**Optimization of process parameters for machining of AISI-1045 steel using Taguchi design and ANOVA**

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# ABSTRACT

Previous published works on the optimization of parameters in orthogonal cutting process have used a single tool. The parameters considered in these works are: surface roughness, power consumption, deformed chip shape, and temperature in the workpiece. This paper is on the optimization of machining parameters with multiple cutting tools. This is required to reduce the cutting forces and temperature while machining AISI 1045 steel. In this study, this has been achieved by using a combination of statistical tools including Taguchi matrix, signal to noise ratio, and analysis of variance (ANOVA). The effects of varying cutting speed, feed rate, depth of cut, and rake angle in orthogonal cutting process have been considered. The Finite Element (FE) simulations have been carried out with a general purpose commercial FE code, ABAQUS, and statistical calculations have been performed with Minitab. Results show that for optimum cutting forces, feed rate and depth of cut are the most important factors while for lower temperatures, cutting speed and rake angle play a significant role. It is concluded that carbide cutting tools is a better option as compared to uncoated cemented carbide cutting tool for machining AISI 1045 steel as it results in lower cutting forces and temperatures.

Keywords: Taguchi design, Finite element modelling, ANOVA, ABAQUS

# Introduction

Modern industrial manufacturing aims to produce high quality products with reduced time and cost. Automated and flexible manufacturing systems such as the computerized numerical control (CNC) machines are employed for that purpose, which are capable of minimizing the processing time while achieving high accuracy. Turning process is one of the most used methods for cutting and the finishing of machined parts. In this process, it is vital to select input (cutting) parameters with precision for achieving high cutting performance. Generally, the required cutting parameters are chosen based on past experience or by following guidelines from a handbook [[[1]](#endnote-1)]. Experiments are condition specific and needs resources and time; therefore, the researchers have adopted a fairly common technique of simulating their hypothesis and comparing the physical results. The finite element method has been extensively employed for cutting process simulations and optimization of the process parameters [[[2]](#endnote-2), 3, 5 - 10].

Linhu Tang et al. [4] used finite element method to simulate the machining of AISI D2 tool steel with CBN cutting tool using dry hard orthogonal cutting process. Authors used experimental data available in literature to verify the FE model. Element removal technique based on nodal stresses was adopted for chip formation using the updated Lagrange model. An iterative technique for finding the friction coefficient was used while isotropic friction coefficient was taken from literature. The FE results deviated from the experimental results by an average of 8%. Xiamon Deng et al. [5] investigated the effects of rake angle and friction coefficient in orthogonal cutting to account for the local temperature rise due to conversion of friction and plastic work into heat. Adiabatic conditions were assumed. The FE model used a chip separation criterion and Coulomb law modeling dry friction at the tool-chip contact. Simulation results were obtained for temperature, stress, strain, and strain rate fields by varying rake angle and coefficient of friction.

Movahhedy et al. [6] used Arbitrary Lagrangian-Eulerian (ALE) formulation which gives better mesh adaptability. However, remeshing technique and chip separation criterion were avoided due to material flow around the tool. Xiamon Deng et al. [7] simulated the orthogonal cutting process and determined the effects of friction on thermo mechanical quantities under plane strain conditions. They used a modified coulomb’s friction law in order to successfully model the phenomena of friction along the tool-chip interface. To simulate the chip separation, finite element nodal release procedure was adopted. Rake angle and friction coefficients were varied and it was shown that the material near the tip of the tool experiences highest amount of plastic strain rate whereas shear straining was observed in the primary shear zone. Large numbers of simulations were carried out using variation of rake angle and coefficient of friction while their effects on temperature and cutting forces were studied.

Sutherland et al. [8] developed a finite element model to simulate the orthogonal metal cutting process with particular emphasis on the effect of crater wear considering plane strain and steady state conditions. Crater wear was identified as a geometric property of the crater formed on the tool rake face. This property was varied and the simulations were carried out to study the effect of crater wear on the process. Size of the crater was reported to have a great influence on the output of the simulation like curling radius. The results were presented on the basis of computational observations only and no physical tests were performed for cross checking of the simulated results. Shet et al. [9] used FEM to simulate orthogonal metal cutting process focusing on the residual stress and strain fields in the workpiece. The chip separation criteria involved separation of joined nodes just ahead of the tip at a specific distance. For energy dissipation modeling, it was assumed that 90% of the plastic work is converted into heat. It was also assumed that 50% of the total heat generated goes back into the tool and 50% into the chip. Simulation was completed in four stages of loading/unloading and the workpiece was allowed to cool off after each stage. Results for residual stresses and strains in the finished workpiece were reported for various coefficients of friction and rake angles.

Faraz et al. [10] used FEA code to simulate orthogonal machining of AISI 4140 steel with cemented carbide tool. Thermal imaging camera was used to find out the amount of heat going into the tool and work piece and to measure temperature during machining. As the elastic modulus of the tool material was very large as compared to that of the workpiece material, the tool was assumed to be perfectly rigid. Plane strain conditions were assumed. A chip separation criterion was defined along a pre-defined chip formation path. To keep the simulation run time under control, it was performed for only a few milliseconds. Flow stress and damage constants were taken from literature and coulomb’s friction law was used to model sticking and sliding regions on the tool-chip interface.

Taguchi techniques have been widely used in engineering design. The main thrust of these techniques is on product or process design that focuses on determining the parameter settings required to produce the best levels of performance measures with minimum variation. ANOVA is the statistical method used to interpret experimental data and make necessary decisions [11]. It detects any differences in the average performance of groups of items tested. There have been many recent applications of Taguchi techniques for process optimization [12 -16]. Statistical methods and Taguchi’s technique have also been used for investigating machinability [17], and optimizing power consumption [18].

AISI 1045 Steel is one of the most widely used grades of steel [2] and has wide application in the manufacturing processes due to its characteristics of low cost and high machinability [3]. Previous work shows optimization of the parameters in orthogonal cutting process for surface roughness, power consumption, deformed chip shape, temperature in the work piece with single cutting tool. However, there has been no reported work on the optimization of parameters with multiple cutting tools while machining AISI 1045 steel. In this study, an attempt has been made to find optimum parameters of the orthogonal cutting process of AISI 1045 steel with different carbide cutting tools in order to reduce the cutting forces and temperature using design of experiments and incorporating Taguchi matrix and ANOVA. Finite element model of orthogonal cutting process was developed and validated with the findings given in the available literature.

# Experimental Design

Different values for each design variable are selected to cover a wide range of cutting conditions. The selected design variables viz. cutting speed, feed rate, depth of cut and rake angle have no interaction with each other and have been considered as independent variables by several researchers [1-4]. Table 1 shows the levels of factors used in the simulations. These ranges are based on various design of experiment (DOE) factor levels used in practice and found in literature [2, 10, 19-21]. Having excess width in the range of these parameters can lead to poor response quality [22] and therefore may not produce the results which would establish the optimum conditions. The response variables for this study are cutting force and temperature. According to the array selector given by Stephanie Fraley et al. [[[3]](#endnote-3)], if there are 4 control variables and 5 levels of each in the DOE, as specified in the previous section, the Taguchi L25(54) array is to be utilized. This array is tabulated in Table 2.

Table 1 DOE Fctors and Level values for simulation with AISI 1045 steel.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameters** | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** |
| **Cutting Speed (m/min)** | 100 | 200 | 400 | 550 | 630 |
| **Feed Rate (mm)** | 0.05 | 0.07 | 0.1 | 0.15 | 0.2 |
| **Rake Angle** | -2 o | 0 o | 3 o | 5 o | 7 o |
| **Depth of Cut (mm)** | 1 | 1.5 | 2 | 2.5 | 3 |

Table 2 Taguchi L25 Array.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Runs | Cutting Speed (m/min) | Feed Rate (mm) | Rake Angle | Depth Of Cut (mm) |
| 1 | 100 | 0.05 | -2 | 1.0 |
| 2 | 100 | 0.07 | 0 | 1.5 |
| 3 | 100 | 0.10 | 3 | 2.0 |
| 4 | 100 | 0.15 | 5 | 2.5 |
| 5 | 100 | 0.20 | 7 | 3.0 |
| 6 | 200 | 0.05 | 0 | 2.0 |
| 7 | 200 | 0.07 | 3 | 2.5 |
| 8 | 200 | 0.10 | 5 | 3.0 |
| 9 | 200 | 0.15 | 7 | 1.0 |
| 10 | 200 | 0.20 | -2 | 1.5 |
| 11 | 400 | 0.05 | 3 | 3.0 |
| 12 | 400 | 0.07 | 5 | 1.0 |
| 13 | 400 | 0.10 | 7 | 1.5 |
| 14 | 400 | 0.15 | -2 | 2.0 |
| 15 | 400 | 0.20 | 0 | 2.5 |
| 16 | 550 | 0.05 | 5 | 1.5 |
| 17 | 550 | 0.07 | 7 | 2.0 |
| 18 | 550 | 0.10 | -2 | 2.5 |
| 19 | 550 | 0.15 | 0 | 3.0 |
| 20 | 550 | 0.20 | 3 | 1.0 |
| 21 | 630 | 0.05 | 7 | 2.5 |
| 22 | 630 | 0.07 | -2 | 3.0 |
| 23 | 630 | 0.10 | 0 | 1.0 |
| 24 | 630 | 0.15 | 3 | 1.5 |
| 25 | 630 | 0.20 | 5 | 2.0 |

# Finite Element Modelling

The geometric model was developed as a simple two dimensional representation of orthogonal cutting as previously done by many authors [2, 5, 8, 10]. The workpiece was kept fixed as tool moves inwards to perform cutting operation thereby separating the chip from the workpiece. Numerical simulations of the machining process were performed by using a general purpose finite element code, ABAQUS. In view of the large elastic modulus (534 and 630 GPa) of the tool materials relative to that of the workpiece (210 GPa), the cutting tool was taken to be perfectly rigid.

The orthogonal cutting process was simulated using a two-dimensional model in ABAQUS/Explicit (version 6.6-1) to analyse turning of AISI/SAE 1045 steel using carbide cutting tools. Input requirements for the model included tool and workpiece geometry, tool and workpiece mechanical and thermal properties and boundary conditions. A two-dimensional model of the cutting edge, which includes chip formation, is shown in Figure 1. A fully coupled thermal stress analysis, in which a temperature solution and a stress solution proceed simultaneously, was applied. As fully coupled thermo-mechanical FE simulations are not able to follow the machining process up to steady-state conditions, therefore to keep the CPU time within reasonable limits only a few milliseconds of the process was simulated. The workpiece length was taken as 2 mm, its height as 0.4 mm (which includes 0.1mm of undeformed chip) and a feed rate of 0.1 mm/rev, as shown in Figure 1. The cutting tool has a clearance angle of 7° and a height of 0.8 mm. These specifications were used for validation of the model and compared with the results generated by a previous FE model [10]. Later in the study, the specifications like rake angle and depth of cut were changed according to the experimental requirements.

Following assumptions were made in FE analysis:

1. Plane strain conditions were assumed as the cutting width was much larger than the undeformed chip thickness.
2. The tool was taken to be perfectly elastic as the elastic modulus of the tool was large as compared to that of the workpiece and therefore small elastic deformations in the tool were negligible against the high plastic deformations of the workpiece.
3. To keep the simulation as simplified as possible, it was also assumed that the tool edge was perfectly sharp.

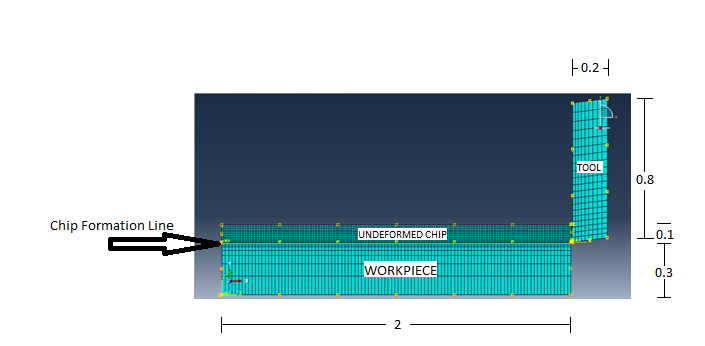


Figure 1 Geometric Assembly and FE meshing.

## Material Flow Properties

According to a comparative analysis described by Shi and Liu [2[[4]](#endnote-4)], Johnson–Cook model is one of the most convenient material models which also produces excellent results describing the material behaviour and chip formation [2[[5]](#endnote-5)]. Also, Johnson–Cook model has been used successfully in high-speed machining region [2[[6]](#endnote-6)-28].

In this work, the Johnson–Cook [29] constitutive model was used to predict the post-yield behaviour of AISI 1045 steel. This model considers the flow stress to be a product of three terms representing the effect of strain, strain rate and temperature [30]. It is given by Eq. 3.1, as follows:

|  |  |
| --- | --- |
|  | Eq. 3.1 |

In eq. 3.1, A, B, C, m & n are the five empirical constants that define the material plastic properties. These constants for AISI 1045 steel are given in Table 3 [30]. The thermo-physical properties of the workpiece and the cutting tool materials are listed in Table 4.

Table 3 Johnson cook constants for AISI 1045 steel.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| A | B | C | n | m |
| 680.5502 | 655.9590 | 0.008626 | 0.13642 | 1.095500 |

Table 4 Material Properties.

|  |  |  |  |
| --- | --- | --- | --- |
| **Properties of Workpiece Material ( AISI 1045 Steel)** | | | |
| Thermal Conductivity (k, W/moC) | | 48.3-0.023T | |
| Young’s Modulus (E, GPa) | | 210 | |
| Specific Heat (Cp, J/KgoC) | | 420+0.504T | |
| Density (ρ, Kg/m3) | | 7862 | |
| Thermal expansion coefficient (α, IoC) | | 1.1 x 10-5 | |
| Poisson Ratio (ν) | | 0.3 | |
|  | |  | |
| **Properties of Tool Materials** | | | |
|  | Carbide Cutting Tool Material | | Uncoated Cemented Carbide Cutting Tool Material |
| Poisson’s Ratio | 0.22 | | 0.26 |
| Specific Heat (J/Kg.K) | 424 | | 334 |
| Young’s Modulus (GPa) | 534 | | 630 |
| Thermal Conductivity (W/m.K) | 67.45 | | 100 |
| Density (Kg/m3) | 11900 | | 11,900 |
| Θroom (room temperature, oC) | 25 | | 25 |

Since machining process at high speeds is not easy to simulate accurately [10], simulations rarely reach steady state (where changes to output per unit time is minimal) and to keep CPU times within practical limits, the simulation were carried out for few milliseconds of machining. The tool was constrained to move in the horizontal direction with specified velocity as a velocity boundary condition. The bottom edge of the workpiece was kept fixed and was given sufficient degrees of freedom to move as appropriate for simulation. Gravity load was applied to the whole domain. A graphical representation of boundary conditions used in the model is given in Figure 2.

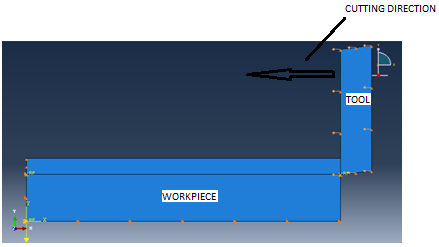


Figure 2 Boundary conditions for the model.

## Chip Separation Criterion

In finite element analysis, there are two commonly used criteria to separate the chip from the machined surface; a geometrical criterion, and an equivalent plastic strain criterion [31, 32]. The geometric criterion is convenient to use but its physical meaning is not well established. Therefore, an equivalent plastic strain criterion was adopted in this study. This is popular and effective in modelling chip separation of metal cutting [33-35]. According to this criterion, the material fails when the equivalent plastic strain reaches a critical value. This criterion was modelled in ABAQUS/Explicit according to a cumulative damage law given by Eq. 3.2 [29] as:

|  |  |
| --- | --- |
|  | Eq. 3.2 |

where D is the damage parameter, is increment of the equivalent plastic strain and is equivalent strain at failure. According to the Johnson–Cook model [28], is updated at every load step, and is expressed by Eq. 3.3,

|  |  |
| --- | --- |
|  | Eq. 3.3 |

depends on the equivalent plastic strain rate , ratio , ratio of hydrostatic (pressure) stress to equivalent stress and temperature (θ). The values of failure constants D1, D2, D3, D4 and D5 are experimentally determined, and used in literature by C.Z. Duan et al. [36] for AISI 1045 steel as 0.06, 3.31, -1.96, 0.0018 and 0.58 respectively. This cumulative damage model is used to perform chip detachment. It is based on the value of the equivalent plastic strain evaluated at element integration points; failure is assumed to occur when damage parameter D, given by Eq.3.2, exceeds 1. When this condition is reached within an element, the stress components are set to zero at these points and remain zero for the rest of the calculations. The hydrostatic pressure stress is required to remain compressive; i.e. if a negative hydrostatic pressure stress is computed in a failed material point during an increment, it is reset to zero [3[[7]](#endnote-7)].

## Element Type

A four-node plane strain quadrilateral element, designated as CPE4RT in ABAQUS/Explicit, was used for the coupled temperature-displacement analysis with automatic hourglass control and reduced integration. Hourglass control was mandatory due to high element deformation. The workpiece consisted of 1,899 nodes and 1,680 elements, the undeformed chip part consisted of 4,635 nodes and 4,220 elements and the tool consisted of 210 nodes and 180 elements when undeformed chip thickness was 0.1 mm. As the undeformed chip thickness was changed due to change in the depth of cut, the number of nodes and elements also changed. The initial configuration of the model with constraints is shown in Figure 2.

## Friction Model

One of the most important aspects of metal cutting is friction. It determines the power required, quality of machined surface, and the rate of tool wear. To accurately model friction, two contact regions, referred to as the sliding and the sticking region, are considered. These regions exist simultaneously along the tool–chip interface. In the sliding region, a coefficient of friction µ is assumed with regard to the Coulomb friction law. In the sticking region, a critical friction stress value τcr is known to exist [7].

There are two types of friction formulations which may be used; “penalty” type, or “kinematic” type. Here, penalty type is used which allows the surface to surface interaction to be closer to the physical situation. A coefficient of friction of 0.3 is assumed for the contact interactions which is similar to the values assumed in previous studies [38, 2, 7].

The interaction between the newly formed chip and the tool used for cutting represents a complex contact problem due to the fact that it involves elastic as well as plastic shear stress and heat conduction along the tool and workpiece surfaces. Experimental observations in literature report the existence of two distinct regions on the rake face of the tool called the sticking and sliding regions [19] [10]. In order to model the tool-chip interface, Coulomb’s friction law was used which is defined by Eq. 3.4, as follows:

|  |  |
| --- | --- |
|  | Eq. 3.4 |
| The formulation involves friction coefficient (μ), equivalent shear stress () and the frictional stress () along the interface between tool and chip. The friction module which is readily available in general purpose code ABAQUS was used as the friction model similar to its usage in many previous studies [10] [8] [[[8]](#endnote-8)] [[[9]](#endnote-9)]. |  |
|  |  |

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## Model Validation

Since performing, analyzing and evaluating physical machining process is lengthy, time consuming, costly and complex process these constraints can be avoided by the use of FE Simulations. To ensure that the results are accurate, the experimental research work found in literature [10, 37] was replicated and validated before FE model was used for further simulations. A detailed modeling of the metal cutting process was conducted by O. Pantalé using JC damage model for modeling the effects of damage on the workpiece 42CrMo4 steel. Since the mechanics and working was similar to the current model, the results obtained and published were replicated by the current FE model. A comparison of the results of cutting forces obtained via various sources as reported by O. Pantalé along with results from the current model are shown in Figure 3 and Figure 4:

The formulation thus involves friction coefficient (μ), equivalent shear stress () and the frictional stress () along the interface between tool and chip. The similar friction module available in ABAQUS was used to model friction as in many previous studies [10, 8 12, 13].

Figure 3 Cutting forces obtained by current model with results for cutting forces published by O. Pantalé [ ].

|  |  |  |
| --- | --- | --- |
| Source | Cutting Force (N) | % difference |
| experimental | 1860 |  |
| Pantale 1 | 1800 | -3.23% |
| pantale 2 | 2096 | 12.69% |
| current model | 2121.571 | 14.06% |
| Oxley | 2328 | 25.16% |
| Joyot | 1740 | -6.45% |

Figure 4 Percentage difference.

Faraz et al. [10] studied the effect of fraction of heat going into the cutting tool during the orthogonal cutting process of AISI 4140 steel. They performed various analyses and provided results which can be used as a benchmark to validate the current model. The comparison between temperatures reported by Faraz et al. and the temperature values at different speeds by current model are shown in Figure 5. The maximum difference between the measured temperatures (using physical experimentation) and the temperatures predicted by the current model is found to be 2.5%.

Figure 5 Comparison of temperature values between the model by Faraz et al. and the current model.

## Mesh Sensitivity Analysis

# Results and Discussion

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## Response data for S/N Ratios:

Response data consists of average SNR, delta, rank and optimum level. The average SNR for each level of each factor forms the body of the table. Delta is the difference between the highest and the lowest average SNR amongst all levels of a particular factor. Rank is given to each factor according to their Delta value arranged in the ascending order. Factor with highest Delta value is the most effective and significant in the process.

Figure 6 shows that feed rate and depth of cut have the most variations in average SNR values. Hence these two factors are important to optimize if cutting forces are to be minimized. The optimum level for feed rate and depth of cut are found to be 0.05 mm and 1 mm respectively, as shown in Figure 8. Figure 7 shows the response data for SNR values of temperature for carbide cutting tool. It was observed that for optimizing the temperature, the cutting speed has the most impact on outcomes followed by Rake Angle. The cutting speed directly affects friction and therefore lower cutting speeds would lead to lower temperature values. Higher rake angle provides better slope for the deformed chip material to flow while a lower rake angle (straight tool) would force the tool to move perpendicular to the motion. The optimum values for the cutting speed and the rake angle are found to be 100 m/min and 7o.

Figure 6 Plots for main effects for SN Ratios on Fc using Carbide cutting tool.

Figure 7 Plots for main effects for SN ratios on temperature using Carbide cutting tool.

Figure 8 shows the response data plots for SNR values of cutting forces for uncoated cemented carbide cutting tool. These plots also indicate that feed rate and depth of cut have most impact on the cutting forces. As shown in Figure 10, the optimum values found for feed rate and depth of cut are 0.05 mm and 1 mm respectively. Figure 9 shows the response data plot for SNR values of temperature for uncoated cemented carbide cutting tool. It is observed that for optimizing the temperature, the cutting speed has the most impact outcomes followed by Rake Angle. The optimum values for the cutting speed and rake angle are found to be 100 m/min and 7o.

Figure 8 Plots for main effects for SN ratios on Fc using uncoated Cemented Carbide cutting tool.

Figure 9 Plots for main effects for SN ratios on temperature using uncoated Cemented Carbide cutting tool.

## Analysis of Variance

Analysis of variance (ANOVA) is used to analyze the experimental results and identify the factors which have a significant effect on the machining output variables i.e. cutting force and temperature. The results of ANOVA are shown in Tables 5 - 8. The p values or probability values show the level of significance of each factor. Lower p values indicate that the factor values have higher probability of falling within the ranges which impact the outcome of the experiment. This should give the lowest p values for the factors which response data for SN ratios (refer to previous section) has identified as having most impact on the outcome. Other indicators include its degree of freedom (DoF) which is defined as k-1 [[[12]](#endnote-12)] (where k is number of levels), treatment sum of squares (SSTR), treatment mean squares (MSTR) and F statistics value.

Residual error was calculated statistically and has no physical influence on the experiment. It is however part of the ANOVA F-statistics test [40]. The DoF for residual error is calculated as (total Dof) – (sum of all treatment Dof). The SSTR or SSE (sum of squared error in case of residual error) was calculated using Eq. 4.1 [40]

|  |  |
| --- | --- |
|  | Eq. 4.1 |

Where 'j' denotes each individual factor, 's2' is the variance and 'n' is the number of observations in the jth factor. Analysis of Variance (ANOVA) was carried out using Minitab.

Table 5 ANOVA Table of Fc using SN data for Carbide cutting tool.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **DoF** | **SSTR** | **MSTR** | **F statistic** | **P value** |
| Cutting Speed | 4 | 1.392 | 0.3481 | 0.79 | 0.564 |
| Feed Rate | 4 | 168.835 | 42.2087 | 95.64 | 0 |
| Rake Angle | 4 | 0.662 | 0.1655 | 0.38 | 0.82 |
| Depth Of Cut | 4 | 264.313 | 66.0782 | 149.72 | 0 |
| Residual Error | 8 | 3.531 | 0.4413 |  |  |
| Total | 24 | 438.733 |  |  |  |

Table 6 ANOVA Table of Temperature using SN data for Carbide cutting tool.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **DoF** | **SSTR** | **MSTR** | **F statistic** | **P value** |
| Cutting Speed | 4 | 43.654 | 10.9136 | 25.06 | 0 |
| Feed Rate | 4 | 7.088 | 1.7721 | 4.07 | 0.043 |
| Rake Angle | 4 | 10.854 | 2.7135 | 6.23 | 0.014 |
| Depth Of Cut | 4 | 2.29 | 0.5725 | 1.31 | 0.343 |
| Residual Error | 8 | 3.485 | 0.4356 |  |  |
| Total | 24 | 67.372 |  |  |  |

Table 7 ANOVA Table of Fc using SN data for uncoated Cemented Carbide cutting tool.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **DoF** | **SSTR** | **MSTR** | **F statistic** | **P value** |
| Cutting Speed | 4 | 0.027 | 0.0068 | 0.05 | 0.994 |
| Feed Rate | 4 | 162.067 | 40.5168 | 308.22 | 0 |
| Rake Angle | 4 | 1.425 | 0.3563 | 2.71 | 0.107 |
| Depth Of Cut | 4 | 278.09 | 69.5225 | 528.86 | 0 |
| Residual Error | 8 | 1.052 | 0.1315 |  |  |
| Total | 24 | 442.661 |  |  |  |

Table 8 ANOVA Table of Temperature using SN data for uncoated Cemented Carbide cutting tool.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **DoF** | **SSTR** | **MSTR** | **F statistic** | **P value** |
| Cutting Speed | 4 | 30.47 | 7.6174 | 9.11 | 0.004 |
| Feed Rate | 4 | 5.294 | 1.3236 | 1.58 | 0.269 |
| Rake Angle | 4 | 9.56 | 2.3899 | 2.86 | 0.096 |
| Depth Of Cut | 4 | 2.221 | 0.5552 | 0.66 | 0.634 |
| Residual Error | 8 | 6.688 | 0.836 |  |  |
| Total | 24 | 54.232 |  |  |  |

As shown in Tables 5 - 8, the p values for feed rate and depth of cut are lowest when cutting forces are taken as output. Similarly, p values for cutting speed and rake angle are lowest when temperature values are considered. This supports the previous results obtained by SN ratios and proves that for optimum values of cutting forces, feed rate and depth of cut should be optimized while for optimum values of temperature, cutting speed and rake angle need to be optimized.

Figure 10 and Figure 11 shows the variations in cutting forces and temperature for all the four factors at different levels for carbide cutting tool and uncoated cemented carbide cutting tool respectively. From the graphs it can be observed that:

1. For both tools, the cutting forces increase when feed rate and depth of cut increase. Increasing feed rate and depth of cut increase material removal rate but also generate higher cutting forces.
2. As the feed rate and depth of cut is reduced, the cutting forces seem to converge which shows stability and less dependence on other factors. The optimum levels for both of these factors is the lowest level since it has the least variance as can be seen from SNR and ANOVA plots.
3. In case of temperature, the cutting speed is observed to follow a specific trend. Temperature converges to lower values when cutting speed is low. It is because low speed generates less friction and therefore less heat is generated. Although cutting speed is a factor which governs the MRR, it is also directly responsible for generating frictional values and hence increasing cutting speed results in increasing temperature.
4. Rake angle, as shown in Figures 10 and 11, is the most irregular of all factors and it seems to barely relate to the cutting forces. However, as it is increased, a converging trend is observed in temperature and hence minimum variance in temperature is observed with highest rake angle values. As the rake angle goes higher, the motion of the chip is less perpendicular to the relative motion of the tool and the workpiece and hence there is less work done against the motion causing lesser friction. This amounts to a decrease in temperature.

Figure 10 (a-d) Plots for Fc and Temperature for all four factors using Carbide cutting tool.

## 

Figure 11 (a-d) Plots for Fc and Temperature for all four factors using uncoated Cemented Carbide cutting tool.

## Optimal design

With the help of response data from S/N Ratio, the optimum levels for feed rate and depth of cut were found to be 0.05 mm and 1 mm respectively. Two other factors are also chosen according to the response data but since their effect is considerably low, they are predictably different for both tools. Optimum levels of all parameters for minimum cutting force are given in Table 9.

Table 9 Optimum levels of input parameters for minimum cutting force.

|  |  |  |
| --- | --- | --- |
| Parameter | Optimum Level for Carbide Cutting Tool | Optimum Level for Uncoated Cemented Carbide Cutting Tool |
| Cutting Speed (m/min) | 400 | 100 |
| Feed Rate (mm) | 0.05 | 0.05 |
| Rake Angle | -2 | 7 |
| Depth Of Cut (mm) | 1 | 1 |

The average for the treatment condition was predicted with the help of the mean values of all outputs for the experiments when they were performed at optimal levels. It was calculated using Eq. 4.2 [20]:

|  |  |
| --- | --- |
|  | Eq. 4.2 |

In Eq. 4.2 the term is the S/N Ratio calculated at the optimum levels determined for minimum cutting force. is the average of all S/N Ratios for Fc. and are the average S/N Ratios for cutting speed, feed rate, rake angle and depth of cut respectively when they were at optimum levels.

|  |  |
| --- | --- |
|  | Eq. 4.3 |

The cutting force output was calculated at optimum levels for both tools with the help of Eq. 4.3 and using from Eq. 4.2. The calculated results were then verified using confirmatory experiments. These experiments were performed using the optimum levels of all 4 factors given in Table 9. Table 10 shows the results for predicted vs simulated outputs of cutting forces.

Table 10 Predicted vs Simulated cutting forces using optimum parameters.

|  |  |  |  |
| --- | --- | --- | --- |
| **Tool** | **Predicted Cutting Force (N)** | **Simulated Cutting Force (N)** | **% error** |
| Carbide Cutting Tool | 130.2 | 136.4 | 4.46 % |
| Uncoated Cemented Carbide Cutting Tool | 136.4 | 140 | 2.64% |

With the help of response table data from S/N Ratios, the optimum level of cutting speed and rake angle were found to be 100 m/min and 7o respectively. Optimum levels of all parameters for minimum temperature are given in Table 11.

Table 11 Optimum levels of input parameters for minimum temperature.

|  |  |  |
| --- | --- | --- |
| Parameter | Optimum Level for Carbide Cutting Tool | Optimum Level for Uncoated Cemented Carbide Cutting Tool |
| Cutting Speed (m/min) | 100 | 100 |
| Feed Rate (mm) | 0.05 | 0.05 |
| Rake Angle | 7 | 7 |
| Depth Of Cut (mm) | 1.5 | 1 |

|  |  |
| --- | --- |
|  | Eq. 4.4 |

Using Eq. 4.2 the S/N Ratio for optimum temperature was calculated by using temperature output data as input. The temperature output at optimum levels for both tools was calculated using Eq. 4.4. For verification, the calculated results were compared with confirmatory experiments performed using the optimum levels of all 4 factors given in Table 11. Table 12 shows the results for predicted vs. simulated outputs of temperature.

Table 12 Predicted vs. Simulated temperature values using optimum parameters.

|  |  |  |  |
| --- | --- | --- | --- |
| **Tool** | **Calculated Temperature (oC)** | **Simulated Temperature (oC)** | **% error** |
| Carbide Cutting Tool | 406.4 | 396.3 | 2.48% |
| Uncoated Cemented Carbide Cutting Tool | 439.5 | 424.2 | 3.47% |

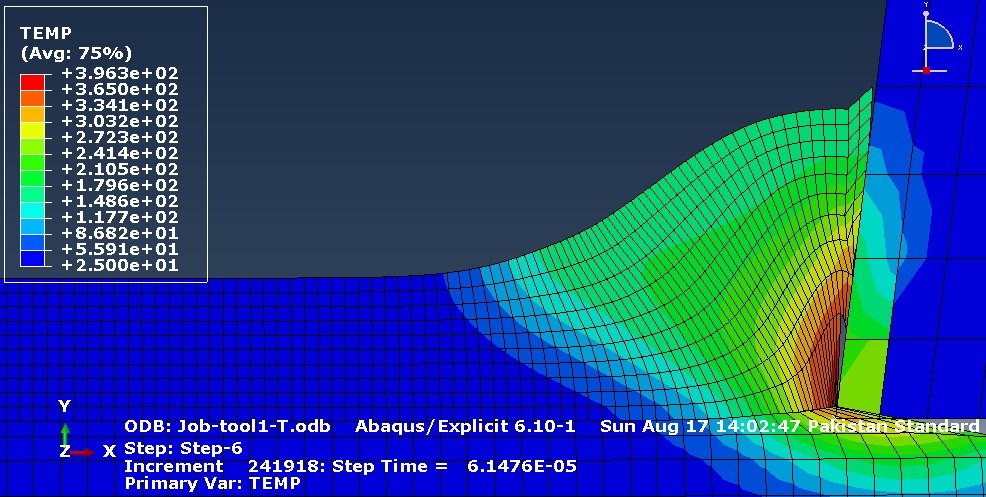


Figure 12 Confirmatory Simulation for Temperature values using Carbide cutting tool.

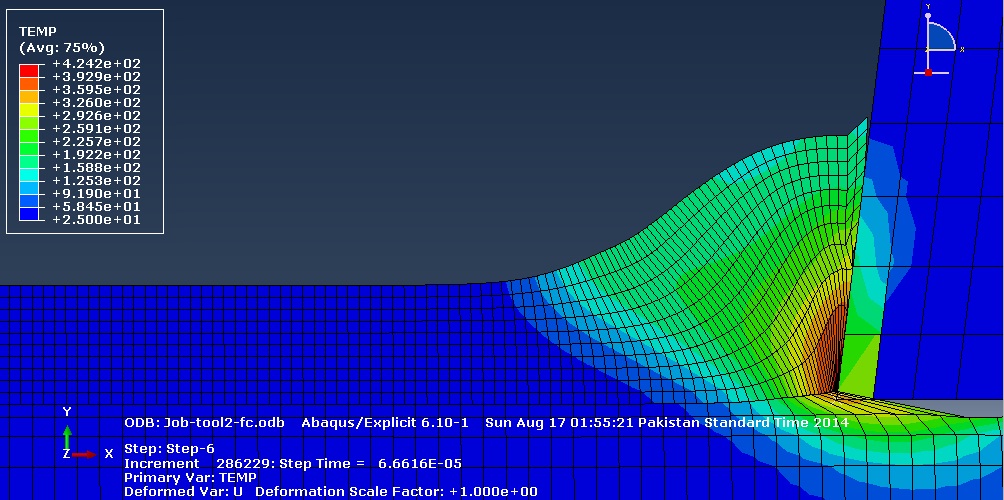


Figure 13 Confirmatory simulation for temperature values using uncoated Cemented Carbide cutting tool.

# Conclusions

Orthogonal cutting process of AISI 1045 Steel has been modeled successfully in this study using general purpose FE code, ABAQUS. The model was validated by experimental results reported in published literature. For simplicity a two-dimensional model was used and the tool was assumed to be rigid. Furthermore, the coefficient of friction was taken to be constant based on published values.

It is found that:

1. The carbide cutting tool is a better option while machining AISI 1045 steel as it results in lower cutting forces and temperature values as compared to uncoated cemented carbide cutting tool.
2. The most significant factors for cutting forces are feed rate and depth of cut with minimum possible p-values of 0 for both tools. Similarly, the most significant factors for temperature is cutting speed with p-values of 0 and 0.004 for the two tools. At a confidence level of 95%, these values fall well under the criteria to be deemed as significant factors.
3. For the carbide cutting tool, the rake angle is observed to be significant for lower temperatures as its p-value of 0.014 is within the range of 95% confidence level but for uncoated carbide cutting tool, rake angle is not found to be significant factor in lowering the temperature as its p-value is at 0.096.
4. The optimum values of cutting force and temperature, as calculated statistically, are well within 5% error range of the simulated results. It shows that the analysis results are satisfactory as the output is optimized by using optimized parameters. ANOVA has reinforced the results of SN ratio by statistically proving the probability factors to be within 5% significance level.

# Nomenclature

|  |  |
| --- | --- |
| Tr | Room Temperature |
| Tm | Melting Temperature |
|  | Strain Rate |
| ν | Cutting speed |
| f | Feed rate |
| d | Depth of cut |
|  | Reference Strain Rate |
| τcr | Critical Friction Stress |
| µ | Coefficient of Friction |
|  | Frictional Stress |
| Fc | Cutting Force |
|  | Average S/N Ratio |
|  | Average treatment condition |
|  |  |
| Fcal | Statistically calculated Cutting Force using optimum parameters |
| Tcal | Statistically calculated Temperature using optimum parameters |

# ACKNOWLEDGEMENT

Financial support for this work by the National University of Sciences and Technology of Pakistan is gratefully acknowledged.

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