A Comprehensive Approach to Improving Accuracy, Tool Life, and Surface Quality in Hole Reaming

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ABSTRACT

This paper aims to improve surface quality and hole accuracy during reaming. A modular cutter-type reamer with rigidly fixed, peackless cutting edges was used to ensure that the finishing reaming operation was highly efficient, increased machining accuracy and quality, and reduced the surface roughness of the machined parts. It was found that when the fourth cutting edge of the reamer engages, the radial component of the cutting forces balances out. Consequently, machining stability increases, tool deflection and vibrations decrease, and the accuracy and quality of hole machining improve. Design modeling of modular cutter-type reamers was performed using the APM WinMachine software package, which increased design productivity and enabled the analysis of multiple cutting conditions on simulated models. Calculations showed that a modular cutter-type reamer with rigid fixation of peackless cutting edges arranged along a helical line has smaller radial displacement than other reamer designs. Consequently, longitudinal and transverse deviations are reduced by 1.2 times, leading to higher accuracy and improved hole quality. Additionally, the load on each peackless cutting edge decreases by 1.5 times, and the tool's strength increases by 1.3 times. This results in an enhanced tool life and durability. Optimal cutting parameters for the modular cutter-type reamer with rigidly fixed peackless cutting edges were experimentally determined: a spindle speed of 160 rpm, a feed rate of 0.2 mm/rpm, and a machining allowance of 0.5 mm. The developed reamer demonstrated high hole machining accuracy within the range of 0.005-0.016 mm (IT5–IT6 tolerance grades), which is 1–2 grades higher than that achieved with boring tools or standard solid or modular reamers. Surface roughness values were obtained within the range of R_a = 0.125-0.8 µm.

Keywords-modular reamer; peackless cutting edge; hole; tool life; accuracy; surface roughness; quality

I. INTRODUCTION

Hole finishing is the most important machining operation for ensuring that the holes in machined parts match exact dimensional and surface quality requirements. This process is important in industries such as aerospace, automotive, medical, electronics, and engineering, including cylinder blocks, cylinder heads, transmission housings, printed circuit boards, and surgical instruments, for which precise hole sizes and surface quality are crucial to performance and reliability [1, 2]. Drilling, boring, and unfolding are machining processes used to create or process holes, each providing a different level of precision and surface quality. Drilling is an internal machining operation that creates an initial cylindrical hole in a solid billet using a spiral drill; the cutting action mainly occurs at the periphery. Drilling uses a combination of rotational force and axial feed to propel the drill bit into the material; both parameters must be adjusted according to the material's machinability and hardness. There are several types of drilling, each of which is applied to specific requirements and materials: spiral drilling, deep drilling, cannon drilling, and trepanning [2, 3]. Boring is a finishing process that expands an existing hole, improving its alignment and surface quality. This operation is often performed using a single-point cutting tool, or cutter. Although boring provides higher accuracy than drilling, it lasts longer [4]. In precision manufacturing, producing holes with an accurate diameter, roundness, straightness, and high surface quality is often difficult. Drilling or boring operations alone often result in surface marks, burrs, or dimensional deviations that exceed allowable tolerances. In such cases, reaming is essential. When performed correctly, reaming produces holes with stable dimensions, tight tolerances, and an excellent surface finish [5, 6]. The cutting tool used in drilling is a reamer, and properly selecting it based on the workpiece material, machining volume, and machine tool settings significantly affects machining quality, productivity, tool life, and overall process cost [7]. Authors in [8-12] focused on developing and improving cutting tool designs, as evidenced by the large number of patents and regular presentations of new developments at industry exhibitions. The main objective of this study is to ensure that the finishing reaming operation is highly efficient, increases machining accuracy and quality, and reduces the surface roughness of machined parts. Authors in [13, 14] analyzed tool designs of hole machining processes, which led to the development of a new cutting tool: a modular, cutter-type reamer with peakless cutting edges. This reamer is used to produce holes with enhanced surface quality and dimensional accuracy [15, 16]. These cutting edges eliminate a main disadvantage of conventional cutters: the tool tip. The tip is the weakest and most wear-prone part of the cutting edge [17]. The modular cutter-type reamer with rigidly fixed peackless cutting edges consists of four insert-type cutters that are mounted in slots with an axial offset relative to each other. The cutters are fastened directly to the body using clamping screws, as shown in Figure 1. The inserts' cutting edges are circular, and the cutting-edge plane is inclined relative to the hole (reamer) axis. Figure 2 shows the design of the peackless cutting edge.

In Figure 1: 1 – reamer body; 2 – four inserted cutting edges of the reamer, axially offset relative to each other; 3 – fastening screws; 4 – replaceable compensation plate with holes for fastening screws; G – successive axial offset of the symmetry planes of the inserted cutting edges and fastening screws; D – diameter of the inserted cutting edges of the reamer; D_n – neck diameter; D_{pgs} – diameter of the preliminary guiding section (catcher); ℓ_1 – length of the preliminary guiding section (catcher) of the body along the unmachined hole; ℓ_2 = 1-1,5 mm – distance from the symmetry plane of the first inserted cutting edge of the reamer to the beginning of the chamfer of the guiding section of the body; ℓ_w – length of the working part of the reamer; ℓ_n – neck length; ℓ_s – shank length.

The first cutting edge acts as a boring tool. The remaining cutting edges, which are arranged along a helical line, calibrate the hole. Initially, the reamer is centered in the pre-machined hole by a pilot section. After passing the central plane of the inserts, the main guiding section ensures centering. Using peackless cutting edges increases the rigidity of the technological system (machine, fixture, tool, and workpiece), improving hole machining accuracy [15].

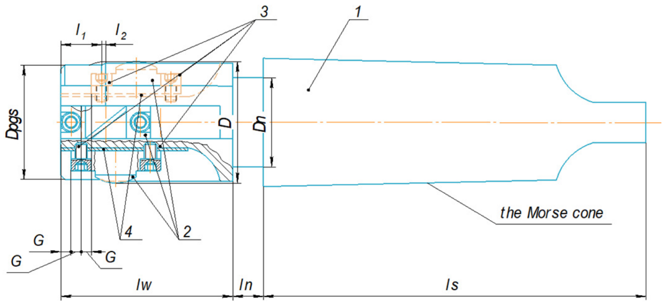


Fig. 1. Design of a modular cutter-type reamer with rigidly fixed peackless cutting edges.

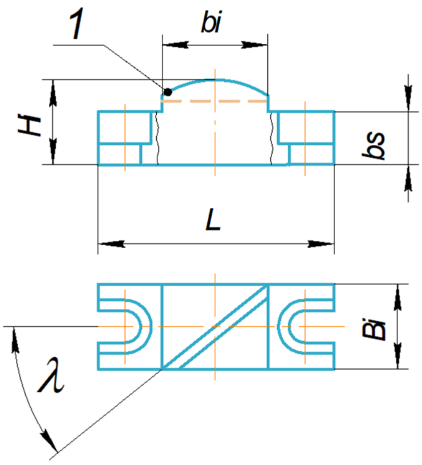


Fig. 2. Design of a peackless cutting edge of a modular cutter-type reamer with rigid fixation: 1 – cutting edge of the inserted cutter; b_s – shoulder height; B_i – width of the inserted cutter; H_i – height of the inserted cutter; L – length of the inserted cutter; λ – inclination angle of the main cutting edge.

II. THEORY AND FORMULA

The hole machining process involves overcoming the resistance forces associated with material separation and chip formation due to the cutting forces generated by the main rotational cutting motion and the axial feed [18]. In a modular cutter-type reamer with fixed, peackless cutting edges, the cutters have no tip, and the cutting edge is a circular arc inclined relative to a plane perpendicular to the reamer's axis. This design reduces mechanical and thermal stresses on the cutting edge, decreases wear, increases tool life, and improves the quality of the machined surface. This includes reduced roughness due to altered chip formation conditions and kinematics. Figure 3 depicts the cutting forces acting on the modular cutter-type reamer during the hole machining process. Force P_z is the circumferential (tangential) force, which is the main component of the cutting force. It acts in the cutting plane in the direction of the primary cutting motion. Force P_z determines the load on the machine tool and the cutting tool. Force P_y is the radial component, which acts perpendicular to the axis of the workpiece. This component deflects the cutting edge away from the workpiece, causing workpiece deformation and affecting machining accuracy. Force P_x is the axial component acting along the workpiece's axis, parallel to the feed direction. This component determines the load on the feed mechanism of the machine tool.

As displayed in Figure 3, when the fourth cutting edge engages, the radial components of the cutting forces balance out. This results in increased process stability, reduced tool deflection and vibrations, and improved hole accuracy and surface quality [19]. The design and analysis were carried out using 3D solid modeling in the KOMPAS-3D CAD system, as presented in Figure 4, and the strength and deformation calculations were performed using APM WinMachine, as shown in Table I. The input data were: reamer body material – Steel 45; insert cutters – T15K6. The machining diameter is 45 mm, and the workpiece material is Steel 45. The cutting conditions were considered in four variants:

- Variant 1: $f = 0.2$ mm/rev; $n = 160$ rev/min; $a_p = 0.25$ mm. Cutting forces on four cutting edges: $P_x = 328$ N; $P_u = 612$ N; $P_z = 918$ N;
- Variant 2: $f = 1.4$ mm/rev; $n = 160$ rev/min; $a_p = 0.25$ mm. Cutting forces on four cutting edges: $P_x = 328$ N, $P_u = 612$ N, $P_z = 918$ N.
- Variant 3: $f = 0.2$ mm/rev; $n = 160$ rev/min; $a_p = 0.5$ mm. Cutting forces on four cutting edges: $P_x = 656$ N, $P_u = 1{,}144$ N, $P_z = 1{,}836$ N.
- Variant 4: $f = 1.4$ mm/rev; $n = 160$ rev/min; $a_p = 0.5$ mm. Cutting forces on four cutting edges: $P_x = 656$ N, $P_u = 1{,}144$ N, $P_z = 1{,}836$ N.

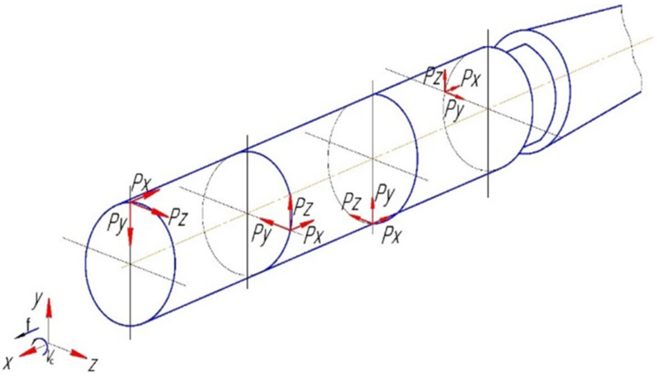


Fig. 3. Cutting forces acting on a modular cutter-type reamer in three-dimensional space.

III. EXPERIMENTAL SETUP

Hole machining was carried out on a 2A135 vertical drilling machine using a modular cutter-type reamer with rigidly fixed peackless cutting edges. Holes with diameters of d = 45 mm and lengths of 20 mm, 45 mm, and 90 mm were machined from steel 45 under dry cutting conditions [20] and with a cutting fluid, specifically Ukrinol-1 [21]. Experimental studies were conducted using a 23 full factorial design. The optimization parameters were diameter deviation and surface roughness, and the factors were spindle speed, feed rate, and depth of cut, as illustrated in Table II. Authors in [22] measured the depth of cut, spindle speed, and feed, considering the specifications of the 2A135 vertical drilling machine, and the upper and lower variation limits. Based on this, a planning matrix was created, and experimental studies were carried out. Graphs showing the effect of cutting conditions on the quality of machining 45 mm holes at a constant depth of cut ap = 0.5 mm were plotted, as portrayed in Figures 5 and 6.

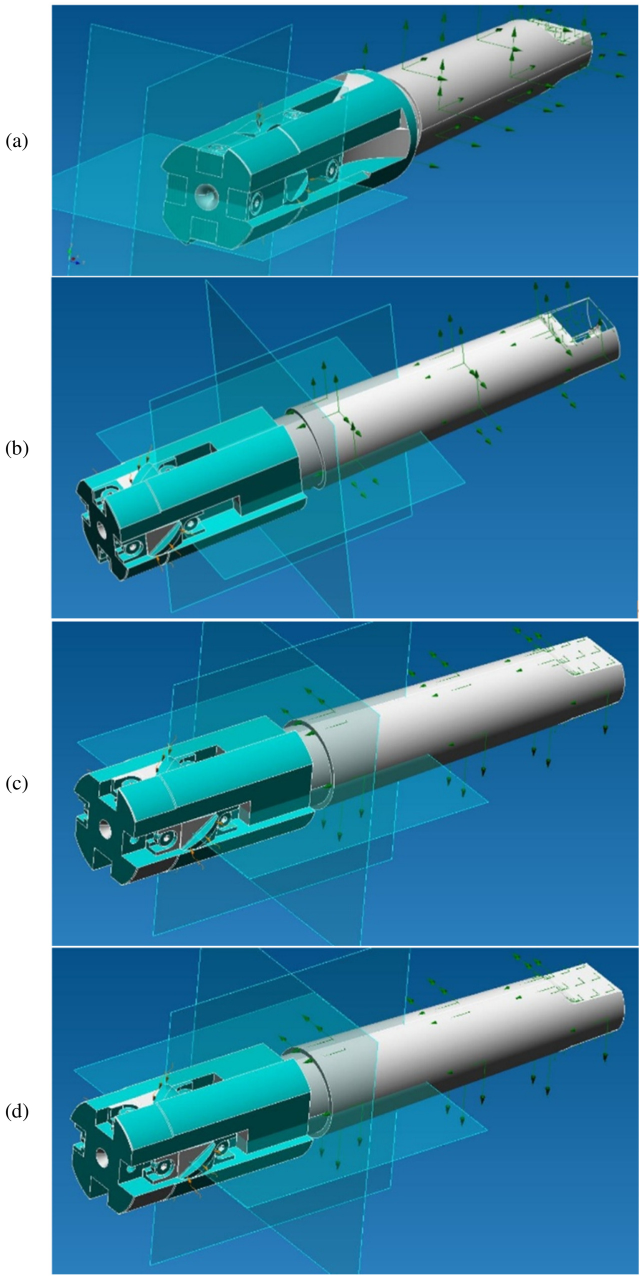
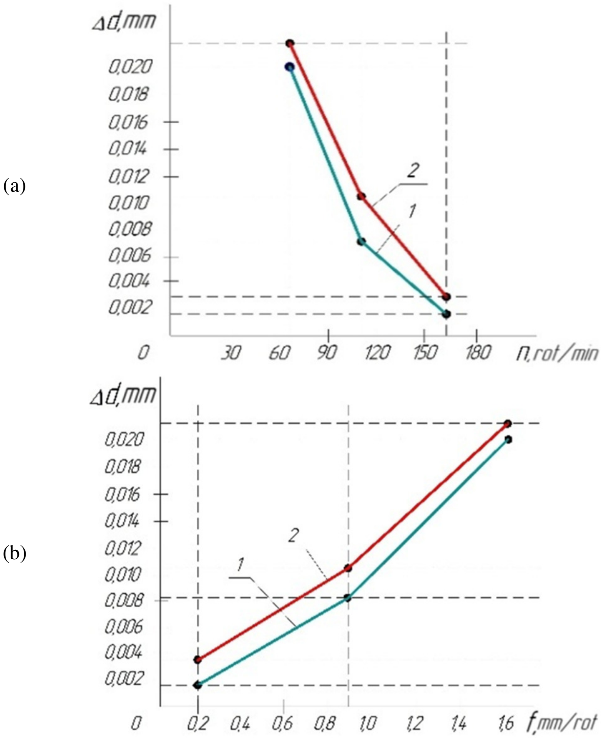


Fig. 4. 3D model of the modular cutter-type reamer with peackless cutting edges: (a) linear arrangement with clamps, (b) linear arrangement without clamps (rigid fixation), (c) helical arrangement with clamps, (d) helical arrangement without clamps (rigid fixation).

Figure 7 shows how spindle speed, feed rate, and depth of cut affect the diameter deviation of 45 mm holes with various machining lengths (20 mm, 45 mm, and 90 mm) at a constant depth of cut (ap = 0.5 mm). The surface roughness of 45 mm holes with various machining lengths (20 mm, 45 mm, and 90 mm; t = 0.5 mm) was measured using a contact profilometer, as depicted in Figure 8.

TABLE I. CALCULATION RESULTS OF MODULAR REAMER DESIGNS

Tool name	**Depth of cut a_p (mm)**	**Equivalent von Mises stress (MPa)**		**Total linear displacement (mm)**		**Safety factor**	
		Min. value	Max. value	Min. value	Max. value	Min. value	Max. value
Reamer with clamps on helical line	0.25	0	57.064	0	0.009	13.668	1000
	0.5		114.524		0.019	6.826	
Reamer with clamps on single line	0.25	0	91.729	0	0.025	11.628	1000
	0.5		179.909		0.048	5.931	
Reamer without clamps on single line	0.25	0	59.239	0	0.012	10.322	1000
	0.5		118.458		0.0245	5.162	
Reamer without clamps on helical line	0.25	0	58.506	0	0.007	18.549	1000
	0.5		115.263		0.014	9.243	



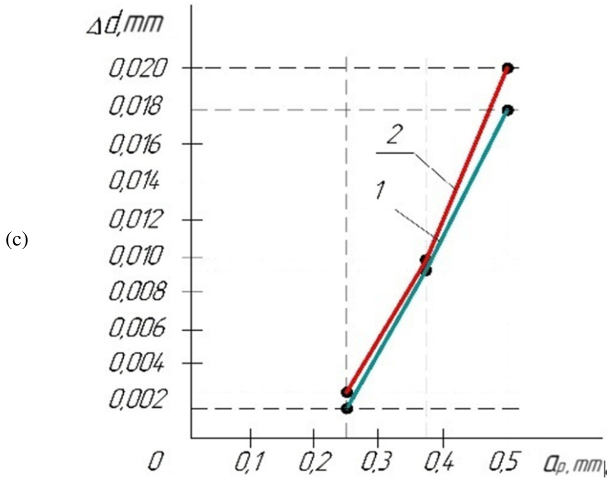


Fig. 5. Effect of cutting modes on diameter deviation: 1 – machining with cutting fluid; 2 – without cutting fluid: (a) vs. spindle speed, (b) vs. feed, (c) vs. depth of cut.

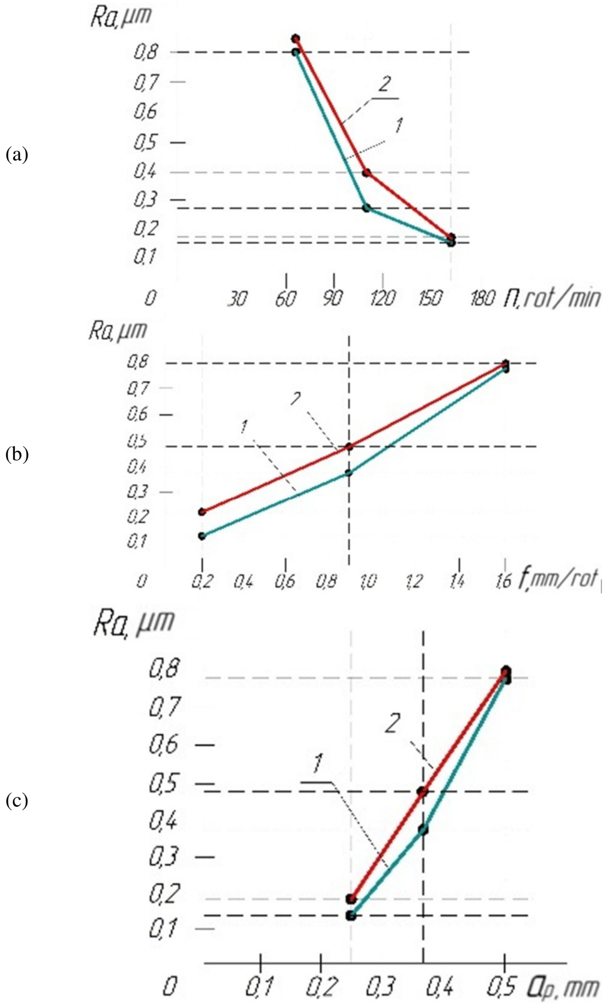


Fig. 6. Effect of cutting modes on surface roughness: 1 – machining with cutting fluid; 2 – without cutting fluid: (a) vs. spindle speed, (b) vs. feed, (c) vs. depth of cut.

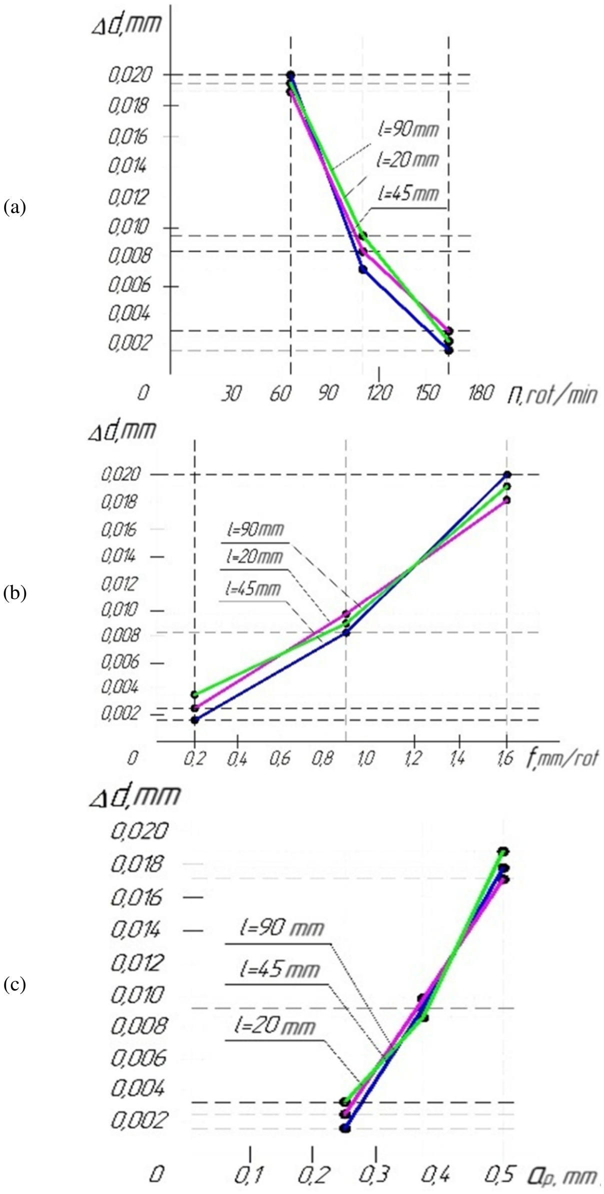


Fig. 7. Effect of cutting modes on diameter deviation: (a) vs. spindle speed, (b) vs. feed, (c) vs. depth of cut.

TABLE II. VALUES OF THE VARIED FACTORS

Factor variation levels	**Factor values**					
	Spindle speed, *n*		**Feed, *f***		**Depth of cut, a_p**	
	natural	**code**	**natural**	**code**	**natural**	**code**
	rot/min	X_1	mm/rot	X_2	mm	X_3
Central (nominal)	114	0	0.9	0	0.375	0
Upper	160	+1	1.60	+1	0.5	+1
Lower	68	-1	0.20	-1	0.25	-1
Variation interval	46	ΔX_1	0.7	ΔX_2	0.125	ΔX_3

IV. RESULTS AND DISCUSSION

An analysis of the hole processing of the modular cutter-type reamer with rigidly fixed, peackless cutting edges showed that hole processing quality increases by 1.2 to 1.3 times with the use of coolant, due to decreased temperature and friction in the cutting zone. These results are consistent with those in [23, 24], where it was demonstrated that using lubricants reduces adhesive wear on the teeth and stabilizes hole size. When machining holes with lengths of 20 mm, 45 mm, and 90 mm with the modular cutter-type reamer with rigidly fixed peackless cutting edges, the diameter deviation increases with the feed and depth of cut, but decreases with the spindle speed. Authors in [25] used ANOVA to demonstrate that cutting depth and feed directly increase error in hole shape and size. Surface roughness decreases with increasing spindle speed and increases with increasing feed and depth of cut. The analysis of experimental surface integrity features [26] showed that a compressive residual stress state and smooth surface roughness can be achieved. Thus, the original design of the modular cutter-type reamer with rigidly fixed peackless cutting edges ensures stable hole machining across different lengths.

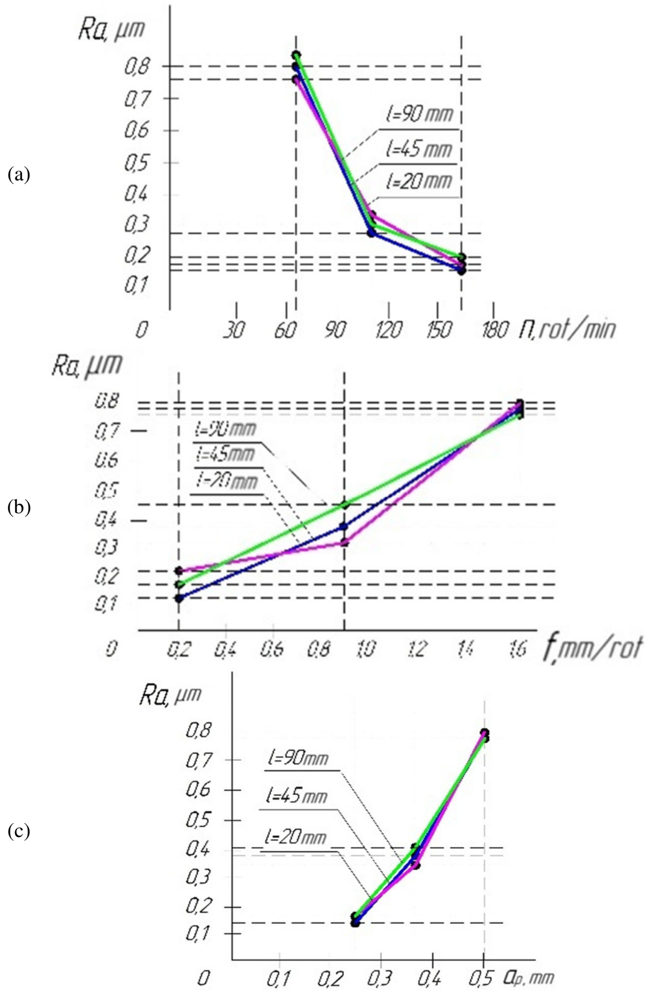


Fig. 8. Effect of cutting modes on surface roughness: (a) vs. spindle speed, (b) vs. feed, (c) vs. depth of cut.

V. CONCLUSIONS

Experimental studies have shown that a modular cutter-type reamer with rigidly fixed, peackless cutting edges ensures that the finishing reaming operation is efficient and stable, improves centering, reduces surface roughness, and enhances the accuracy and quality of the holes being machined. APM WinMachine calculations demonstrated that the reamer with peackless cutting edges arranged along a helical line exhibits smaller radial displacement than other design variants. Consequently, longitudinal and transverse deviations are reduced by 1.2 times, the load on each cutting edge decreases by 1.5 times, and tool strength increases by 1.3 times. This leads to an improvement in tool life. Based on these results, the problem of enhancing surface quality and hole accuracy was solved by determining the optimal cutting parameters: a spindle speed of 160 rpm, a feed rate of 0.2 mm/rpm, and a machining allowance of 0.5 mm. The developed reamer achieved a hole accuracy of 0.005–0.016 mm (IT5–IT6 tolerance grades), which is 1-2 grades higher than that obtained using boring tools or conventional solid or modular reamers. Surface roughness values were within Ra = 0.125–0.8 μm. These scientific results contribute to the theory and practice of hole machining using metal-cutting tools.

DECLARATION OF COMPETING INTERESTS

There are no competing interests. The publication of this scientific article does not violate the copyrights of third parties.

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DATA AVAILABILITY

The experimentally acquired data utilized in this study are mentioned within this paper and can be available from the corresponding author.

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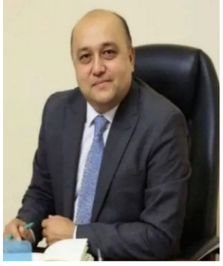

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