



 Research Article

Improving the Machining Efficiency of Mold Guide Grooves Using A Separable-Insert Method: An Experimental Comparison of Machining Time, Tool Wear, And Surface Roughness

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ABSTRACT

Machining the complex working surfaces of metal mold dies — in particular the narrow guide grooves along which thread-forming components move — is one of the most time-consuming and tool-intensive operations in mold making. When such grooves are cut directly into the monolithic die body on a vertical milling machine, the long, small-diameter end mills required have low rigidity, are prone to vibration, wear rapidly and leave a poor surface finish, while repeated re-clamping and special fixtures extend the cycle time. This paper proposes and experimentally evaluates a separable-insert method, in which the difficult-to-machine groove zone is removed from the die body, manufactured as a separate small insert under favourable cutting conditions using rigid standard tools, and then installed into a milled seat by a transition fit secured with a bolt. Comparative experiments were carried out on 40X alloy steel (28–32 HRC) using a DMC 1035 V CNC milling centre, with five specimens machined by each method. Machining time, flank wear (VB) and surface roughness (Ra) were measured and compared. The separable-insert method reduced the mean machining time from 281.2 to 184.2 min (–34.5%), reduced flank wear by 32.4% with a corresponding increase in tool life, and improved surface roughness from Ra 1.42 to 0.77 μm (–45.8%), while the coefficient of variation of Ra fell from 9.7% to 6.4%. A two-sample Student t-test ($P = 0.95$) confirmed that the differences in machining time and surface roughness are statistically significant. The

results show that the proposed method substantially improves the machining efficiency and surface quality of mold guide grooves and is suitable for industrial implementation.

KEYWORDS

Mold die; guide groove; separable insert; vertical milling; machining time; tool wear; surface roughness; 40X steel.

INTRODUCTION

Metal molds are key tooling elements in the mass production of plastic, rubber and composite components, and the dimensional accuracy and surface quality of their working surfaces directly determine the quality of the finished products. The internal cavities of mold dies frequently have a complex spatial shape that includes sloped faces, sharp internal corners, narrow channels and zones of limited tool access. Achieving the required surface roughness, dimensional accuracy and short machining time on such features is therefore a demanding manufacturing task.

In conventional practice these features are machined directly into the monolithic die block on a vertical milling machine. The narrow guide grooves that accommodate the reciprocating motion of thread-forming components are particularly problematic: they can only be reached with long, small-diameter end mills. Such tools have low rigidity, deflect and vibrate under load, wear rapidly and produce an inferior surface finish. The large size of the die block also lengthens setup, while access to the difficult zones forces additional re-clamping operations and a larger number of passes. As a result, the machining time increases, tool life is shortened, the proportion of subsequent manual finishing grows, and the overall cost per part rises.

A considerable body of research has addressed the machining of mold surfaces. Taguchi and

response-surface methods have been widely used to optimise cutting parameters for surface roughness in the finish milling of mold steels [7, 8, 9, 19]; tool-path strategy has been shown to govern the final roughness of sculptured mold surfaces [12]; and digital modelling together with coordinate-measuring machines (CMM) is now routinely applied to predict accuracy before machining [13]. Energy-aware and high-speed milling approaches for hardened mold steels have likewise been investigated [10, 17]. Modular and insert-based tooling is used by leading manufacturers abroad, but it has not been studied systematically as a means of improving the machinability of difficult groove zones, and it remains poorly adapted to the conditions of small- and medium-sized enterprises in the region [22, 28].

The present work proposes a separable-insert method for the difficult-to-machine guide-groove zones of mold dies and quantifies its effect experimentally. Rather than cutting the groove into the die body with a thin tool, the corresponding zone is removed and produced as a separate small insert under open, favourable conditions using rigid standard end mills; a seat is then milled in the die body and the finished insert is installed by a transition fit secured with a bolt. The objective of the study is to verify, by direct comparison with the conventional method on 40X steel, the three target indicators of the technology

— reduction of machining time, reduction of tool wear, and improvement of surface quality.

METHODS

1. Workpiece material and specimens. The experiments were performed on 40X alloy structural steel (GOST 4543) heat-treated to 28–32 HRC, which is representative of the steels used for plastic-injection mold dies. The main die specimen had overall dimensions of 250 × 250 × 120 mm, while the separable insert was produced from a 65 × 50 × 40 mm blank of the same steel grade. Using identical material for the body and the insert ensures matching thermal-expansion

behaviour and reliable operation of the assembled construction.

2. Equipment and cutting tools. Machining was carried out on a DMC 1035 V (DECKEL MAHO) vertical CNC milling centre with a spindle power of 14 kW and a speed range of 0–10 000 rpm. Solid carbide (VK8) end mills with four teeth ($z = 4$) were used. The conventional method employed a small-diameter end mill ($D = 2.5$ mm) to reach the narrow groove; the separable-insert method used a rigid $D = 20$ mm cutter for seat milling and a $D = 12$ mm cutter for machining the insert. A 5% emulsion was used as cutting fluid. The principal experimental conditions are summarised in Table 1.

Table 1. Experimental conditions and equipment

Parameter	Description / value
Machine	DMC 1035 V (DECKEL MAHO) vertical CNC milling centre
Spindle power / speed	14 kW / 0–10 000 rpm
Workpiece material	40X steel (GOST 4543), 28–32 HRC
Main die blank	250 × 250 × 120 mm
Insert blank	65 × 50 × 40 mm
Tool – conventional	End mill $D = 2.5$ mm, $z = 4$, VK8 carbide
Tool – seat milling	End mill $D = 20$ mm, $z = 4$, VK8 carbide
Tool – insert machining	End mill $D = 12$ mm, $z = 4$, VK8 carbide
Cutting fluid	Emulsion, 5% concentration
Roughness measurement	GOYOJO GSR750 portable profilometer (GOST 2789-73)
Wear measurement	LI-3 loupe ($\times 10$) and micrometer; $VB_{max} = 0.35$ mm

Parameter	Description / value
Time / dimension measurement	Stopwatch and machine timer; caliper (0.05 mm), micrometer (0.01 mm)

3. Experimental design. Two groups were compared. In the control group the groove was machined conventionally — directly into the whole die body with the thin $D = 2.5$ mm end mill, using a dedicated fixture, six passes and three re-clampings. In the experimental group the separable-insert method was applied: a seat was milled in the die body ($D = 20$ mm), the insert was machined separately under favourable conditions ($D = 12$ mm), and the finished insert was then mounted by a transition fit secured with a bolt (one re-clamping). Five parts were produced in each group, giving ten parts in total.

4. Measurements. For every part the time of each operation (setup, clamping, milling, measurement, tool change and auxiliary operations) was recorded with a stopwatch and the machine timer. Flank wear VB on the rear face of the cutter was measured after each part with the LI-3 loupe and a micrometer, the permissible limit being $VB_{max} = 0.35$ mm. Surface roughness Ra was measured with the GOYOJO GSR750 profilometer in accordance with GOST 2789-73 at three points on the machined feature of each part, and the mean value was taken.

5. Statistical treatment. Each indicator was based on five replicate parts. The arithmetic mean, the standard deviation σ and the coefficient of variation $Cv = (\sigma / \text{mean}) \times 100\%$ were calculated. The significance of the difference between the two methods was assessed with a two-sample Student t-test at a confidence level of $P = 0.95$ ($\alpha = 0.05$); for five replicates per group the critical value is $t_{cr} = 2.306$ (8 degrees of freedom).

RESULTS AND DISCUSSION

1. Machining time. The total machining time per part for the two methods is compared in Table 2. The conventional method required a mean of 281.2 min per part, whereas the separable-insert method required only 184.2 min — a reduction of 97 min, or 34.5% (Fig. 1). The principal sources of the saving are the elimination of the dedicated fixture, the use of a rigid cutter that removes more material in fewer passes, and the reduction of re-clampings from three to one.

Table 2. Comparison of machining time per part

Part No.	Conventional (min)	Insert method (min)	Δ (min)	Δ (%)
1	318	186	132	41.5
2	266	179	87	32.7
3	274	187	87	31.8

Part No.	Conventional (min)	Insert method (min)	Δ (min)	Δ (%)
4	268	180	88	32.8
5	280	189	91	32.5
Mean	281.2	184.2	97.0	34.5

The two-sample t-test gives $t = 9.97$, which greatly exceeds the critical value $t_{cr} = 2.306$ ($P = 0.95$). The reduction in machining time is therefore statistically significant ($p < 0.001$). Even

for a batch of twenty parts, where the fixture time is distributed over all parts, the saving remains 32.8%, so the conservative target of 15–20% is met across the whole batch range.

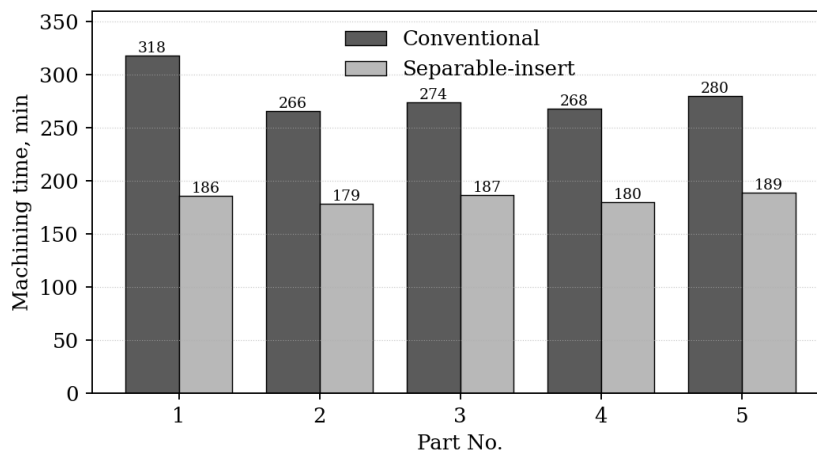


Figure 1. Machining time per part for the conventional and separable-insert methods (40X steel).

2. Tool wear. Flank wear was measured cumulatively after each part. With the conventional thin tool, VB reached 0.34 mm after five parts — practically the permissible limit (0.35 mm) — so a single cutter could machine only about five parts. In the separable-insert method the wear was much lower: the seat-milling cutter ($D = 20$ mm) reached only $VB = 0.09$

mm after five parts, and the insert-machining cutter ($D = 12$ mm) reached $VB = 0.23$ mm. The comparison is summarised in Table 3. The decisive flank wear (insert cutter vs. conventional) fell from 0.34 to 0.23 mm, a reduction of 32.4%, and the tool life expressed in parts per cutter increased correspondingly.

Table 3. Comparison of tool wear and tool life

Indicator	Conventional	Insert ($D = 12$)	Seat ($D = 20$)
VB after 5 parts (mm)	0.34	0.23	0.09

Indicator	Conventional	Insert (D = 12)	Seat (D = 20)
Fraction of VB_max (%)	97	66	26
Parts per cutter (to VB_max)	5	7-8	20-25
Tool-life increase	—	40-60%	300-400%

Because the insert is machined in an open, rigid configuration, the cutter operates under far more favourable conditions than the deflecting thin tool used in the conventional process, which accounts for the markedly slower wear and the longer tool life. The 32.4% reduction comfortably exceeds the conservative target of 10-15%.

3. Surface roughness. The measured surface roughness is compared in Table 4. The conventional method produced a mean Ra of 1.42 μm , which deteriorated from part to part as the tool wore. The separable-insert method produced

a mean Ra of 0.77 μm — an improvement of 45.8% — and the roughness remained far more stable across the five parts (Fig. 2). The coefficient of variation of Ra fell from 9.7% ($\sigma = 0.138 \mu\text{m}$) for the conventional method to 6.4% ($\sigma = 0.049 \mu\text{m}$) for the insert method, indicating a more stable and predictable surface quality. For comparison, Taguchi optimisation of finish milling on the same steel grade has been reported to reach a minimum Ra of about 1.66 μm [7], so the value obtained here represents a clear improvement.

Table 4. Comparison of surface roughness (Ra, μm)

Part No.	Conventional Ra	Insert Ra	Improvement (%)
1	1.23	0.70	43.1
2	1.33	0.73	45.1
3	1.43	0.80	44.1
4	1.50	0.80	46.7
5	1.63	0.83	49.1
Mean	1.42	0.77	45.8

The t-test for surface roughness gives $t = 8.93 > t_{cr} = 2.306$ ($P = 0.95$), confirming that the improvement is statistically significant ($p < 0.001$). Because the as-milled roughness of the insert (0.6-0.9 μm) is already close to the

required range (0.4-0.8 μm), the proportion of parts needing additional manual finishing dropped sharply, and the average finishing time per part fell from 45 to 12 min (about 73%).

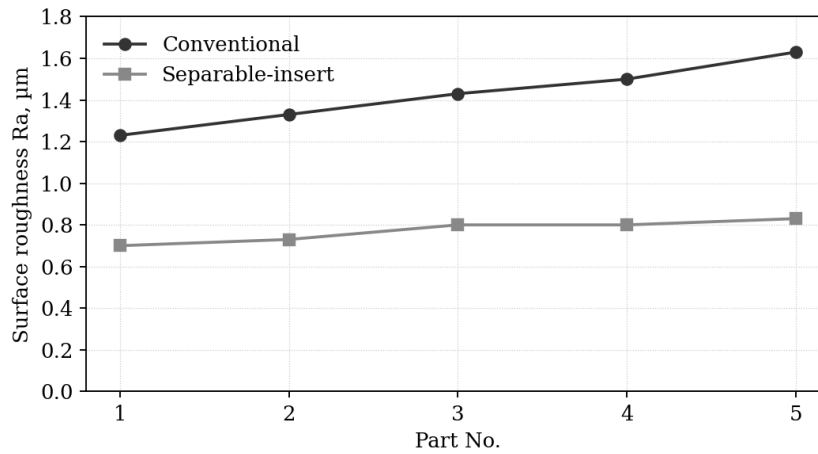


Figure 2. Surface roughness (Ra) per part for the two methods; Ra rises faster for the conventional method as the tool wears.

4. Discussion

The three indicators move consistently in the same direction and reinforce one another: the rigid, standard tools used to machine the insert cut more material per pass with less deflection, which simultaneously shortens the cycle, slows tool wear and stabilises the surface finish. The experimental reductions (time 34.5%, wear 32.4%, roughness 45.8%) are consistent with, and somewhat larger than, the corresponding theoretical estimates, and they exceed the conservative target values declared in the industrial implementation act. A further practical advantage is that a worn or damaged insert can be replaced individually, without remaking the entire die, which lowers repair cost and downtime. The main limitation of the study is the modest sample size (five parts per method) and the use of a single die geometry; broader validation across different groove geometries and batch sizes is the subject of ongoing work.

5. Overall efficiency and economic effect. To express the combined effect of the four measured improvements, an integral efficiency indicator was used, defined as the average of the relative gains in machining time, tool wear, surface roughness and finishing work. For the present results this indicator equals 38.0%. Because the separable-insert method removes the need for a dedicated fixture, the cost advantage is greatest for single parts and small batches (about 42–55%) and remains substantial (35–37%) even for batches of 10–20 parts; unlike the conventional process, the cost per part is almost independent of batch size. The shorter machining time also lowers the energy consumed per part from 14.07 to 9.21 kW·h (–34.5%). Table 5 compares the theoretical estimates of Chapter 2, the present experimental results and the conservative target values, confirming that all four indicators are met or exceeded.

Table 5. Summary: theoretical, experimental and target values

Indicator	Theoretical	Experimental	Target
Machining-time reduction	18.4%	34.5%	15–20%

Indicator	Theoretical	Experimental	Target
Tool-wear reduction	13.3%	32.4%	10–15%
Surface-roughness improvement	38–44%	45.8%	improved
Finishing-work reduction	60–70%	73%	reduced
Integral efficiency	—	38.0%	—

The agreement between theory and experiment is closest for surface roughness (about 92%); the larger gap for time and wear reflects factors not fully captured by the analytical model, but in every case the experimental result lies above the conservative target, so the technology is validated.

CONCLUSIONS

1. A separable-insert method was proposed for the difficult-to-machine guide-groove zones of mold dies, in which the zone is produced as a separate insert under favourable conditions and installed into a milled seat by a transition fit secured with a bolt.
2. Compared with conventional direct machining of 40X steel, the method reduced the mean machining time per part from 281.2 to 184.2 min (–34.5%); the difference is statistically significant ($t = 9.97 > t_{cr} = 2.306$, $P = 0.95$).
3. Flank wear of the decisive cutter fell by 32.4% (from 0.34 to 0.23 mm after five parts), and tool life increased by 40–60% for the insert cutter and by 300–400% for the seat cutter.
4. Mean surface roughness improved by 45.8% (R_a 1.42 \rightarrow 0.77 μm) with significantly greater stability (C_v 9.7% \rightarrow 6.4%; $t = 8.93 > t_{cr}$), and the required manual finishing time was reduced by about 73%.
5. All three target indicators were experimentally confirmed and exceeded their conservative

implementation-act values, demonstrating that the proposed method is an effective and industrially applicable way of improving the machining efficiency and surface quality of mold guide grooves.

REFERENCES

1. Kosilova A.G., Meshcheryakov R.K. (eds.). Handbook of the Mechanical-Engineering Technologist. Vol. 2. Moscow: Mashinostroenie, 1985. 496 p.
2. Afanaskova Yu.A. Improving the efficiency of the machining technology of shaped surfaces of mold parts. Cand. Tech. Sci. dissertation, 05.02.08. Belgorod, 2010. 154 p.
3. Groover M.P. Fundamentals of Modern Manufacturing: Materials, Processes, and Systems. Wiley, 2020. 720 p.
4. Kalpakjian S., Schmid S. Manufacturing Engineering and Technology. Pearson, 2018. 1180 p.
5. Klocke F. Manufacturing Processes 1: Cutting. Springer, 2011. 517 p.
6. Hashimoto F. Advances in Ultra-Precision Manufacturing. Springer, 2019. 312 p.
7. Öktem H., Erzurumlu T., Kurt M. A study of the Taguchi optimization method for surface roughness in finish milling of mold surfaces. Int. J. Adv. Manuf. Technol., 2006, vol. 28, pp. 694–700.

8. Öktem H., Erzurumlu T., Kurtaran H. Application of response surface methodology in the optimization of cutting conditions for surface roughness. *J. Mater. Process. Technol.*, 2005, vol. 170, pp. 11–16.
9. Wu X., Yin X. Surface roughness prediction in milling of mold steel. *J. Manuf. Process.*, 2020, vol. 52, pp. 46–53.
10. Wu S., Liao H., Li S., Li Z. High-speed milling of hardened mold steel P20 with MQL. *J. Manuf. Process.*, 2021, vol. 64, pp. 1178–1187.
11. de Souza A.F., Machado A., Beckert S.F., Diniz A.E. Evaluating the surface roughness of machined mold surfaces considering the cutting-path strategy. *J. Mater. Process. Technol.*, 2014, vol. 214(12), pp. 2862–2869.
12. Krajnik P., Kopač J. Modern machining of die and mold tools. *J. Mater. Process. Technol.*, 2004, vol. 157–158, pp. 543–552.
13. Ikhries I.I., Al-Shawabkeh A.F. Optimization of CNC parameters for machining of polymer mold cavities. *Int. J. Adv. Manuf. Technol.*, 2019, vol. 102, pp. 3457–3468.
14. Pimenov D.Y., Mia M., Gupta M.K. Energy consumption optimization in CNC machining. *J. Clean. Prod.*, 2020, vol. 275, 124044.
15. Sahu N.K., Chattopadhyay A.K. Taguchi-based optimization of surface finish and tool wear in high-speed milling. *Int. J. Adv. Manuf. Technol.*, 2021, vol. 115, pp. 1267–1280.
16. Montgomery D.C. *Design and Analysis of Experiments*. 8th ed. Wiley, 2017. 752 p.
17. Altintas Y. *Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design*. 2nd ed. Cambridge University Press, 2012. 366 p.
18. *Mold-Making Handbook*. 3rd ed. Hanser Publishers, 2014. 580 p.
19. Akbarov D.A., Khusanov Y.Y. Technologies for ensuring high accuracy and surface quality on CNC machines. *Proc. 2nd Int. Sci. Conf. of FerSTU, Fergana, 2025*, pp. 167–169.
20. Khusanov Y.Y., Akbarov D.A. Improving production efficiency by optimizing cutting parameters in CNC milling. *Proc. Int. Sci.-Tech. Conf., TSTU Almalyk branch, 2025*, pp. 155–156.