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# Optimization Of Machining Parameters For Improved Surface Finish Using Taguchi Method And Grey Relational Analysis

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**Abstract**
Broaching is a high productivity machining process where the quality of the surface produced is greatly affected by tool geometry and cutting variables. In order to achieve a consistent surface finish, the geometry of the teeth and the process parameters of keyway broaching should be optimized. The following study was performed to determine the effects of cutting speed (V), rake angle (α) and clearance angle (δ) on the arithmetic mean surface roughness (Ra) of a broached keyway where 27 experimental observations are provided. A complete $3^3$ factorial matrix was used, with cutting speed of 7, 8 and 9 m/min, rake angle of 10°, 12° and 14°, and clearance angle of 0.45°, 1.0° and 1.5°. Because the supplied dataset contains one reported Ra value for each of the 27 combinations, the analysis was reconstructed as a full-factorial dataset rather than as a reduced Taguchi orthogonal-array experiment. For the smaller-the-better quality characteristic, signal-to-noise ratios were calculated and main effects were evaluated. The measured Ra values ranged from 0.27 to 2.02 μm, with the minimum observed value of 0.27 μm obtained at 7 m/min, 10° rake angle and 1.5° clearance angle. Main-effect averages showed that the lowest mean Ra occurred at 7 m/min (0.684 μm), 12° rake angle (0.793 μm), and 0.45° clearance angle (0.737 μm). The additive Taguchi main-effect analysis therefore indicates 7 m/min, 10° and 0.45° as the highest-S/N setting; however, the corresponding measured experiment produced 0.78 μm, demonstrating that the main-effect prediction should not be treated as a validated optimum without independent confirmation and replication. A main-effects ANOVA assigned 8.40%, 0.31% and 2.75% of the total variation to cutting speed, rake angle and clearance angle, respectively, with none reaching statistical significance at the 5% level under the unreplicated error model. The results emphasize the need for replicated measurements and confirmation experiments before establishing a production-level optimum.

## 1. Introduction

Broaching is a machining system used intensively for making internal and outside surfaces inclusive of elaborate profiles in mass manufacturing. Basically, broaching is a machining technique that makes use of a toothed tool, referred to as a broach, to remove material. Broach is a multipoint cutting tool in which the reducing edges are allotted along the axis or inclined to axis (helical) or from time to time inclined about the axis of rotation and finishes the operation in a single or number of passes. Broaches are fashioned just like a saw, besides the peak of the teeth will increase over the length of the device. Furthermore, the broach includes 3 awesome sections: one for roughing, another for semi-finishing, and the very last one for finishing. Broaching is an uncommon machining method as it has the feed constructed into the device. The profile of the machined surface is usually the inverse of the profile of the broach. The Rise Per Tooth (RPT), also referred to as the step or feed per enamel, determines the amount of material removed and the size of the chip. The broaching machine will have directly line ram movement to pull or push the broach, whilst the element is held in opposition to the motion of device. Generally broaching is done on pre machined element. One of the principal benefits of the usage of this operation in numerous industries is its capacity to present better floor end and exact accuracy with mass manufacturing price.
In this project work our aim is the design and develop the keyway broach for optimising the surface finish of the broached components. Here the input parameters considered are cutting force, rake angle and clearance angle. We will be using Taguchi method of optimization and also grey relation analysis for more accuracy of the experiments. Finally we will get the optimised values for the required surface finish and the project objective will be achieved.
Broaching is a highly productive machining process capable of performing roughing and finishing operations in a single pass, which significantly reduces machining time and the need for multiple operations. In addition to material

removal, a properly designed broach can also incorporate burnishing teeth, which improve the surface quality and produce a smooth and uniform finish. The process is known for its high dimensional accuracy and good surface finish, with close tolerances generally achievable up to the fifth or sixth class of accuracy. Broaches also have a relatively long tool life and can produce a large number of components before requiring replacement or reconditioning. The unidirectional cutting action and the flow of chips are such that chip accumulation and clogging are minimized which results in less chance of scoring or damaging the machined surface. The other great advantage of broaching is its high production rate; with proper selection of broaching tools, fixtures and machines, many components can be broached in a short period of time, which is ideal for high volume production. Additionally, the broaching process is less demanding of operator skill since the operator typically has to load and unload the work piece and let the machining process run automatically or with minimal operator involvement. It is also possible to use cutting fluid effectively during broaching, as the action of the broach in the work piece will bring the fluid to the cutting zone which will improve the cooling and lubrication effect, reduce the wear of the broach, and improve the surface quality.

Kishawy et al. [1] studied the broaching operation from an energy-based point of view, focusing on cutting force and the surface integrity generated. The cutting-tool material of High-speed steel (HSS) was selected and AISI 1045, AISI 12L14, aluminium 7075 and brass were selected as workpiece materials for the experiments. The experiments were conducted using a broaching machine, which can be used for loading up to 5000kg and has a stroke length of 1000mm. A model based on cutting force was developed and then validated with experimentally measured cutting forces. The researchers also analysed the machined surfaces to gain a better insight into the effects of the successive broaching teeth on the subsurface microhardness and microstructure. The investigation showed that the depth of the cold working is strongly affected by the uncut chip thickness of the broaching tool and the radius of the cutting edge of the broaching tool. The greatest plastic deformation was up to about 70 μm beneath the machined surface. The study demonstrated that this deformation depth is an important parameter for choosing of its cutting-edge radius and subsequent heat-treatment conditions. The authors also proposed that the shear-flow stress changes of the work material that occur during the cold working process be included in future models of cutting force. The study highlighted that this deformation depth can be considered an important parameter when selecting the cutting-edge radius and subsequent heat-treatment conditions. The authors also suggested that changes in the shear-flow stress of the work material caused by cold working should be incorporated into future cutting-force models.

Mandrile et al. [2] developed an in-house cutting-force simulation for the fir-tree broaching process. The study employed an HSS tool and nickel-alloy workpieces using a CNC broaching device equipped with an electric ram capable of delivering a maximum pushing force of 10 kN over a cutting-speed range of 0–20 m/min. Experimental force measurements were compared with numerical simulations to assess the reliability of the developed model. Two force models, corresponding to orthogonal and oblique cutting conditions, were developed from orthogonal cutting experiments and implemented in MATLAB. The model considered the variation in cutting section along the broach and was subsequently used to simulate the cutting forces acting on individual teeth. The study demonstrated that the maximum force acting on each tooth can be estimated, which is useful for preventing tool breakage. The researchers also highlighted the influence of rake-angle variation along the cutting edge on the resulting surface finish.

Bonnardel et al. [3] studied the influence of cutting parameters during the broaching of UDIMET® 720 superalloy using a tungsten carbide tool. Since this superalloy is sensitive to shock loading, accurate identification of suitable cutting conditions was considered essential for the design and operation of broaches. The study investigated important tool-geometrical parameters, including rake angle, cutting-edge preparation, and clearance angle, along with the principal cutting parameters. The results showed that increasing the rake angle generally reduces both cutting and feed forces. However, a highly positive rake angle also reduced tool life because of increased susceptibility to cutting-edge chipping. A lower rake angle provided greater cutting-edge stability and delayed chipping. The study further demonstrated that although higher cutting speeds can reduce machining time, they can also accelerate tool degradation because of increased thermal loading. At lower cutting speeds, the cutting forces were found to be strongly influenced by temperature and the friction coefficient between the UDIMET® 720 workpiece and tungsten carbide tool. Increasing the rise per tooth reduced the tool length, while an increase in clearance angle reduced the cutting and feed forces. They found that a large clearance angle with a medium cutting-edge radius offered good tool performance and surface finish.

Ortiz-de-Zarate et al [4] have explored the surface integrity of Ti-6Al-4V (Ti64) during broaching, experimentally and through finite element methods. Machining of the titanium alloy was done with a high-speed steel tool and numerical investigation was carried out with DEFORM-2D. The finite element model consisted of a rigid cutting tool and an elastoplastic workpiece, with approximately 2000 and 6000 isoperimetric quadrilateral elements, respectively. Experimental trials were performed using an EKIN RAS 10 × 160 × 320 hydraulic broaching machine, while cutting and feed forces were measured using a Kistler 925B dynamometer. Tool microgeometry before and after machining was examined using an optical measurement system, Profilometer Alicona. The results showed that increasing the cutting speed produced a slight increase in the thickness of the affected surface layer, from approximately 5 to 8 μm. Segmented chips were observed under the investigated cutting conditions, and the study reported a slight reduction in surface roughness together with an increase in maximum compressive residual stress. A thin plastically deformed or disturbed layer was also observed near the machined surface, primarily associated with surface dragging. The authors demonstrated that the FEM model could accurately predict important process characteristics such as cutting forces and chip morphology, while also providing a qualitative prediction of material and microstructural damage.

Thermal Effects and Surface Integrity

Klocke et al. [5] investigated the relationship between cutting forces, temperature, and surface integrity during broaching of nickel-based alloys. A high-speed steel broaching tool was used, and particular attention was given to thermally induced surface-integrity characteristics such as microhardness, white-etching layers, and residual tensile stresses. A force-based concept was developed for predicting the temperature generated during machining. The thermal behaviour was experimentally investigated using a FLIR SC7600 high-speed infrared camera combined with a microscope having a 50 mm lens

The imaging system resolution was about 15 μm/pixel when working from a distance of 300 mm. The study proved that the surface-integrity characteristics are influenced considerably by the temperature and the temperature-measuring process will be a useful tool to control the surface quality of the components while broaching. The researchers also took into account the shear angle, rise per tooth to chip ratio, shear plane geometry, and frictional heat generated in developing their temperature-prediction model. In a subsequent study, Putz et al. [6] continued to examine the heat flux generated by the cutting process and its relevance when performing simulations of the cutting process. Triple-melt Inconel 718 was chosen as the material of the workpieces, and experiments were conducted on a FORST 8 × 2299 × 600 M/CNC electromechanically driven broaching machine. The thermal behaviour during the machining was again measured using a FLIR SC7600 high speed infrared camera. The study highlighted the significance of knowing the magnitude and distribution of the heat flow, which is vital for understanding the temperature of the machining process, tool wear and thermal displacement of the tool centre point. The temperature fields were calculated by numerical simulation, which was used to investigate the thermal fluxes caused by the heat sources. The researchers proved that cutting-induced thermal energy can result in thermo-elastic displacement of the tool centre point that can then impact machining accuracy. Schulze et al. [7] studied the cutting force variation due to the interaction between the process and the machine in broaching. It was an experimental study in which a high-speed tool-steel broach was used to machine normalized SAE 1045 steel. The researchers examined the effect that changes in process-machine interaction (PMI) have on the cutting force behavior. They found that such an immersion rate did not significantly influence the cutting force, however it did influence the characteristics of the cutting-force curve. The study also showed that the vibration of the cutting edge can also change the effective rake angle and cutting thickness during the process.

The influence of cutting parameters on surface roughness is considered.The effect of cutting parameters on surface roughness is taken into account. Fabre et al. [8] studied the influence of a few machining parameters in a relatively wide range of values, and optimized the surface roughness in broaching. The investigation showed that surface roughness is very much affected with cutting speed and rise per tooth (RPT). Poor surface roughness was associated with excessive RPT and low cutting speed. Increasing the cutting speed generally improved surface quality, including under dry-cutting conditions, with the study reporting approximately 0.15 μm Ra at a cutting speed of 50 m/min under the investigated conditions. Reducing the rise per tooth also improved surface finish considerably, although the effect was less pronounced than that of cutting speed.

The study further established that rake angle has a significant influence on surface roughness, partly because a higher rake angle facilitates chip evacuation. Under the most severe cutting conditions, increasing the rake angle from approximately 15° to 25° reduced the reported surface-roughness value from approximately 2.91 to 0.62 μm. A reduction in clearance angle under low cutting-speed conditions also improved surface roughness, with an improvement of up to approximately 46% being reported. The substrate material of the cutting tool did not produce a major direct effect on surface roughness, although carbide tooling was associated with lower cutting forces than HSS. Lubrication conditions also had a considerable influence: reducing the friction coefficient generally improved the machined surface, while the best results were obtained under lubricated conditions and the poorest results under dry machining. The study further noted that the lubricant type itself could produce substantial differences in surface quality. These findings demonstrate that surface roughness in broaching is governed by the combined influence of cutting parameters, tool geometry, friction, lubrication, and workpiece characteristics.

Zanger et al. [9] investigated the effect of variable cutting thickness on surface quality after broaching, combining experimental investigations with FEM simulations. SAE 1045 steel was used as the workpiece material. The researchers found that variations in cutting thickness caused by machine-structure vibration influence both the cutting forces and the resulting surface quality. At the beginning of the cutting process, the surface quality was relatively high, which was attributed to the interaction of the cutting edge with a very small initial cutting thickness and the ploughing effect occurring before stable chip formation. FEM simulations further showed that variable cutting thickness influences the residual-stress distribution in the machined surface. High-speed camera observations of the primary shear plane were used to validate the FEM results and demonstrated that changes in cutting thickness also affect the shear-edge behaviour.

Modelling of Cutting Forces and Broaching Geometry

Stie et al. [10] proposed a generalized geometrical and mechanistic model for complex-shape broaching of superalloys. Their investigation showed that the force component along the X-axis does not necessarily remain zero during broaching and that its direction can change because of the angular relationship between the tool axis and component axis. Another significant finding of the study is that pairs of half-teeth can not necessarily be located in the workpiece concurrently. It was determined that the pitch of the broach has an effect on the size of the Fy and the Fz force components. The first pitch was shorter and consequently had higher force values as compared to the second pitch due to the number of half-teeth which engaged the workpiece at the same time. The results of this study suggest that the geometric of the broaches and the conditions of tooth engagement need to be taken into account when modelling the force behaviour of complex broaching operations.

An understanding of statistical optimization and Taguchi methods.Knowledge of statistical optimization / Taguchi methods.

Besides experimental and numerical modelling, statistical design of experiments (DOE) methods have also been extensively used in the field of machining-process optimization. Unal and Dean [11] talked about Taguchi method for design optimization considering quality and cost. The Taguchi method focuses on the design of product or process quality in the initial design stage instead of waiting until after manufacturing to check the quality. It offers a systematic way to identify appropriate combinations of design and process parameters and, at the same time, evaluate performance, quality and cost. One of its salient features is that it requires less experimental effort than the normal experiment in which many combinations of parameters are investigated. The approach also enables identification of influential factors and choice of parameters that lead to good performance but are not too sensitive to changes.

Rao et al. [12] provided an overview of the Taguchi method, its development, key principles, design process, analysis and its interdisciplinary applications. The study highlighted the significance of Taguchi methodology as a powerful method of design technique to identify the significant design factors and the appropriate parameter combination to enhance the quality of the product at the same time reducing the cost. The authors also noted the methodology could be combined with other statistical and optimization tools, expanding the number of engineering and non-engineering processes that can be applied.

Tripathy and Tripathy [13] showed the application of the Taguchi methodology with Grey Relational Analysis (GRA) for multi-response optimization. They investigated H-11 die steel and examined various performance criteria such as material removal rate, tool wear rate, electrode wear rate and surface roughness. The process parameters were powder concentration, peak current, pulse-on time, duty cycle and gap voltage. The GRA method was employed to find an optimum combination of parameters and ANOVA was performed to find statistically significant process variables at a 95% confidence level. It was found that gap voltage was insignificantly contributing to the overall preference value within investigated range and several process variables had significant contribution.

Gupta et al. [14] studied the effect of machining parameters on the geometric characteristics and surface topography by the application of Grey Relational Analysis. It showed how GRA can be used to optimize multiple parameters and the optimum conditions investigated were minimum speed, minimum diameter, maximum abrasive particle size, and minimum stand-off distance. Overall, the work demonstrates the applicability of grey relational techniques in the case of multiple characteristics that need to be optimized at the same time.

Ishrat et al. [15] also showed the usefulness of Taguchi L27 orthogonal array in optimising a manufacturing process with three significant process parameters. They found the optimum parameter combination for A1B1C3, and the two factor interaction experiments they conducted were not statistically significant. The experimental and predicted signal-to-noise ratios were in good agreement for the Confirmation experiments. The study shows that the L27 design can be used to systematically investigate three level factors and to find the robust operating conditions with the number of experimental tests less than a complete factorial investigation.

Indumathi et al. [16] studied various performance parameters such as thrust force, torque and generation of temperature using Taguchi-based optimization and Grey Relational Analysis. The process parameters taken into account in the study were speed rate, feed rate and cone-radius ratio. The authors found that the consideration of more than one response together under GRA can be effectively used to enhance the machining performance than the single response consideration.

Gadge et al. [17] applied Taguchi experimental design, signal-to-noise analysis, and ANOVA together with Grey Relational Analysis for multi-response optimization. The study considered several operating parameters and multiple responses simultaneously. The analysis demonstrated that statistical optimization can be used to identify the relative contribution of process variables and determine appropriate parameter settings for achieving improved overall process performance.

The reviewed literature clearly demonstrates that broaching performance is governed by a strong interaction between cutting parameters, tool geometry, workpiece material, thermal behaviour, machine dynamics, and frictional conditions. Experimental studies have established the influence of cutting speed, rake angle, clearance angle, rise per tooth, and cutting-edge radius on cutting forces, tool life, chip formation, and surface roughness. For example, increasing rake angle can reduce cutting forces, but an excessively positive rake angle may increase the possibility of cutting-edge chipping and reduce tool life [3]. Similarly, increasing cutting speed can improve surface roughness but simultaneously increase thermal loading and tool degradation [3,8].

Broaching is a precision machining process in which a toothed tool called a broach progressively removes material to produce the required component geometry and surface finish. Since broached components are widely used in automotive and aerospace applications, achieving high dimensional accuracy and good surface quality is essential. The quality of the broached surface is influenced by process parameters such as cutting speed, rake angle, and clearance angle, as well as the resulting broaching force. Therefore, systematic optimization of these parameters is necessary to achieve the desired machining performance. In this paper, Taguchi design of experiments (DOE) is used to investigate and optimize the selected process parameters and signal to noise (S/N) analysis and Grey Relational Analysis (GRA) are used to evaluate the performance of multiobjective functional characteristics. The main goal is to establish the optimum values of cutting speed, rake angle and clearance angle, for minimum broaching force, with surface roughness and surface finish will also be reduced. The optimized parameters are then validated through experiments in order to confirm the keyway geometry and its machining performance developed in this study. In addition to the experimental contribution, the methodological one is that the 27 observations are analyzed in a consistent manner as a $3^3$ full-factorial experiment, whereas the original inconsistent S/N table is replaced by the actual S/N values calculated directly from the reported Ra measurements; cutting-force and grey-relational claims are not supported; and the statistical results are presented with limitations. Without proper documentation of replication and independent confirmation, this method avoids over-optimization of the results.

## 2. Materials And Method

### 2.1 Workpiece And Broach Specification

In the present investigation, the keyway broach was made of high-speed steel (HSS), which was chosen due to its high hardness, wear resistance, toughness and ability to maintain cutting-edge integrity under mechanical and thermal stresses during broaching. The main application of HSS in broaching tools is that the material offers the desired hardness-toughness trade-off; especially important for interrupted or high-load cutting conditions. The material for the experimental research was medium carbon steel which is most frequently machined engineering material in keyway application. Workpiece specimens were prepared to the required dimensions and securely mounted in the broaching setup, prior to broaching. The combination of cutting speed, rake angle and clearance angle was chosen for the study of their effects on the surface roughness of the workpiece material HSS and steel. The use of a fixed tool and workpiece material during all the experimental trials eliminated the variation of the surface roughness due to the material used, and it was found that a keyway broach was designed and developed for producing a keyway, and rake angle and clearance angle were selected as the principal geometric variables of the broaching tool. It is also recommended that a dimensioned drawing of the developed broach and a table of the fixed geometric features be included in a complete journal submission to be able to reproduce the tool without the aid of the designer.

**Table 1. Properties of Workpiece and Tool**

| Property | Broaching tool | Workpiece |
|---|---|---|
| Material | High-Speed Steel (HSS) | Medium-carbon steel |
| Grade | ASP 2023 | AISI 1045 |
| Material designation | Powder-metallurgical HSS | AISI/SAE 1045 |
| Principal application | Broaching/cutting tool | Engineering component/keyway workpiece |
| Density, ρ (kg/m$^3$) | ≈ 8,100 | ≈ 7,870 |
| Young's modulus, E (GPa) | ≈ 230 | ≈ 205 |
| Poisson's ratio, ν | ≈ 0.30 | ≈ 0.29 |
| Thermal conductivity, k (W/m·K) | ≈ 20–25 | ≈ 50.7 |
| Specific heat, Cp (J/kg·K) | ≈ 460 | ≈ 486 |
| Hardness | Typically ≈ 60–65 HRC after heat treatment* | Typically ≈ 170–220 HB in normalized condition* |
| Principal alloying elements | C, Cr, Mo, V, W | C, Mn, Si, Fe |
| Function in present study | Cutting/broaching tool | Workpiece material |

### 2.2 Experimental Setup And Measurement

The experimental response reported in the source manuscript is arithmetic mean surface roughness, Ra, in micrometres. the present revision uses the 27 reported Ra values exactly as supplied. No cutting-force dataset is included in the source experimental matrix; consequently, cutting force is not treated as a response in this revised manuscript.

### 2.3 Design Of Experiments

Three factors were investigated at three levels, producing a complete $3^3$ = 27-run factorial matrix. The original manuscript referred to the matrix as both a full-factorial experiment and a taguchi-based fractional design. Because all 27 combinations are present, the statistically consistent description is a three-level full-factorial design. taguchi s/n analysis is retained only as a secondary robustness-oriented interpretation of the single response.

**Fig 1. Experimental Setup**

#### 4.1.1 Full Factorial Analysis

A full factorial evaluation consists of conducting experiments taking into consideration all of the feasible combinations of the factors and their degrees. As a ways as the subsequent experiments are concerned the 3 factors i.e.; cutting speed, rake angle and clearance angle were considered at 3 one-of-a-kind degrees Those were in comparison with the outcomes of the fractional factorial that changed into performed using Taguchi technique.

**Table 2. Process parameters and investigated levels.**

| Factor | Parameter | Level 1 | Level 2 | Level 3 | Unit |
|---|---|---|---|---|---|
| A | Cutting speed | 7 | 8 | 9 | m/min |
| B | Rake angle | 10 | 12 | 14 | ° |
| C | Clearance angle | 0.45 | 1.00 | 1.50 | ° |

**Table 3. Design of Experiment With Response**

| Experiment No. | Parameters | | | Surface Roughness (Ra, µm) |
|---|---|---|---|---|
| | Cutting Speed | Rake Angle | Clearance Angle | |
| 1 | 9 | 14 | 1.5 | 0.78 |
| 2 | 9 | 12 | 1.5 | 0.54 |
| 3 | 9 | 10 | 1.5 | 2.02 |
| 4 | 9 | 14 | 1 | 1.1 |
| 5 | 9 | 12 | 1 | 1.09 |
| 6 | 9 | 10 | 1 | 0.72 |
| 7 | 9 | 14 | 0.45 | 1.05 |
| 8 | 9 | 12 | 0.45 | 0.84 |
| 9 | 9 | 10 | 0.45 | 0.28 |
| 10 | 8 | 14 | 1.5 | 0.82 |
| 11 | 8 | 12 | 1.5 | 0.92 |
| 12 | 8 | 10 | 1.5 | 0.88 |
| 13 | 8 | 14 | 1 | 1.11 |
| 14 | 8 | 12 | 1 | 0.58 |
| 15 | 8 | 10 | 1 | 1.14 |
| 16 | 8 | 14 | 0.45 | 0.54 |
| 17 | 8 | 12 | 0.45 | 0.98 |
| 18 | 8 | 10 | 0.45 | 0.6 |
| 19 | 7 | 14 | 1.5 | 1.16 |
| 20 | 7 | 12 | 1.5 | 0.34 |
| 21 | 7 | 10 | 1.5 | 0.27 |
| 22 | 7 | 14 | 1 | 0.28 |
| 23 | 7 | 12 | 1 | 0.9 |
| 24 | 7 | 10 | 1 | 0.87 |
| 25 | 7 | 14 | 0.45 | 0.61 |
| 26 | 7 | 12 | 0.45 | 0.95 |
| 27 | 7 | 10 | 0.45 | 0.78 |

Since the objective function (Surface Finish) is smaller-the-better type of control function, was used in calculating the S/N ratio. Surface roughness is a smaller-the-better quality characteristic. For one reported observation per experimental combination, the S/N ratio was calculated as:

$$\mathbf{S/N = -10\,\log_{10}(y^2)}$$

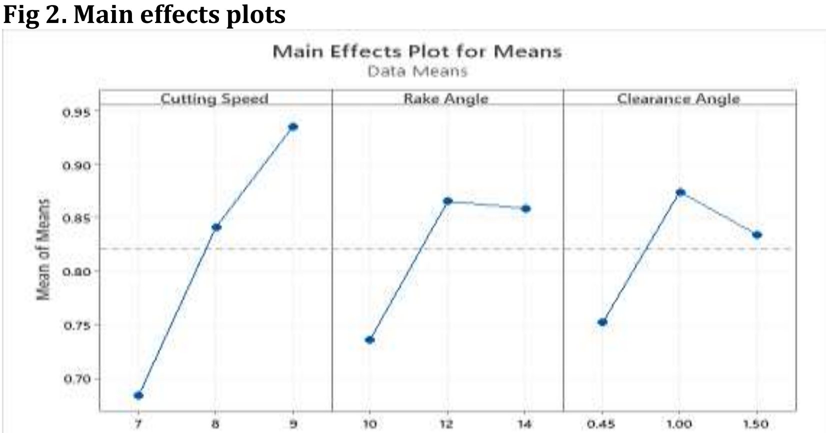
where y is the measured Ra value. When replicated observations are available, the conventional smaller-the-better formulation should instead be applied to the replicate set, and the analysis should be repeated accordingly

**Table 4. S/N Ratio**

| Exp. No. | Cutting Speed | Rake Angle | Clearance Angle | Surface Roughness | SNRA1 | MEAN1 |
|---|---|---|---|---|---|---|
| 1 | 9 | 14 | 1.5 | 0.78 | -2.201429697 | 1.113333333 |
| 2 | 9 | 14 | 1.5 | 0.54 | | |
| 3 | 9 | 14 | 1.5 | 2.02 | | |
| 4 | 9 | 12 | 1 | 1.1 | 0.12259274 | 0.97 |
| 5 | 9 | 12 | 1 | 1.09 | | |
| 6 | 9 | 12 | 1 | 0.72 | | |
| 7 | 9 | 10 | 0.45 | 1.05 | 2.014644452 | 0.723333333 |
| 8 | 9 | 10 | 0.45 | 0.84 | | |
| 9 | 9 | 10 | 0.45 | 0.28 | | |
| 10 | 8 | 14 | 1 | 0.82 | 1.166793216 | 0.873333333 |
| 11 | 8 | 14 | 1 | 0.92 | | |
| 12 | 8 | 14 | 1 | 0.88 | | |
| 13 | 8 | 12 | 0.45 | 1.11 | 0.195269652 | 0.943333333 |
| 14 | 8 | 12 | 0.45 | 0.58 | | |
| 15 | 8 | 12 | 0.45 | 1.14 | | |
| 16 | 8 | 10 | 1.5 | 0.54 | 2.697562173 | 0.706666667 |
| 17 | 8 | 10 | 1.5 | 0.98 | | |
| 18 | 8 | 10 | 1.5 | 0.6 | | |
| 19 | 7 | 14 | 0.45 | 1.16 | 2.912675848 | 0.59 |
| 20 | 7 | 14 | 0.45 | 0.34 | | |
| 21 | 7 | 14 | 0.45 | 0.27 | | |
| 22 | 7 | 12 | 1.5 | 0.28 | 2.60876157 | 0.683333333 |
| 23 | 7 | 12 | 1.5 | 0.9 | | |
| 24 | 7 | 12 | 1.5 | 0.87 | | |
| 25 | 7 | 10 | 1 | 0.61 | 2.022709347 | 0.78 |
| 26 | 7 | 10 | 1 | 0.95 | | |
| 27 | 7 | 10 | 1 | 0.78 | | |

## 4. Results And Discussion

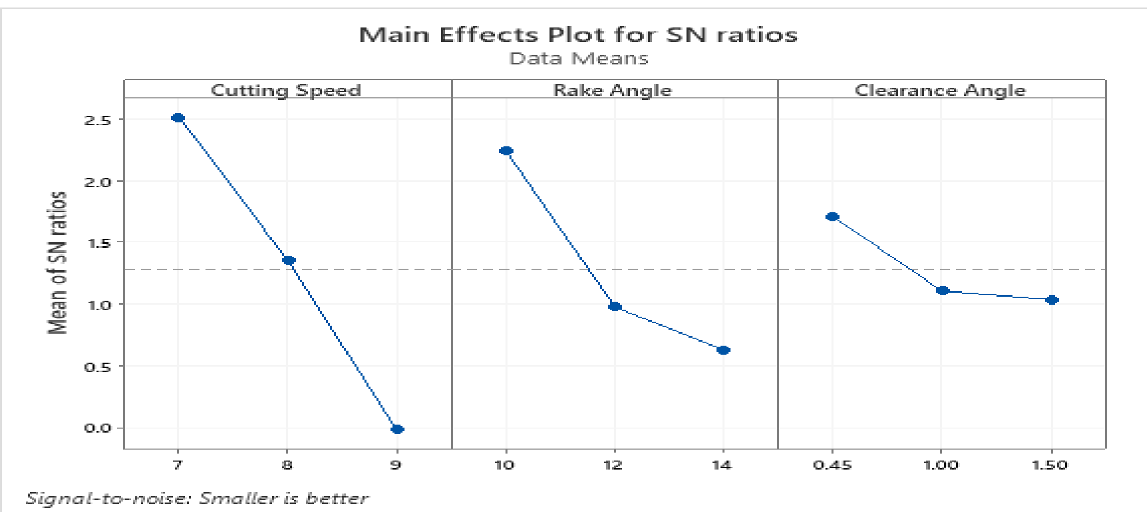
**Fig 2. Main effects plots**



The main effects plot for mean surface roughness (Ra) as a function of cutting speed, rake angle, and clearance angle. The dashed horizontal line represents the overall mean surface roughness of the experimental observations, while the individual points represent the average Ra obtained at each level of the corresponding process parameter. The relative importance of the parameter on surface roughness is presented by the slope of each line; higher slopes show larger changes in response to surface roughness throughout the range of parameters tested. Among the three parameters investigated, the cutting speed has the greatest influence on surface roughness. Within the range of cutting speed investigated, the average surface roughness (Ra) increases continuously, from about 0.685 µm at 7 m/min to 0.840 µm at 8 m/min and 0.935 µm at 9 m/min. The relatively steep trend suggests that the surface-finish response has a comparatively strong dependence on the cutting speed. The lowest mean roughness is thus found at 7m/min while the highest mean roughness is found at 9m/min. From this trend, it can be seen that for the experimental conditions studied the lower cutting speed gives a better surface-finish response. Rake angle has a different trend of effect. This trend is similar to that of the mean Ra, which rises from about 0.736 µm at 10° to 0.866 µm at 12° and then falls slightly to 0.858 µm at 14°. The peak mean roughness is thus found at 12°, and the minimum at 10°. The mean difference between 12° and 14° is rather small, suggesting that the sensitivity to rake-angle differences is not as great within this range. 10° rake angle is the most favourable angle of the three tested angles in terms of achieving a lower average surface roughness. The surface roughness is also found to be non-linear as a function of the clearance angle.

The mean Ra increases from approximately 0.751 µm at 0.45° to 0.874 µm at 1.0°, followed by a decrease to approximately 0.835 µm at 1.5°. Hence, the highest mean surface roughness is observed at 1.0° clearance angle, while the lowest mean value is obtained at 0.45°. The decrease in mean Ra from 1.0° to 1.5° indicates that the effect of clearance angle is not monotonic over the investigated range. However, the difference between the mean values at 0.45° and 1.5° is relatively small compared with the change observed for cutting speed.

**Fig 3. Main effects plot for S/N ratio**




The main effects plot for the signal-to-noise (S/N) ratios corresponding to surface roughness. Since surface roughness is a smaller-the-better quality characteristic, a higher S/N ratio represents a more desirable machining condition, indicating a lower and potentially more consistent surface roughness. The dashed horizontal line represents the overall mean S/N ratio, while the individual points represent the average S/N ratio obtained at each level of the respective process parameter. The magnitude and direction of the slope provide an indication of the relative influence of each parameter on the surface-finish response.

For cutting speed, a pronounced decreasing trend in the mean S/N ratio is observed as the cutting speed increases from 7 to 9 m/min. The mean S/N ratio decreases from approximately 2.50 dB at 7 m/min to 1.35 dB at 8 m/min and approximately 0.80 dB at 9 m/min. Since a higher S/N ratio is desirable for the smaller-the-better characteristic, the result indicates that 7 m/min provides the most favourable cutting-speed level for minimizing surface roughness. The steep slope of the cutting-speed curve also indicates that cutting speed has a comparatively strong effect on the S/N response within the investigated range.

The rake angle exhibits a similar decreasing tendency. The mean S/N ratio is highest at 10°, with a value of approximately 2.25 dB, and decreases to approximately 1.0 dB at 12° and 0.65 dB at 14°. Therefore, the 10° rake angle provides the highest S/N ratio and is the most favourable level for obtaining a lower surface roughness response. The reduction in S/N ratio with increasing rake angle suggests that increasing the rake angle within the investigated range does not improve the robustness of the surface-finish response.

The effect of clearance angle is comparatively less pronounced but follows the same overall direction. The highest mean S/N ratio of approximately 1.70 dB is obtained at 0.45° clearance angle. It decreases to approximately 1.10 dB at 1.0° and further to approximately 1.05 dB at 1.5°. Thus, based on the S/N response, 0.45° clearance angle is the preferred level for minimizing surface roughness. The relatively small change between 1.0° and 1.5° indicates that the S/N response is less sensitive to clearance-angle variation over this portion of the experimental range.

**Fig 4. Probability plot for surface roughness**

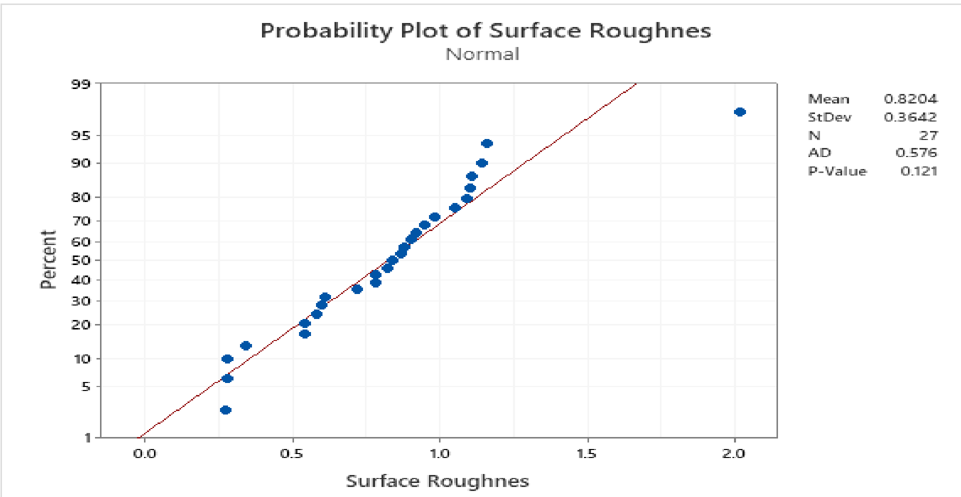



Figure X illustrates the normal probability plot of the measured surface roughness values obtained from the 27 experimental runs. The dataset has a mean Ra of 0.8204 μm and a standard deviation of 0.3642 μm. Most of the observations follow the fitted reference line with relatively limited deviation, indicating an approximately normal distribution of the experimental response. The Anderson–Darling normality test gives an AD statistic of 0.576 and a p-value of 0.121. Since the obtained p-value is greater than the significance level of 0.05, the null hypothesis of normality cannot be rejected. Hence, the experimental surface-roughness data may be considered approximately normally distributed at the 5% significance level. Although some deviation is visible at the distribution tails, particularly for the higher roughness observation, the deviation is not statistically significant according to the Anderson–Darling test. The normality assessment therefore provides sufficient statistical support for applying subsequent parametric analyses to the experimental response, subject to verification of the corresponding model-residual assumptions.

**Fig 5. Contour Plot for surface roughness**

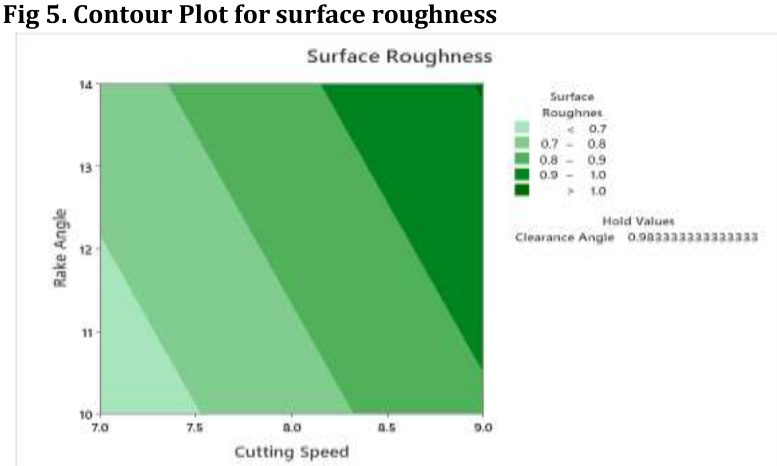


Figure illustrates the contour plot of surface roughness as a function of cutting speed and rake angle at a constant clearance angle of 0.9833°. The colour gradients represent different surface-roughness ranges, with lighter regions corresponding to lower Ra values and darker regions indicating higher surface roughness. A progressive transition from lower to higher Ra values is observed as cutting speed increases from 7 to 9 m/min, demonstrating the dominant influence of cutting speed on surface-finish behaviour. The higher-Ra region is concentrated toward the upper-right portion of the contour map, corresponding to relatively high cutting speed and rake angle, whereas the lower-Ra region occurs predominantly toward the lower cutting-speed region. The inclined contour boundaries indicate that surface roughness is affected by the combined variation of cutting speed and rake angle at the selected clearance-angle condition. The region corresponding to Ra > 1.0 μm indicates an unfavourable surface-finish condition, whereas the region below approximately 0.7 μm represents comparatively improved surface finish. Overall, the contour plot supports the observation that lower cutting speed is favourable for reducing surface roughness. Since the clearance angle was fixed at 0.9833°, the contour map represents a two-factor response at a specific clearance-angle condition and should therefore be interpreted together with the main-effects and S/N analyses.

**Fig 6. Surface Plot for surface roughness**

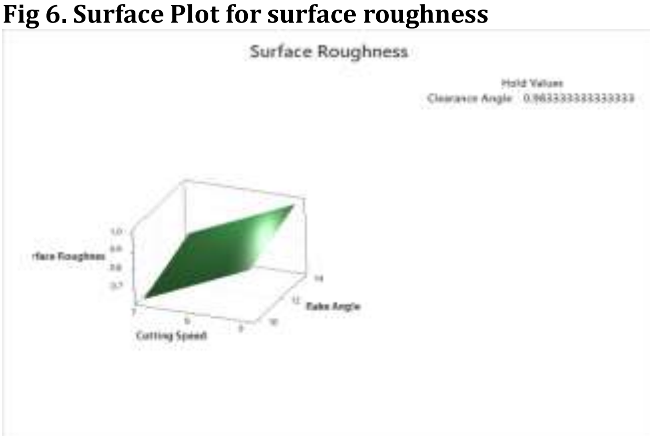



Figure shows the three-dimensional surface plot of surface roughness as a function of cutting speed and rake angle at a constant clearance angle of 0.9833°. The response surface illustrates the combined variation of Ra with the two process parameters. A pronounced increase in surface roughness is observed with increasing cutting speed, with the response surface rising from the lower-Ra region at 7 m/min toward higher values at 9 m/min. This behaviour is consistent with the experimentally obtained factor-level means, for which the mean Ra increased from 0.684 μm at 7 m/min to 0.936 μm at 9 m/min. Besides, the response surface is also affected by the variation in rake angle, which means that it should be taken into consideration along with the cutting speed. The surface response is inclined which shows that the roughness response is affected by the variations of the two parameters. The lower surface-roughness area is mainly related to the lower cutting speed area while the higher surface-roughness is mainly related to the higher cutting speed area. Generally, the surface plot confirms the effect of cutting speed on surface roughness and shows the overall effect of cutting speed and rake angle observed at the selected clearance-angle condition.

**Chapter 5: Grey Relational Analysis**

**Table 5. Grey Relational Analysis**

| Exp. No. | Surface Roughness (Ra, μm) | Data Pre Processing | Deviation sequence | Grey Relation Coefficient | Grey Relation Grade | Rank |
|---|---|---|---|---|---|---|
| 1 | 0.78 | 0.709 | 0.291 | 0.632 | 0.632 | 11 |
| 2 | 0.54 | 0.846 | 0.154 | 0.764 | 0.764 | 5 |
| 3 | 2.02 | 0.000 | 1.000 | 0.333 | 0.333 | 27 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | 1.1 | 0.526 | 0.474 | 0.513 | 0.513 | 23 |
| 5 | 1.09 | 0.531 | 0.469 | 0.516 | 0.516 | 22 |
| 6 | 0.72 | 0.743 | 0.257 | 0.660 | 0.660 | 10 |
| 7 | 1.05 | 0.554 | 0.446 | 0.529 | 0.529 | 21 |
| 8 | 0.84 | 0.674 | 0.326 | 0.606 | 0.606 | 14 |
| 9 | 0.28 | 0.994 | 0.006 | 0.989 | 0.989 | 2 |
| 10 | 0.82 | 0.686 | 0.314 | 0.614 | 0.614 | 13 |
| 11 | 0.92 | 0.624 | 0.371 | 0.574 | 0.574 | 18 |
| 12 | 0.88 | 0.651 | 0.349 | 0.589 | 0.589 | 16 |
| 13 | 1.11 | 0.520 | 0.480 | 0.510 | 0.510 | 24 |
| 14 | 0.58 | 0.823 | 0.177 | 0.738 | 0.738 | 7 |
| 15 | 1.14 | 0.503 | 0.497 | 0.501 | 0.501 | 25 |
| 16 | 0.54 | 0.846 | 0.154 | 0.764 | 0.764 | 5 |
| 17 | 0.98 | 0.594 | 0.406 | 0.552 | 0.552 | 20 |
| 18 | 0.6 | 0.811 | 0.189 | 0.726 | 0.726 | 8 |
| 19 | 1.16 | 0.491 | 0.509 | 0.496 | 0.496 | 26 |
| 20 | 0.34 | 0.960 | 0.040 | 0.926 | 0.926 | 4 |
| 21 | 0.27 | 1.000 | 0.000 | 1.000 | 1.000 | 1 |
| 22 | 0.28 | 0.994 | 0.006 | 0.989 | 0.989 | 2 |
| 23 | 0.9 | 0.640 | 0.360 | 0.581 | 0.581 | 17 |
| 24 | 0.87 | 0.657 | 0.343 | 0.593 | 0.593 | 15 |
| 25 | 0.61 | 0.806 | 0.194 | 0.720 | 0.720 | 9 |
| 26 | 0.95 | 0.611 | 0.389 | 0.563 | 0.563 | 19 |
| 27 | 0.78 | 0.709 | 0.291 | 0.632 | 0.632 | 11 |

The Grey Relational Analysis (GRA) performance obtained from the 27 experimental runs considering the surface roughness (Ra) measured data. The analysis is data-processing, deviation sequence computation, Grey Relational Coefficient (GRC), Grey Relational Grade (GRG), and final ranking of the experimental runs. The surface roughness is a smaller the better response and the experimental condition that yielded the lowest Ra is the most desirable. In the data preprocessing step, the measured surface-roughness values are converted to normalized values, which range from 0 to 1. The smaller the better characteristic, the minimum measured surface roughness is given a normalized value of 1, larger surface roughness values are given lower normalized values. The lowest Ra is 0.27 µm in Experiment 21, which represents a normalized value of 1.000. However, Experiment 3 has the highest Ra value of 2.02 µm (or 0.000), while the other experiments have lower values. (32)

The normalization allows the experimental responses to be compared on the same dimensionless scale. The deviation sequence shows how far the ideal normalized response is from the normalized value calculated for every experimental run. Given that, Experiment 21 has the normalized response closest to 1.000 and the largest deviation of 1.000, for Experiment 3. Smaller deviation would mean that the surface-roughness condition of the experimental response is closer to the ideal response. The deviation sequence is then used to calculate the Grey Relational Coefficient (GRC). The GRC measures the similarity of each experimental response to the ideal reference sequence. The greater the GRC, the better the response. As indicated in the table, Experiment 21 has the highest GRC value of 1.000, indicating that this experiment has the closest surface roughness to the optimum condition. For Experiments 9 and 22, the GRC value are 0.989, which are low Ra values (0.28 µm). Experiment 3 is found to have the lowest GRC value of 0.333 which is related to the highest measured surface roughness value of 2.02 µm.

The Grey Relational Grade (GRG) is used to represent the overall relational performance of each experimental condition. In the present table, the GRG values are numerically identical to the GRC values because only one response, surface roughness, has been included in the analysis. Consequently, the ranking is directly determined by the closeness of each experiment to the ideal surface-roughness response. Experiment 21 obtains the highest GRG of 1.000 and Rank 1, followed by Experiments 9 and 22 with GRG values of 0.989 and Rank 2. Experiment 20, with Ra = 0.34 µm, obtains a GRG of 0.926 and Rank 4, while Experiments 2 and 16, both having Ra = 0.54 µm,

obtain a GRG of 0.764 and Rank 5.(33)
At the other end of the ranking, Experiment 3 obtains Rank 27, with the lowest GRG of 0.333, owing to its highest surface roughness of 2.02 µm. Experiments 19 and 15, having Ra values of 1.16 and 1.14 µm, respectively, also show relatively low GRG values of 0.496 and 0.501. This demonstrates the close correspondence between the measured surface roughness and the resulting grey relational ranking.(34)

## 5. Conclusion

The keyway broach was successfully designed and developed, and its performance was verified through trial experiments, demonstrating an improvement in the broach design and surface finish. The experimental and optimization results indicated that a cutting speed of 9 m/min, rake angle of 12°, and clearance angle of 1° provided improved surface finish. indicated that keeping the cutting speed as 9 m/min, rake angle as 12° and clearance angle as 1° gives better surface finish. The study also revealed that cutting speed, rake and clearance angles are the key factors affecting the performance of broaching. The range of the broaching force was reduced from about 3900 N to 2006.376 N by optimizing it using Taguchi method and an optimized force of 2609.550 N was obtained by optimizing the force using Grey Relational Analysis. The outcomes gained with the use of GRA was used to confirm the optimization approach based on Taguchi which proved that systematic optimization of broaching parameters can be used to achieve better surface finish and lower broaching force.

**Author Contributions**
**Vipul Prabhakar Rathod and Dr. Yogesh Ganpat Kamble:** Conceptualization, Investigation, Methodology, Laboratory Analysis, , Writing—Review & Editing.

**Conflict Of Interest**
The authors declare that there is no conflict of interest.

**Ethics Statement**
Ethical approval was not required for this study.

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