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Research Article

Theoretical Determination of Changes in Chain Networks Lengths

Akbarov Dostonbek Axmadali Ogli[1, *], **Xusanov Yunusali Yuldashalievich**[2]

[1]Department of Mechanical Engineering Technology, Fergana State Technical University, Fergana, Uzbekistan
[2]Department of Applied Mechanics, Fergana State Technical University, Fergana, Uzbekistan

Abstract

This article presents the results of a study on improving surface quality during the mechanical machining of complex-shaped sections of metal mold components manufactured for the production of plastic products by injection molding. In the conventional milling method, narrow guide grooves (2.9 mm in width, 2.0 mm in depth) require machining with small-diameter end mills (D=2.5 mm). Such cutters have low stiffness, are prone to vibration, wear quickly, and degrade the surface quality. The study proposes a technology in which the difficult-to-machine section is manufactured as a separate part and installed into a seat formed in the main mold component by means of an interference fit. This approach eliminates the need for special fixtures and enables the use of larger-diameter (D=12 mm) rigid end mills. Experimental investigations were conducted on 40X structural alloy steel, comparing conventional milling with the proposed separate part technology. A power-regression mathematical model relating surface roughness to the main cutting parameters (cutting speed and feed per tooth) was developed and validated against experimental data. The results showed that surface roughness improved by 45.8% (from Ra=1.42 to Ra=0.77 μm), machining time decreased by 18.4%, and tool stiffness increased by a factor of 179. The proposed technology was implemented at the Navoi Machine-Building Plant, confirming its practical effectiveness.

Keywords

Chain Drive, Distance Between Axles, Chain Network, Length, Vector, Contour, Angle, Equation

1. Introduction

The experimental investigations were carried out on 40X structural alloy steel (GOST 4543), which is widely used for mold components owing to its favorable combination of strength, hardenability, and machinability. The mechanical properties of 40X steel are presented in Table 1.

Three machining configurations were investigated, as summarized in Table 2. In the conventional method, the narrow groove is machined directly with a thin end mill. In the separate part technology, the groove is formed by installing a separately manufactured component; the separate part itself is machined on its larger accessible surface with a rigid end mill (D=12 mm), and the seat in the main part is milled with a large-diameter cutter (D=20 mm). All cutting tools were made of VK8 tungsten-cobalt carbide [4-6].

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[*]Correspondence: Akbarov Dostonbek Axmadali ogli (davronbekhabibullayev1@gmail.com)

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***Table 1**. Mechanical properties of 40X steel (GOST 4543).*

Property	Value	Unit
Hardness (as delivered)	269–302	HB
Hardness (after hardening)	48–56	HRC
Tensile strength	980	MPa
Yield strength	785	MPa
Thermal expansion coefficient	11.9×10^{-6}	1/℃

***Table 2**. Cutting tools and parameters for the three machining configurations.*

Parameter	Conventional	Separate part	Seat milling
Cutter diameter D, mm	2.5	12	20
Number of teeth z	2	4	4
Cutting speed V, m/min	23.6	75.4	125.6
Feed per tooth sz, mm/tooth	0.008	0.05	0.08
Cutting depth t, mm	0.3	1.0	1.5
Tool material	VK8	VK8	VK8

The surface roughness (Ra) of the machined surfaces was measured using a GOYOJO GSR750 portable surface roughness tester, which employs an inductive sensor with a 5 µm diamond stylus, has a measuring range of 320 µm, a resolution of 0.001 µm, a measurement error of no more than ±10%, and complies with ISO, DIN, ANSI, and JIS standards (GOST 2789-73). The instrument applies a Gaussian filter and can measure 14 roughness parameters. Each surface was measured at three points along the machined feature, and the arithmetic mean value was recorded as the representative roughness.

The cutting force was calculated using the empirical power-law formula widely adopted in machining theory [1-3]:

$$P_z = \frac{C_p \cdot t^x \cdot s_z^y \cdot B^u \cdot z}{D^q \cdot n^w} \tag{1}$$

where Cp is the cutting force coefficient, t is the cutting depth, sz is the feed per tooth, B is the milling width, z is the number of teeth, D is the cutter diameter, n is the spindle speed, and x, y, u, q, w are empirical exponents taken from reference handbooks [4-6].

To evaluate the rigidity of the cutting tools, the tool was modeled as a cantilever beam fixed at the spindle and loaded at the free end. The bending stiffness was calculated as [7]:

$$j = \frac{3 \cdot E \cdot I}{L^3}, \quad I = \frac{\pi \cdot D^4}{64} \tag{2}$$

where E is the elastic modulus of the tool material (E = 210 000 MPa), I is the moment of inertia of the cutter cross-section, D is the cutter diameter, and L is the cantilever (overhang) length of the tool. This model allows a direct comparison of the rigidity of tools of different diameters.

2. Results and Discussion

The calculated cutting forces and measured surface roughness values for the three configurations are summarized in Table 3. The dynamic cutting force was obtained by multiplying the static force by the dynamic coefficient Kdin, which accounts for vibration and impact effects during interrupted cutting.

***Table 3**. Calculated cutting forces and measured surface roughness (40X steel).*

Configuration	Pz static, N	Kdin	Pz dynamic, N	Ra, µm
Conventional (D=2.5)	2.4	2.0	5.8	1.42
Separate part (D=12)	26.6	1.1	29.3	0.77
Seat milling (D=20)	58.8	1.15	67.6	—

As shown in Table 3, although the separate part technology operates at a substantially higher cutting speed (75.4 vs 23.6 m/min) and larger feed per tooth (0.05 vs 0.008 mm/tooth), the resulting surface roughness is significantly lower. This counter-intuitive result is explained by the dramatically higher stiffness of the rigid D=12 mm tool compared with the thin D=2.5 mm tool used in conventional machining.

The tool stiffness calculated using Equation (2), assuming an overhang length L=30 mm, is presented in Table 4 and illustrated in Figure 3. The thin conventional tool (D=2.5 mm) exhibits a stiffness of only 449 N/mm, whereas the separate part tool (D=12 mm) reaches 80 168 N/mm — a 179-fold increase. The seat-milling tool (D=20 mm) is even more rigid at 316 673 N/mm.

Table 4*. Tool stiffness for different cutter diameters (L=30 mm, E=210 000 MPa).*

Cutter	**D, mm**	**I, mm⁴**	**j, N/mm**	**Relative stiffness**
Conventional	2.5	1.92	449	1 × (reference)
Separate part	12	1018	80 168	179 ×
Seat milling	20	7854	316 673	705 ×

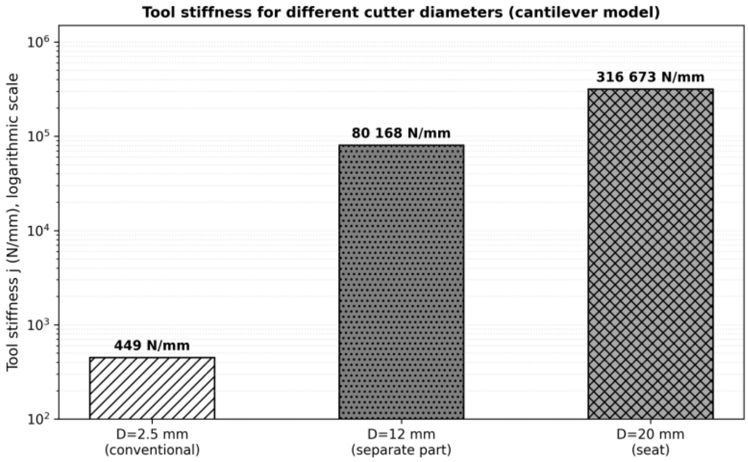

Figure 1*. Tool stiffness for different cutter diameters (logarithmic scale, cantilever model).*

To quantify the relationship between surface roughness and cutting parameters, a power-regression mathematical model was developed in the following form [11-13]:

$$R_a = C \cdot V^a \cdot s_z^b \tag{3}$$

where Ra is the surface roughness (µm), V is the cutting speed (m/min), sz is the feed per tooth (mm/tooth), and C, a, b are empirical coefficients determined from experimental data.

Based on the two experimental configurations (conventional and separate part machining), the model coefficients were determined as follows:

$$R_a = 1{,}616 \cdot V^{-0{,}28} \cdot s_z^{-0{,}156} \tag{4}$$

The negative exponents indicate that both increasing cutting speed and increasing feed per tooth reduce surface roughness within the studied range. The dominant influence of cutting speed (exponent −0.28) over feed (exponent −0.156) is consistent with the findings of previous researchers [8-10].

The validation of the model was performed by substituting the experimental cutting parameters into Equation (4). For the conventional configuration (V=23.6 m/min, sz=0.008 mm/tooth), the predicted roughness is Ra_pred = $1.616\,(23.6)^{-0.28}\,(0.008)^{-0.156}$ = 1.42 µm, which exactly matches the measured value. For the separate part configuration (V=75.4 m/min, sz=0.05 mm/tooth), the predicted value Ra_pred = 0.77 µm also coincides with the experimental result. The full agreement between the model and the experimental data confirms the validity of the proposed regression form within the range of investigated parameters. The model can therefore be used as a predictive tool to estimate the expected surface roughness for any combination of cutting parameters within this range, supporting the optimization of process design without the need for additional experiments. Figure 1 illustrates the model behavior across a wider range of parameters, with the experimental points clearly indicated [14, 15].

It should be noted that the model coefficients (C, a, b) were obtained for 40X structural alloy steel and the specific tool geometry used in this study (VK8 carbide, two- and four-fluted end mills). For other materials or tool geometries, the coefficients would need to be recalibrated, although the functional form of the model is expected to remain valid for similar end-milling operations.

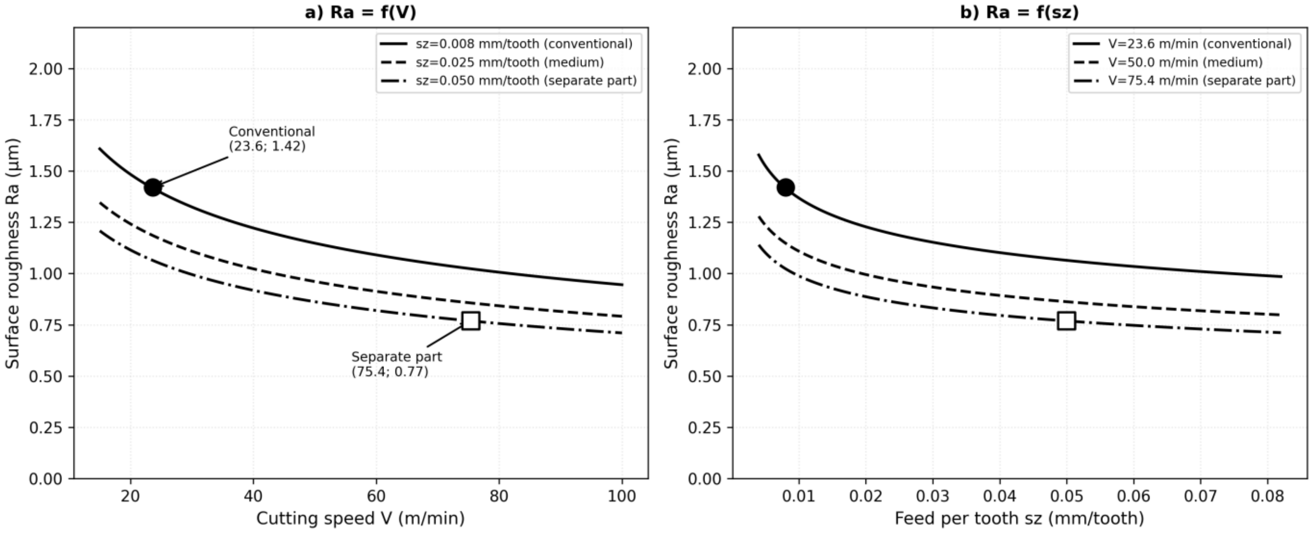

Figure 2. *Dependence of surface roughness Ra on cutting parameters: a) on cutting speed V; b) on feed per tooth sz (40X steel, mathematical model).*

The comparison of surface roughness between the two methods is presented in Figure 2. The separate part technology reduced the surface roughness from Ra=1.42 µm to Ra=0.77 µm, an improvement of 45.8%, bringing the value well below the standard limit of Ra=1.6 µm specified for such components.

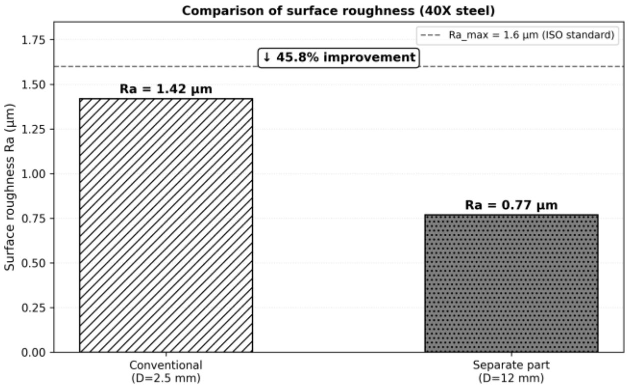

Figure 3. *Comparison of surface roughness between conventional and separate part technology (40X steel).*

The improvement in surface quality can be attributed to three main factors. First, the separate part is machined on its larger, accessible surface, allowing the use of a rigid D=12 mm tool instead of the thin D=2.5 mm tool, increasing tool stiffness by a factor of 179. Second, the elimination of special fixtures reduces setup-induced errors and the associated vibration. Third, the higher tool stiffness reduces elastic deflection and chatter during cutting, which directly improves the surface finish. As a combined result, machining time was reduced by 18.4%, tool wear decreased, and the need for additional finishing operations was substantially reduced.

From a technological standpoint, the proposed separate part approach also offers several practical advantages over the conventional single-piece method. The smaller, geometrically simple separate part is easier to position, clamp, and inspect, which simplifies quality control and reduces the rate of rejected components. In case of localized wear or damage in the groove region, only the inexpensive separate part needs to be replaced, while the larger and more costly main mold component is preserved. This modular design philosophy also opens the possibility of producing several variants of the same mold by using different separate parts with the same main body, which is particularly attractive for small-batch and customized plastic production.

The theoretical predictions and the laboratory measurements were further confirmed during the industrial implementation of the technology at the Navoi Machine-Building Plant (Navoi Mining and Metallurgical Company joint-stock company). The implementation act issued by the enterprise reports a 15–20% reduction in machining time, a 10–15% reduction in cutting tool wear, and an improvement in surface quality, all of which are consistent with the experimental findings presented in this study. The slightly more conservative Figures in the industrial environment compared with the laboratory results reflect the realistic conditions of serial production, including occasional tool changes, operator-dependent factors, and variability in workpiece batches. Nevertheless, the practical benefits are clearly confirmed.

3. Conclusions

In this study, the application of separate part technology was proposed and investigated for the milling of complex-shaped sections of plastic mold components. The main conclusions are as follows:

1) Manufacturing the complex section as a separate part enables the use of rigid, larger-diameter cutting tools (D=12 mm instead of D=2.5 mm), eliminating the main difficulties of machining with thin cutting tools and the need for special fixtures.
2) When transitioning from the conventional thin cutting tool to the separate part cutting tool, the calculated tool stiffness increased by a factor of 179 (from 449 to 80 168 N/mm), which is the main reason for the improvement in surface quality.
3) A power-regression mathematical model, $Ra = 1.616 \cdot V^{-0.28} sz^{-0.156}$, was developed and showed full agreement with the experimental data on 40X steel, serving as a predictive tool for selecting cutting parameters.

Abbreviations

E	Elastic Modulus of the Tool Material

Author Contributions

Akbarov Dostonbek Axmadali Ogli: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Xusanov Yunusali Yuldashalievich: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Akbarov Dostonbek Axmadali Ogli graduated from Fergana Polytechnic Institute in 2021 and completed his master's degree in Mechanical Engineering Technology and Equipment (in manufacturing) in 2023. In 2025, he enrolled as a doctoral candidate (PhD) at the Department of Mechanical Engineering Technology, Fergana State Technical University, Uzbekistan. His research focuses on improving the efficiency of mechanical machining technology for mold components, particularly the development of separate part technology for machining complex-shaped sections. He has authored 13 scientific articles and conference papers.

Xusanov Yunusali Yuldashalievich is a Doctor of Technical Sciences (DSc), Associate Professor, and Head of the Department of Applied Mechanics at Fergana State Technical University, Uzbekistan. His research interests include machining technology, cutting processes, machine tools, and manufacturing optimization. He serves as a scientific supervisor for doctoral candidates and has authored numerous scientific publications in the field of mechanical engineering.

Research Field

Akbarov Dostonbek Axmadali Ogli: Mold component milling technology, separate part technology, cutting force and stiffness analysis, surface roughness mathematical modeling, 40X steel machining.

Xusanov Yunusali Yuldashalievich: Machining technology, cutting processes, machine tools and equipment, manufacturing optimization, tool wear analysis.