EFFECT OF INSERT GROOVE GEOMETRY ON CHIP BREAKING PERFORMANCE

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ABSTRACT

The insert groove geometry is an important part of turning tool design. In this article, a systematic design approach is presented for the chip breaker design in turning. The chip breaking ability of various groove geometry of a turning insert is investigated. The ratio of chip thickness to chip curl radius is taken as the index of chip breaking performance. Taguchi method is applied to analyze the contribution to chip breaking performance of each geometric parameter. Response surface methodology is then used to construct a predictive model evaluating the effect of turning conditions and groove geometry on chip breaking performance. The result of this study shows that the feed rate significantly affects chip breaking performance, and that insert with larger land angle, higher back wall and smaller groove is more effective in chip breaking. Among the parameters of the insert groove, the width of the groove has the greatest contribution to chip breaking than the others. The simulation results and predictions are validated by turning experiments.

Keywords: Turning, Insert geometry, Chip breaking.

1. INTRODUCTION

A properly designed chip breaking groove geometry is essential for turning operations. Poor chip breaking capability in turning can cause adverse effects on the part quality and user safety and compromises the productivity of turning processes. The machining processes are characterized by complicated elasto-visco-plasticity behaviors of the work and tool materials, which are highly dependent on the cutting speed and material properties. An optimal chip breaker design for a certain work material under certain cutting conditions is often not applicable for a different type of material or under a different cutting speed or feed rate. The iterative process of tool design, manufacturing and validation experiments in designing a new, optimal insert for a specific material under given cutting conditions is often time consuming and costly. It is the purpose of this paper to present a systematic, effective approach by combining the Taguchi method and response surface methodology (RSM) to yield an optimal chip breaker design. SS316 is commonly considered to be the type of material with poor chip breaking property and is chosen as the target material for this work.

Nakayama [1] proposed a chip breaking criterion by using the ratio of chip thickness to the chip curl radius. Some researchers established database of different geometry parameters of insert groove for insert groove design [2]. The concept of equivalent parameters was applied to study the geometric relationship between the chip and the tool [3]. The same concept was used by other researchers to predict chip formation of turning tools [4]. Neural network was used to evaluate the performance of chip breaker [5]. The simulation software, AdvantEdge, was applied to analyze the low-feed processes in turning AISI 4140 with different types of insert groove, and the study indicated that simulation results serve well as a reference for insert groove design [6]. The chip breaking performance of an asymmetric groove type in turning medium carbon steel was presented in [7]. Experiments were conducted within common ranges of six geometric parameters. From these experimental results, multiple linear regressions were used to find the minimum feed and minimum depth of cut for chip breaking performance.

Both Taguchi method and RSM are frequently applied as tools for design of experiment in many different fields especially in engineering. Taguchi method and its associated analysis of variance (ANOVA) method are efficient tools in qualitatively analyzing and identifying the contribution to performance index of each influencing factor. In comparison, the response surface meth-

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odology can be used to construct a quantitative response surface as functions of the major influencing factors so that the effects of factors can be quantitatively investigated and an optimal combination of factors can be obtained for desired performance measures. Taguchi method has been applied to analyze the effects of cutting conditions on surface roughness in face milling [8] and turning [9-11]. They were also used in the design of other types of tool such as the optimization of micro drill geometry [12]. A combination of RSM and Taguchi methods have been used by many researchers to investigate the effects of various turning parameters on the surface roughness as presented by Ranganath *et al*. in [13]. However, the use of RSM or the combination of Taguchi method and RSM for chip breaker design has not been reported.

In this article, a systematic approach combining the Taguchi method and RSM is presented to find the optimal chip breaker design in turning SS316 under a certain feed rate and cutting velocity. The finite element analysis software, AdvantEdge, is applied to simulate the turning process with different designs of insert. This approach disposes of the typical iterative cycle of design, fabrication and validation in a new insert development, and can be conveniently adapted for other type of work materials or under different cutting conditions. In the following, Taguchi method is first applied to analyze and validate the contribution to chip breaking performance of main geometric parameters. RSM is then adopted to construct a predictive model prescribing the effect of turning conditions and groove geometry on chip breaking performance. The proposed design using this model is finally validated by experiments.

2 PARAMETRIC ANALYSIS BY TAGUCHI METHOD

In the Taguchi method, the control factors as the inputs to the system and the performance index have to be specified. The ratio of chip thickness to chip curl radius (t_c/R_c) is taken as the index of chip breaking performance and also as the quality characteristic of Taguchi analysis. Based on the existing design of the insert groove for the SS316, three main geometry parameters are chosen as the control factors in this study as shown in Fig. 2. Table 1 shows three common levels for the three parameters. An L9 orthogonal array is used to analyze the effect of the three parameters on chip breaking performance. The values of t_c and R_c are found from the machining simulation. To simplify the simulation, a true turning process is approximated by the 2D orthogonal simulation as shown in Fig. 1.

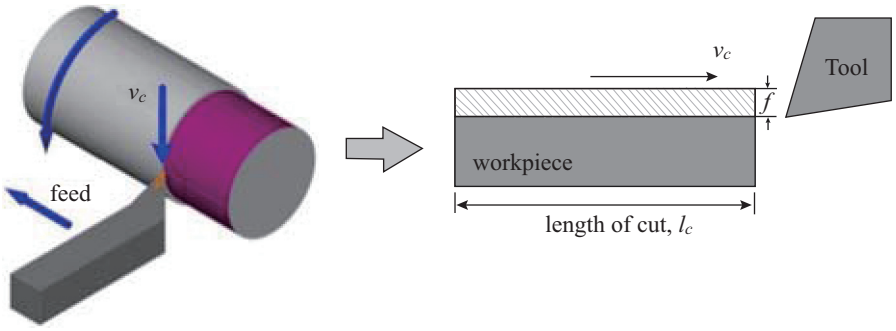


Fig. 1 The simplified orthogonal turning parameters adapted in simulation.

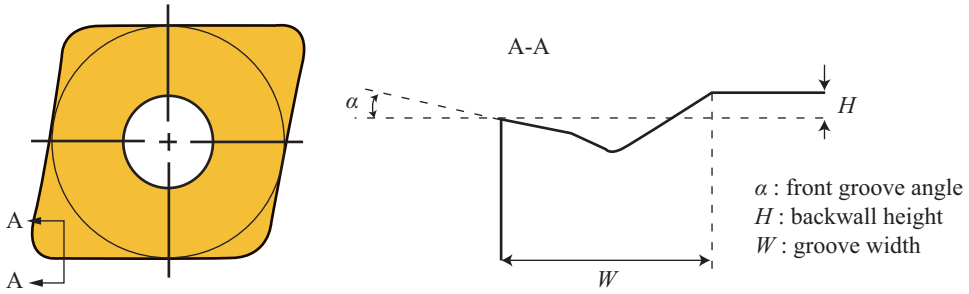


Fig. 2 Main geometry of turning insert groove.

For the intended turning operation for SS316, the cutting conditions in the simulations are set at V_c = 150 m/min, a_p = 2 mm and f = 0.2 mm/rev. The design of experiments and measured t_c/R_c values are listed in Table 2. Since the higher quality characteristic value, t_c/R_c, the better the chip breaking performance is, a high S/N ratio (η) is the design target of the analysis. The S/N ratios were calculated by using Eq. (1) and given in

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Table 1 Three levels of the groove geometry parameters.

	α (deg)	W (mm)	H (mm)
Level 1	12	1.2	0
Level 2	15	1.5	0.05
Level 3	18	1.8	0.1

Table 2 The results of the simulations and *S/N* ratios.

EXP	A (deg)	W (mm)	H (mm)	t_c/R_c	η
1	12	1.2	0	0.376	-8.474
2	12	1.5	0.05	0.296	-10.574
3	12	1.8	0.1	0.268	-11.409
4	15	1.2	0.05	0.571	-4.853
5	15	1.5	0.1	0.392	-8.117
6	15	1.8	0	0.248	-12.104
7	18	1.2	0.1	0.737	-2.64
8	18	1.5	0	0.385	-8.29
9	18	1.8	0.05	0.334	-9.511

Table 2.

$$\eta = -10\log\left[\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

Table 3 is the response table for t_c/R_c with respect to different levels of control factors as depicted in Fig. 3. Figure 3 indicates that insert with a larger land angle, higher back wall and narrower groove is more effective in chip breaking. Table 4 lists the contribution (ρ) of each factor to the quality characteristics. The groove width is shown to have greater contribution than the other factors.

Table 3 S/N response table for t_c/R_c index.

	α	W	H
Level 1	-10.153	-5.323	-9.623
Level 2	-8.358	-8.994	-8.313
Level 3	-6.814	-11.008	-7.389

3. ESTABLISHMENT OF THE FITNESS ODEL

The Taguchi analysis in section 2 identifies in an efficient way the main geometric parameters, but only provides a qualitative comparison of their contributions to the chip breaking performance. In order to find the optimal parametric values for the chip breaker, RSM is applied to establish a quantitative fitness model so that the best chip breaking index within the whole parametric

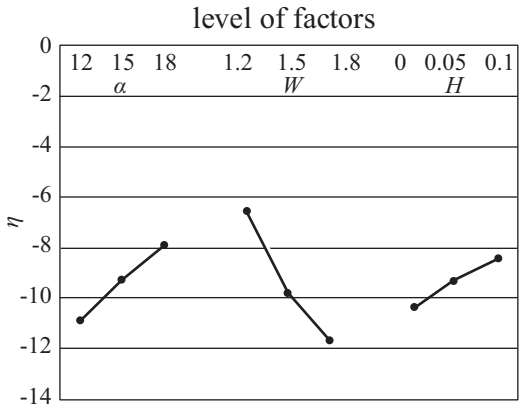


Fig. 3 The mean of S/N ratios versus factor levels.

Table 4 ANOVA table of the groove geometry parameters.

	SS	DoF	Var	ρ (%)
α	16.752	2	8.376	22.464
W	49.857	2	24.928	66.857
H	7.563	2	3.782	10.142
error	0.4	2	0.2	0.537
total	74.572	8	---	100

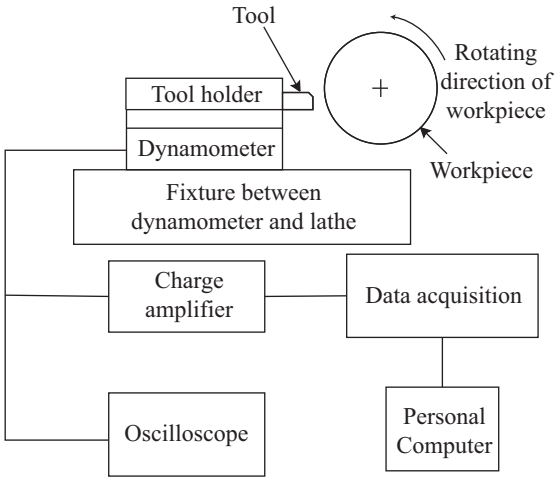


Fig. 4 Setup for force measurements.

space can be found and the best parametric combination can be identified. As the feed rate is the main factor affecting the chip thickness, it is taken as the fourth factor in constructing the fitness model. The response surface methodology uses a 4-factor Box-Behnken design with 25 sets of parametric combinations. From the results of these 25 simulations, three linear regression models are constructed: the first order model, the first order model with interaction, and the second order model. The R^2_{adj} and standard deviation of each model are found to be (0.955, 0.078), (0.960, 0.074) and (0.978, 0.032), respectively. The second order model has the

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best R^2_{adj} and minimum standard deviation, and is chosen as the fitness model with

$$\frac{t_c}{R_c} = 0.868 - 0.548W - 2.455H - 0.027\alpha W + 0.183\alpha H + 0.219\alpha f - 0.677WH - 3.051Wf + 10.321Hf + 0.371W^2 - 4.710H^2 + 8.499f^2 \quad (2)$$

This fitness model is verified using several sets of parameters. The model predictions are presented in Table 5 to agree very well with simulation results.

Table 5 Verification results of the fitness model.

No.	α	W	H	f	t_c/R_c obtained by FEM simulation	t_c/R_c by Eq. 2	Err. (%)
1	15	1.66	0.1	0.2	0.381	0.388	1.84
2	12	1.8	0.05	0.2	0.272	0.285	4.78
3	18	1.2	0.1	0.2	0.716	0.72	2.37
4	15	1.2	0	0.1	0.516	0.523	1.36
5	12	1.8	0.05	0.15	0.244	0.254	4.1
6	18	1.5	0.1	0.25	0.687	0.718	4.51

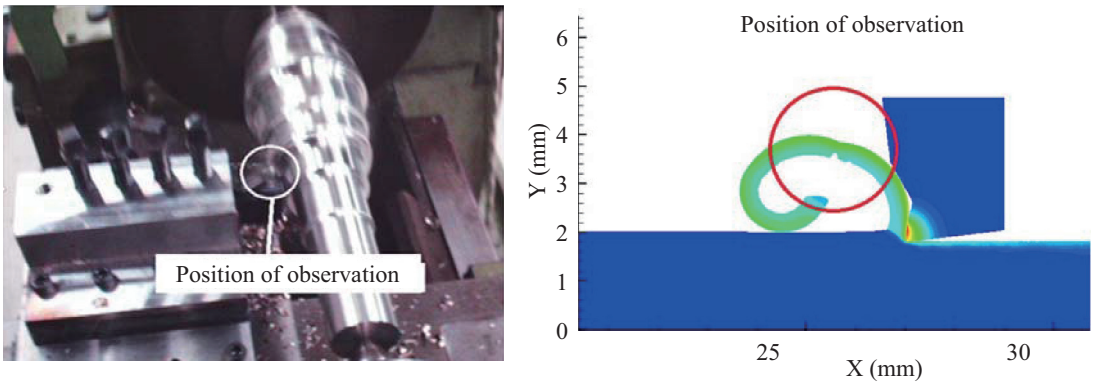


Fig. 5 The temperature measurement point.

This model is then used to obtain the optimal groove geometry at a specific range of feed rate. The desired range of feed rate for the model is set to be between 0.15~0.25 mm/rev. This is the most commonly adopted range in the machining industry for the intended intermediate turning operations of SS316. The optimal groove geometry is determined at the feed rate of 0.2 mm/rev. The variable f is substituted by 0.2 and a genetic algorithm is used to obtain the optimal values of α, W and H in making t_c/R_c a maximum value. The optimal parameters are given in Table 6.

Table 6 Optimal groove geometry for feed rate = 0.2 mm/rev.

α (deg)	17.922
W (mm)	1.221
H (mm)	0.1
Fitness value (t_c/R_c)	0.717

4. COMPARISON BETWEEN SIMULATION AND EXPERIMENTAL RESULTS

As the evaluation of performance index, t_c/R_c, in both the Taguchi method and RSM rely on the machining simulation, the simulation results need to be first validated. In this section, the results of simulation and experiment are compared in three parts: cutting force, cutting temperature and chip morphology. The work material is SS316 with yield and tensile strengths of 290 and 580 MPa, respectively. Each set of experiment were repeated for three times with the same cutting conditions. Experimental cutting forces are measured by a piezoelectric dynamometer, KISTLER Type-9254B in the cutting and feeding directions. The setup for the force measurement is shown in Fig. 4 with results listed in Table 7. Cutting temperatures are measured by a thermographic camera, NEC TVS-200EX. Figure 5 depicts the position where the thermal images were taken. Temperatures measured by simulation and ex-

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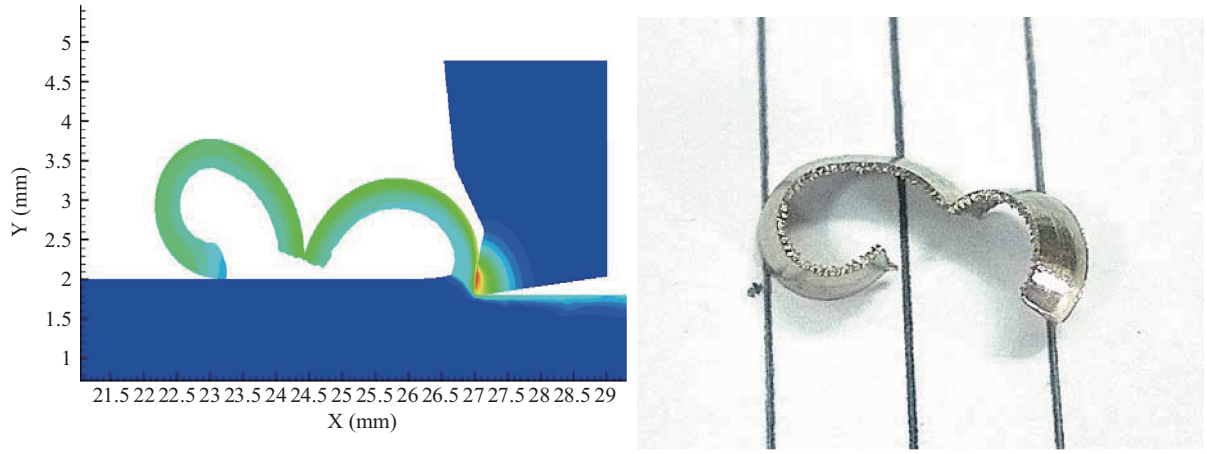


Fig. 6 Chip morphologies from simulation and experiment. f = 0.2 mm, a_p = 2.0 mm, V_c = 150 m/min.

Table 7 Comparison of cutting forces between simulation and experiment.

Cutting conditions	f = 0.15 mm, a_p = 2.0 mm, V_c = 150 m/min			f = 0.2 mm, ap = 2.0 mm, V_c = 150 m/min		
	Sim.	Exp.	Err.	Sim.	Exp.	Err.
Cutting force, F_t (N)	650 ± 20	720 ± 20	9.72%	805 ± 20	880 ± 20	8.52%
Feeding force, F_r (N)	330 ± 20	350 ± 20	5.71%	350 ± 20	375 ± 20	6.67%

Table 8 Temperatures by simulation and experiments.

Cutting speed, V_c (m/min)	120			150		
	Sim.	Exp.	Err.	Sim.	Exp.	Err.
Temperature (°C)	365 ± 15	323.7 ± 10	-13.00%	380 ± 15	333.3 ± 10	-14.11%

Table 9 Chip thicknesses and chip curl radiuses measured in simulation and experiment.

Turning conditions: V_c = 150 m/min, f = 0.2 mm/rev, a_p = 2 mm		
	Sim.	Exp.
t_c (mm)	0.369	0.36
R_c (mm)	0.932	0.96

periments are listed in Table 8. The chip morphologies from simulation and experiment are also shown to be quite similar in Fig. 6; Table 9 presents the predicted and measured chip thickness and chip curl radius. The simulation measurements agree quite well with the experimental results. The deviations in the cutting force, chip thickness and cutting temperature could result from differences between the true material properties of the workpiece and the material constants used for the constitutive equation in the simulation software. The orthogonal cutting condition in the simulation is an approximation of the true turning conditions of more complex tool/work contact and could also be a source of difference. Based on the simulation and experimental results, the finite element software AdvantEdge can be justified for its use in the turning process simulations.

5. RESULTS OF VERIFICATION EXPERIMENTS FOR INSERT DESIGN

Three uncoated turning inserts with different groove designs were fabricated and compared through experiments in this section to validate the fitness model. The geometry parameters of these three inserts are given in Table 10. Insert 1 is the one available on the market, insert 2 is the optimal design in Table 6 obtained in the last section, and insert 3 is predicted as the one with the worse performance at chip breaking than the other two. The chip morphologies for the three inserts are displayed in Figs. 7, 8 and 9. Figure 8 confirms that inert 2 has the best performance for the intended ranges of cutting parameters with a feed rate of 0.15 to 0.25 mm. At feed rates of 1 and 1.5 mm, both insert 1 and 3 yield continuous chip for a smaller width of cut, but insert 2 still delivers desired chip breaking performance. The feed rate is demonstrated to significantly affect the chip breaking performance of an insert and a properly designed groove width needs to match with the desired range of feed rate. The experimental results further find that, although the insert with a smaller groove width is better at chip breaking at the intended range of feed rate, its cutting force is larger because the smaller groove width incurs a higher chip compression ratio.

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Table 10 Geometric parameters of the three inserts.

	α (deg)	W (mm)	H (mm)
No. 1	15	1.66	0.1
No. 2	18	1.2	0.1
No. 3	12	1.8	0.1

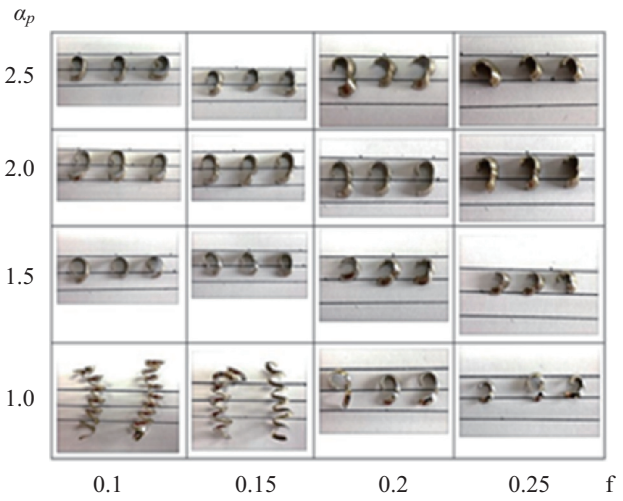


Fig. 7 Chip morphologies of insert 1 with respect to feed and depth of cut.

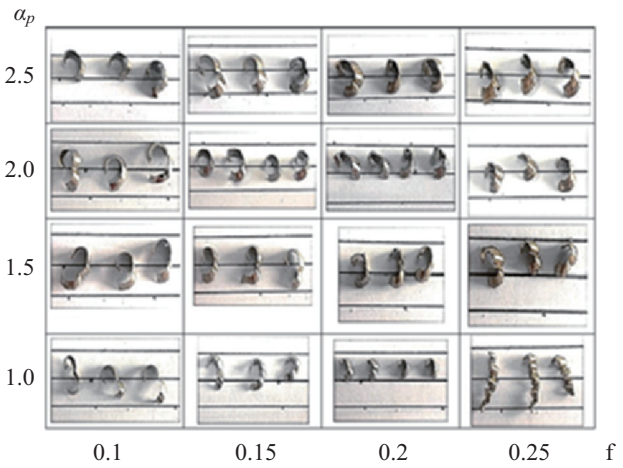


Fig. 8 Chip morphology of insert 2 with respect to feed and depth of cut.

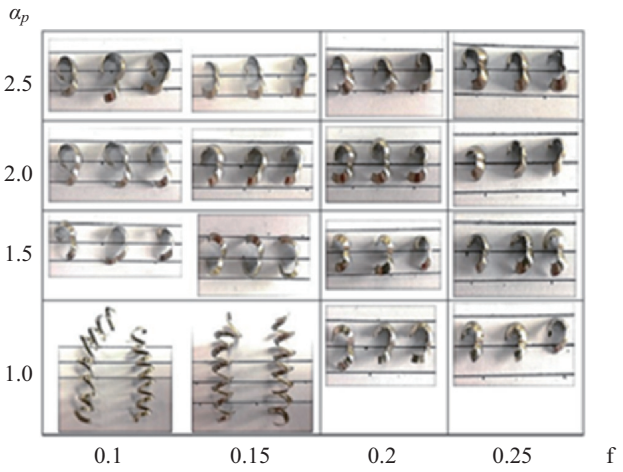


Fig. 9 Chip morphology of insert 3 with respect to feed and depth of cut.

6. CONCLUSIONS

A systematic design approach has been presented for the chip breaker design in turning. The chip radius to thickness ratio obtained from the finite element simulation is used as the criterion of chip breaking performance for various groove geometry of the turning insert. Taguchi method is adopted to investigate the effect of various insert groove geometry on chip breaking performance. A fitness model by RSM to estimate the chip breaking performance is then established and is used to obtain the optimal groove geometry at a specific feed rate. Experimental results show that the presented systematic approach and predictive model are effective in selecting appropriate groove parameters for chip breaking performance at the desired federate and cutting velocity. Inserts with a larger land angle, higher back wall and smaller groove is more effective in chip breaking. Among the main parameters of the insert groove geometry, the width of groove has the greatest contribution to chip breaking than the others. At conditions of lower feed rate, a smaller groove width has better chip breaking performance.

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REFERENCES

1. Nakayama, K., "A study on chip-breaker." *Bulletin of JSME*, **5**, pp. 142-150 (1962).
2. Jawahir, I. and Fang, X., "A knowledge-based approach for designing effective grooved chip breakers—2D and 3D chip flow, chip curl and chip breaking," *The International Journal of Advanced Manufacturing Technology*, **10**, pp. 225-239 (1995).
3. Rahman, M., Seah, K., Li, X. and Zhang, X., "A three-dimensional model of chip flow, chip curl and chip breaking under the concept of equivalent parameters," *International Journal of Machine Tools and Manufacture*, **35**, pp. 1015-1031 (1995).
4. Choi, J. P. and Lee, S. J., "Efficient chip breaker design by predicting the chip breaking performance," *International Journal of Advanced Manufacturing Technology*, **17**, pp. 489-497 (2001).
5. Kim, H. G., Sim, J. H. and Kweon, H. J., "Performance evaluation of chip breaker utilizing neural network," *Journal of Materials Processing Technology*, **209**, pp. 647-656 (2009).
6. Sreekala, P. and Visweswararao, K., "A Methodology for Chip Breaker Design at Low Feed Turning of Alloy Steel using Finite Element Modeling

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Methods," *International Journal of Mechanical Engineering and Technology*, **3**, pp. 263-273 (2012).

7. Fang, N., "Influence of the geometrical parameters of the chip groove on chip breaking performance using new-style chip formers", *Journal of Materials Processing Technology*, **74**, pp. 268-275 (1998).
8. Bagci, E. and Aykut, S., "A study of Taguchi optimization method for identifying optimum surface roughness in CNC face milling of cobalt-based alloy (stellite 6)," *The International Journal of Advanced Manufacturing Technology* **29.9-10**, pp. 940-947 (2006).
9. Thamizhmanii, S., Saparudin, S. and Hasan, S. "Analysis of surface roughness by turning process using Taguchi method," *Journal of Achievements in Materials and Manufacturing Engineering*, **20**, pp. 503-506 (2007).
10. Krishankant, J. T., Bector, M. and Kumar, R., "Application of Taguchi method for optimizing turning process by the effects of machining parameters," *International Journal of Engineering and Advanced Technology*, **2**, pp. 263-274 (2012).
11. Singari, R. M. and Vipin, "Optimization of Process Parameters in Turning Operation Using Taguchi Method and Anova: A Review", *International Journal of Advance Research and Innovation*, **1**, pp. 31-45 (2013).
12. Yoon, H.-S., Wu, R., Lee, T.-M. and Ahn, S.-H., "Geometric optimization of micro drills using Taguchi methods and response surface methodology," *International Journal of Precision Engineering and Manufacturing*, **12**, pp. 871-875 (2011).
13. Singari, R. M., Vipin and Harshit, "Optimization of Process Parameters in Turning Operation Using Response Surface Methodology: A Review", *International Journal of Emerging Technology and Advanced Engineering*, **4,** pp. 351-360 (2014).

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