate that milling cutters with non constant pitch can be very effective in suppressing chatter. The angle–solid–block analysis was developed to establish the new cutter geometry model by Wang et al. [9]. Relationship between tool design and performance of milling is discussed in Su et al. [10] while smaller width of cut – to – chip thickness ratio improves chatter characteristics in milling as shown by Karpuschewski and Batt [11]. Results from Lin [12] introduce data on reliability of milling based on feed rate range. One of very features in research of milling cutters is that it combines design of milling cutters with testing of their performance, the latter, however, is defined in very diverse ways. There is but another aspect – design of advanced shapes of milling cutters and their testing as whole. Of various solutions presented in near past, shank style of tool inserts' holder turned out to be innovative design of milling cutters for enabling wide flexibility in producing planar surfaces as given by Trung [13].

2. Design of milling cutter with shank style of tool inserts' holder

Main feature of proposed milling cutter design in Fig. 1 is that it applies mechanical components to join tool insert and tool body indirectly, i.e., shank style of tool inserts' holder includes locating surfaces depending on shape of indexable insert. Milling cutter body shown in Fig. 1(a) and 1(c), however, differs in design itself, for applying various form of locating screws to fix shank of insert holder. The whole assembly of components in Fig. 1 hardly resembles known original solutions (as for instance, so called Peter's design from app 1950, cutters set up with brazed HSS blades, etc.) for providing definite number of holes perpendicular to the main spindle axis. Number of holes is no arbitrary quantity for having relationship to the diameter of the shank style's tool insert holder shown in Fig. 1(b) and 1(d). Two socket head screws TORX M5 gather all components into entire milling cutter; one head screw joins tool insert and holder while another unifies the latter with the tool body. Based on results from [14] and [15], there is theoretically applicable number of insert holders to mount into tool body, true number, however, depends on operations which such milling cutter is assumed to carry out. There is another circumstance of developing such type of cutters for making possibility to use different types of insert's shapes. Thus, locating surfaces in shank style's insert holder are shaped in form of right–angled Vee block and position of locating surface depends on insert shape, Fig. 1(b) and 1(c).

3. Experimental and testing methodology

In order to identify performance of designed milling cutters from Fig. 1, experimental methodology was developed for two kinds of cutter positioning shown in Fig. 2. Power capability was investigated in conventional milling while axial depth of cut $a_e = D_a/1{,}6$; a condition corresponding to the general rule in positioning of milling cutter: 1/4 to 1/3 overhang of D_e on entry side of workpiece produces chip thickness equal or greater than 80% of the feed f_z [1]. Forces F_c, F_f and F_p were measured by three components dynamometer Kistler 9255B, and force responses were evaluated by software. Two different types of steel were used as workiece: C45 (C 0.42%, Si 0.40%, 0,58%, Cr, Mo Ni max 0.63%) and 21CrMo5 (0.45% C, 0.40% Si, 0.95% Mn, 1.2% Cr, 0.33% Mo), steel blocks 100 x 80 x 300 mm were machined (machine tool Heckert FX 400).



(a) (b) (c) (d)

Fig. 1 Prototypes of milling cutters with shank style of tool insert's holder, D_e = 80 mm, z = 8: (a) tool body and assembled insert holders; (b) holder of the octagonal shape of tool insert OCKX; (c) tool body mounted into C style arbor; (d) holder of the round shape of tool insert RCKX

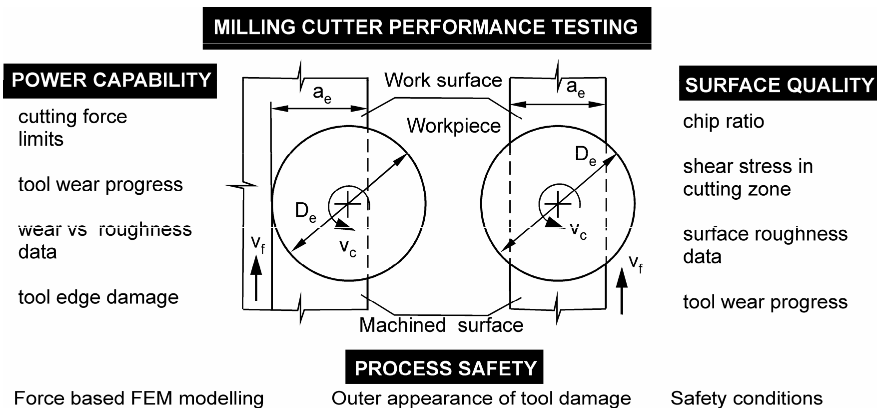


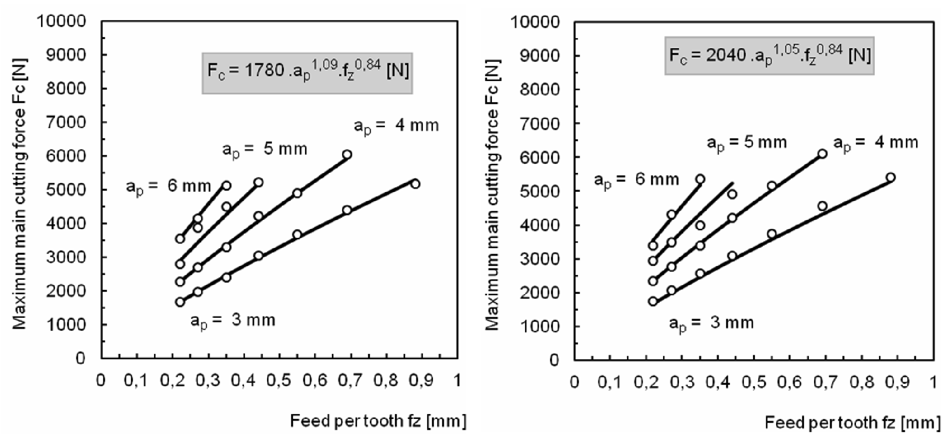
Fig. 2 Methodology of performance testing when milling by cutters with shank style of tool inserts's holders

Insert shape OCKX1616 ADR–TR (γ_n = 23°, α_n = 7°) and RCKX 1606 TR (γ_n = 25°, α_n = 7°) made from LC225S sintered carbide were applied, while cutting conditions as v_c, f_z and a_p were taken from recommendation for semi–finish milling of mild carbon steel. Measured forces, tool wear progress as well as outer appearances of tool edge damage were studied. All results of power capability studies were compared with the milling by commercial milling cutter (D_e = 80 mm, z = 8, tool inserts as those mentioned above).

Studies of surface finish have been carried out by milling cutter from Fig. 1(c). Steel 12 050.1 (identical with C45) was used as workpiece (steel blocks 60 x 60 x 250 mm) and machine tool FA5B TOS Kuřim was employed. Workpiece was centrally positioned by Fig. 2 and applied cutting conditions were chosen regarding finishing cut. Chip ratio K and shear stress τ_{sh} were identified by authors' methodology from [16], surface roughness *Ra* was measured by standard measuring technique.

4. Results and discussion

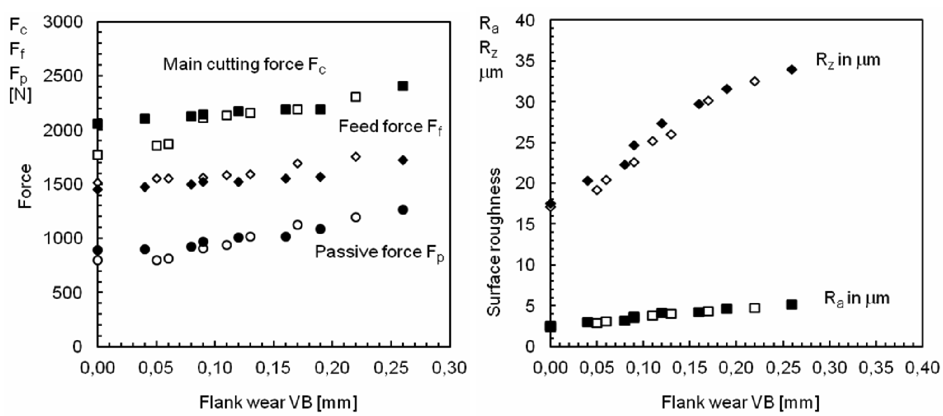
Initial tests of power capability were performed to identify effect of insert shape on cutting forces when milling by cutters shown in Fig. 1(a) and 1(c). Constant parameters v_c = 115 m/min, a_e = 50 mm and a_p = 2 mm as well as variable feed rates v_f = 32 – 250 mm/min were used when milling C45 workpiece. Results showed that there is very small effect of insert shape RCKX and OCKX on maximum force F_c. If measured data assume their magnitude less than 10^3 N, insert shape RCKX gives force response app 80 – 100 N greater than that of OCKX. But if forces vary within order 10^3 – 4.10^3 N, very small effect was found out, i.e., RCKX insert gives force response about 40 – 60 N greater than that of the insert RCKX. It can be said, the greater v_f the smaller effect of insert shape. Thus, measured force data for insert OCKX can be used for modelling of shank style insert holder provided with insert shape RCKX from Fig. 1(d). Further step of identifying power capability was estimating of cutting force limits. Fig. 3 shows influence of f_z on maximum main cutting force F_c whereas results are expressed in form of relationship shown in Fig. 3(a – b).



(a) (b)

Fig. 3 Maximum force limits of power capability for identical feeds per tooth and depth of cut and v_c = 43 m/min – workpiece C45: (a) milling cutter by Fig. 1(a), insert shape OCKX; (c) commercial milling cutter with D_e = 80 mm, z = 8

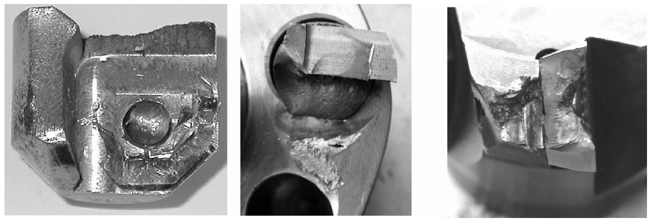
Basically, formulae in Fig. 3 express both effects of cutting conditions and resultant specific forces C_{Fc} for cutter in Fig. 1(a) and commercial cutter, C_{Fc} = 1780 N/mm^2 and C_{Fc} = 2040 N/mm^2, respectively. Similar relationships for C_{Ff} and C_{Fp}, specific feed force and specific passive force, respectively were made up from measured data and three conclusions have been made. Firstly, effect of $f_z^{0,84}$ shows no changes for all force components, effect of a_p varies from $a_p^{1,05}$ to $a_p^{1,25}$. Furthermore, if data for commercial tool are taken as base, cutter in Fig. 1(a) gives considerable reduction of specific force about 12 % for C_{Fc}, about 30% for specific feed force C_{Ff} and about 80% for specific passive force C_{Fp}. Tool wear progress gives another evidence of better power capability of milling tool in Fig. 1(a) when milling steel 21CrMo5 shown in Fig. 4(a) wherein F_c was found app 75% that of commercial cutter. Nevertheless, there was found out no considerable reduction of F_f and F_p, further effect is evident from Fig. 4(b), i.e., reduced roughness *Rz* due to removal by shank style insert holder.



(a) (b)

Fig. 4 Results for commercial milling cutter (black bullets) vs. shank style insert holder (white bullets, insert shape OCKX), v_c = 115 m/min, f_z = 0,36 mm, a_p = 3 mm: influence of flank wear VB when milling steel 21CrMo5: (a) increasing of cutting forces; (b) flank wear vs surface roughness.

Tool edge deterioration appears here due to two factors: gradual tool wear is the first of them whereas flank wear VB = 0,28 – 0,30 mm is limiting value leading to the sudden chipping of tool edge. Cutting force limits turned out to be another factor being present in sudden damage of tool cutting part as such. Maximum cutting force which is less than F_c = 5000 N (see Fig. 3) as well as corresponding forces F_f and F_p (1600 N and 3600 N, respectively) are assumed as limit of process safety for milling steel C45. If F_c exceeds limit mentioned above, milling operation is accompanied with instant deterioration of cutting parts. There is very difficult to predict certain uniformity in milling cutter deterioration, however, three characteristic features have been found out as shown in Fig. 5. Ductile fracture of shank style insert holder in Fig. 5(a) represents the first of them and the rest of the holder remains usually seized in the hole, the another feature of insert holder deterioration shown in Fig. 5(b). Commercial type of milling cutter in Fig. 5(c) undergoes not only complete destruction of tool insert but also damage of tool body. Milling of steel 21CrMo5 pointed to different limit of process safety illustrated in Fig. 4. Range of VB = 0,28 – 0,30 mm is accompanied with chipping of tool edge shown in Fig. 6 which appears due to reduction of fracture toughness in interrupted chip–tool contact. Having used identical scaling of tool edge chipping area in Fig 6(a – b), design of cutter shown in Fig. 1(a) shows better ability to resist mechanical load from cutting forces than that of commercial milling cutter in Fig. 6(b)



(a) (b) (c)

Fig. 5 Outer appearance of full damage of active parts of milling cutters, v_c = 45 m/min, f_z = 0,88 mm, a_p = 4 mm: (a) ductile fracture of shank style insert holder; (b) seizure of broken shank in mounting hole; (c) fracture of tool insert and damage of tool body – commercial milling cutter

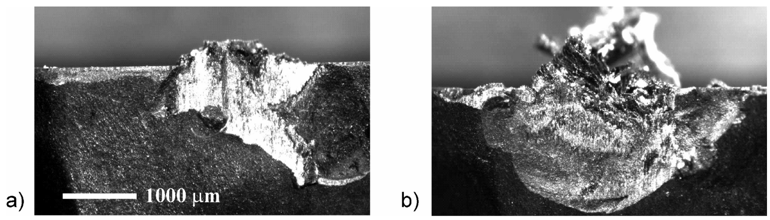


Fig. 6 Features of tool edge chipping within flank wear VB = 0,28 – 0,30 mm, v_c = 115 m/min, f_z = 0,36 mm, a_p = 3 mm: shank style of tool insert holder (b) commercial milling cutter

In order to explain safety conditions of milling cutters in Fig. 1, FEM modelling was performed. Cutter body is characterised by contact surfaces and joints made from socket head screws. Loading conditions at tool edge spread into shank insert holder and charging further screw joints and shank itself. In order to analyse such spreading of stresses within overall shank holder, temperature independent mechanical properties of steel 42CrMo4 (0,47% C, 0,43 % Si, 0,94 % Mn, 1,25 % Cr, 0,33% Mo) from Table 1 have been applied in FEM analysis. Software package CosmosWorks/SolidWorks 2008 SP 0.0 has been used to create models of milling cutter's mechanical components. The aim of static analysis was to find out mechanical stresses due to loading conditions, mechanical stresses were derived from components of cutting force, F_c, F_f and F_p. Because of z = 8, 1/8 sector was taken from cutter body to identify contact surfaces shown in Fig. 7(a): cylinder (shank – hole), flat (shank – body face) as well as locating surface (screw – hole). The highest stress was found out at the tool edge – Fig. 7(b), however, this part presents another material which does not undergo fracture for having TRS about 2300 N/mm^2. Head screw that produces joint between shank style holder and tool body assumes stress approaching to the tensile strength from Table 1. Such stress in head screw is an outset wherein damage of mounted components begins.

Table 1. Properties of 42CrMo4 steel used to manufacture milling cutter body and shank style insert holders

Elastic modulus	Poisson's ratio	Tensile strength	Yield strength	Expansion
200.10^3 N/mm^2	0,29	1200 N/mm^2	750 N/mm^2	1,23.10^{-5} 1/K

Incorporating of component of cutting force into FEM analysis points out that shank's design is capable of absorbing stress but chamfering of internal thread is not. Chamfering as design element to join shank and tool body is a spot in which stress concentration appears. If maximum stress is not greater than yield stress in Table 1, so that designed milling cutter works safely in semi–finishing milling operation. Forces illustrated in Fig. 7 are experimental data resulting from following cutting conditions: a_p = 4 mm, a_e = 50 mm, f_z = 0,69 mm. FEM in Fig. 7(c) shows that shank would be capable of stress absorbing if it were not for chamfering of internal thread for the chamfering is a spot in which maximum stress is far greater than yield stress. That is true reason, why shank style insert holder fails to tear up and such loading conditions brings about stress concentration at the chamfering of internal thread.

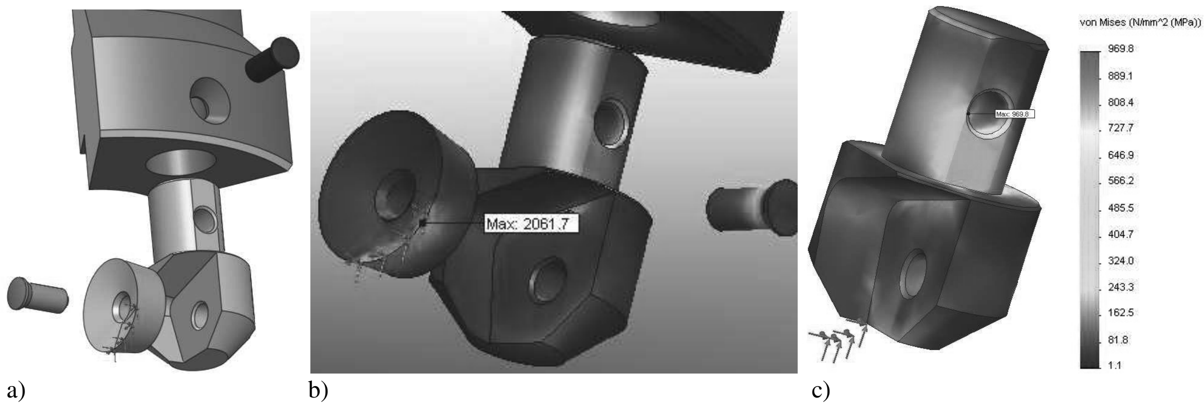


Fig. 7. FEM analysis of shank style's insert holder – forces applied: F_c = 5200 N, F_f = 3600 N, F_p = 2000 N: (a) 1/8 sector of cutter body to define contact surfaces, (b) maximum stress at tool edge, (c) distribution of von Misses stress in shank style insert holder

Based on methodology of performance testing shown in Fig. 2, centrally positioning of milling cutter relative to the workpiece was applied to investigate surface quality. Speed v_c = 115, 180 and 280 m/min were chosen for finish cut while feed f_z varied within 0,05 – 0,35 mm to conform feed rate v_f. In order to prevent vibrations due to changes in the direction of cutting forces, constant axial depth of cut a_p = 2 mm was held in experiments. Surface roughness data *Ra* were measured six times in the centre line of workpiece within both side of workpiece and four locations between them. Moreover, produced chips were collected to identify two variables: $h_{c,max}$ and mHV. Chip ratio $K = h_{c,max}/h_{max}$ is very infrequent quantity in research of milling. Based on methodology from [16], ratio K was identified at least from ten measurements of $h_{c,max}$ while h_{max} is calculated from basic formulae for milling. Fig. 8 illustrates how these two quantities correlate: K is controlled by feed f_z while *Ra* is under strong effect of speed v_c and that is simple conclusion expressed from statistical formulae shown in Fig. 8(a – b). It can be noted that K and *Ra* assume their maximum values conversely: the higher K the smaller *Ra*. Moreover, no sign of process instability does occur when milling by cutter from Fig. 1(c), therefore, resultant roughness *Ra* = 0,86 – 6 μm can be assessed to operation of surface finishing.

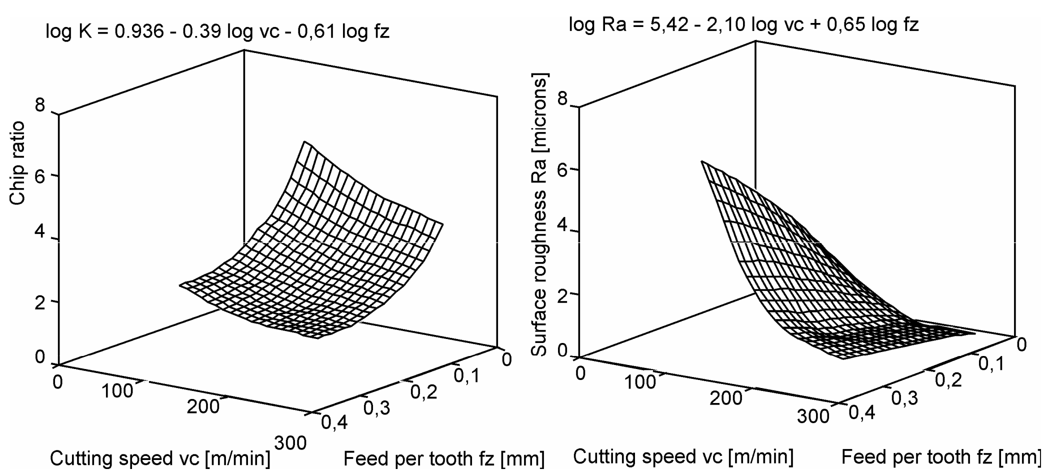


Fig. 8 Influence of cutting speed and feed per tooth on results of centrally positioned milling – insert RCKX: a) chip ratio; b) surface roughness

Finally, two further circumstances are associated with finish milling by tested cutter in Fig. 1(c). The first of them is that designed milling cutter turns out to be energy saving cutting tool for reducing shear stress in cutting zone. According to the data from [17], shear stress in precision milling is about 1000 N/mm^2. Having measured microhardness of chip being produced in face milling, it varies within 3200 – 4000 N/mm^2. Based on simple relationship mHV = 5,2.τ_{sh} from [18], shear stress shown in Fig. 9 is never greater than 800 N/mm^2. Another circumstance of applying of mentioned milling cutter is that there are no marks of tool failures as chipping, thermal cracking and tool edge deformation which appear in such type of operations. As shown in Fig. 10, flank wear show very small marks of edge notching when cutting speed is 180 m/min and more. Ranges of flank wear in Fig. 10, VB = 0,124 – 0,168 mm follow from entire length of cutting 5.000 mm.

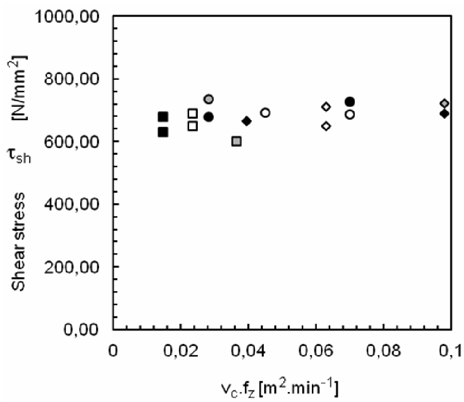
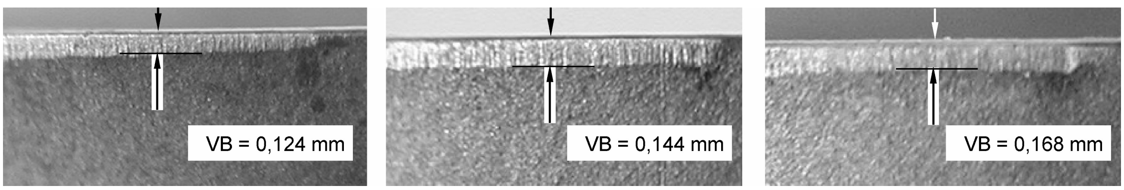


Fig. 9. Influence of speed and feed per tooth on shear stress in cutting zone when milling by insert shape RCKX 1606 TR



(a) (b) (c)

Fig. 10. Outer form of tool flank wear – shank style tool insert holder, insert shape RCKX: a) v_c = 115 m/min; b) v_c = 180 m/min; c) v_c = 280 m/min (feed f_z = 0,14 mm, a_p = 2 mm)

5. Conclusion

Combination of experimental testing and FEM studies have been used to identify both process capability and operation safety of newly designed milling cutters. Cutting forces, flank wear and surface roughness were studied in conventional milling when axial depth of cut being $a_e = D_e/1,6$. Results show that instant cutting forces greater than F_c = 5000 N are disposed to damage socket head screws and shank style's insert holder. Usually, forces mentioned above appear if depth of cut a_p is up to 4 mm and feed per tooth f_z is app equal to 0,65 mm and more. Three characteristic features of tool damage have been identified and there are specific features of damaging shank's style insert holder and socket head screw as follows:

- deformation of socked head appears due to stress concentration at hole chamfering
- socket head screw is deformed by plastic bending within grip length, a distance between screw head and thread length
- plastic deformation of grip length tears up shank style's insert holder at such spot wherein maximum stress appears, a chamfering of the shank
- stress at tool edge show no effect on tool insert damage for not exceeding transverse rupture strength of modern sintered carbides
- if overall damage of tool inserts appears, such damage means no effect of cutting force but plastic bending within head screw's grip length.

In finishing operations of milling, chip ratio and surface roughness were found to behave themselves conversely and resultant roughness varies within *Ra* = 0,86 – 6 μm. Reduction of shear stress in cutting zone was determined. Wear progress in finish milling depends on cutting speed. No cases of tool edge failure were found in finish milling tests.

Last but not least, the very advantage of such design of milling cutters is that no damage of tool body appears in heavy duty operations. If any damage occurs, usually a change of shank style insert holder is needed. Results in operations of finish milling mean challenge for their further development and improvement.

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