# Influence of process parameters on cutting forces and Taguchi based prediction of T42 - CT H.S.S single point cutting tool deflection

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**Abstract** - Deflection of cutting tools during machining on a lathe affects their tool life, surface roughness and dimensional correctness. For an optimum turning operation, correct selection of cutting parameters as well as tool extension length are essential. In this work, deflection of a T-42 CT H.S.S single point cutting tool is investigated by varying rake angle, cutting feed and tool extension length during turning operation on lathe. The selection of process parameters were determined by using Taguchi's experimental design method. Cutting force components during turning operation were measured by lathe tool force dynamometer and detailed deflection analysis was conducted by using ABAQUS finite element program. The degree of influence of each process parameter on cutting force and deflection was studied and the optimal values that minimize deflection were determined. Finally an empirical relationship between deflection and input parameters is formulated. As turning of different grades of steel using H.S.S is one among the major machining operations in manufacturing industry, the revelation made in this research would significantly contribute to optimization of cutting parameters.

*Index Terms*— Deflection, Taguchi, Cutting forces, FEM, Design of experiments, ANOVA

## I. INTRODUCTION

The life of a cutting tool is affected by factors like cutting speed, feed, depth of cut, heat treatment of the tool, work material, tool material, tool extension length and nature of cutting. The main characteristics of a good cutting tool material are its hot hardness, wear resistance, impact resistance, abrasion resistance, heat conductivity, strength, etc. Tool life is likely to get affected by the changes in these characteristics at high temperature because the metal cutting process is always associated with generation of high amount of heat, and hence high temperatures. The tool material which can withstand maximum cutting temperature without losing its principal mechanical properties especially hot hardness and geometry will ensure maximum tool life, and hence will give the most efficient cutting of metal. In order to produce any machine part with desired quality by any metal removal process, cutting parameters should be selected properly [1].

It is clear from studies based on cutting forces in chip removal process that the acting forces directly influence cutting parameters [2]. In the case of single point cutting tool, force required to overcome the developed stresses during chip formation process can be resolved into three components: Cutting force ($F_S$), Feed force ($F_V$) and Radial force ($F_P$).
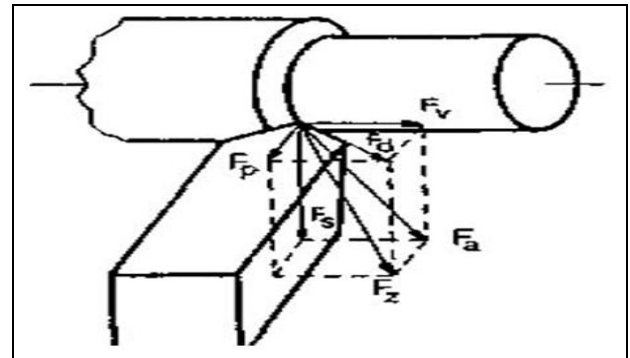


**Fig 1 Cutting forces acting on the cutting tool during turning [3]**

Cutting force ($F_S$) acts against the work piece during turning motion and forces the cutting tool downwards perpendicular to the work piece axis. Feed force ($F_V$) acts parallel to the work piece turning axis and it is in the reverse direction of the feed. Radial force ($F_P$) acts perpendicular to the machined surface and forces the cutting tool backward. Fig.1 shows the details of component forces in turning.

The cutting force analysis plays a vital role in studying the various characteristics of the machining process such as dynamic stability, positioning accuracy of the tool, surface roughness of the machined part, dimensional errors in machined component etc. In order to get an accurate surface finish and exactly dimensioned machined component in metal cutting process, deflection of a cutting tool due to cutting forces should ideally be zero. However, this is not possible in real cutting conditions and a deflection value of less than 0.1 mm is permitted in rough turning operation. But in the case of finishing operation, its value should not be greater than 0.05 mm [1]. It has been reported that about 15% of the tool breakage results from the wrong selection of cutting parameters and premature failure of cutting tools are mainly caused by excessive vibration, chipping and cracking due to excessive stress developed at the cutting edge.

Deflection of single point cutting tools during turning operations were usually found out by considering cutting tool as a cantilever beam and applying the main cutting force ($F_S$) at its free end and deflection is calculated from the simple beam equation

$$\text{Deflection, } y = F_S L^3 / 3EI$$

where, L is the length of the tool, E is the modulus of elasticity and I is the moment of inertia. Abdullah Duran and Muammer Nalbant [3] conducted the bending analysis of a cutting tool using Castigliano's theorem and compared the deflection

values with the values obtained by finite element method [5,6]. Their study show that difference between deflection values obtained by both methods is negligible when side cutting edge angle is 90° and the difference increases as the side cutting angle decreases and a maximum of 8% deviation in the deflection value is reported when side cutting edge angle is 60°.

Even though a lot of researches regarding the machining performance, wear analysis and surface roughness have taken place in the field of turning operations, only few studies were reported on bending analysis. In this work, detailed finite element analyses of deflection of T42-CT H.S.S single point cutting tools were conducted by applying experimentally measured cutting forces using 3 component lathe tool dynamometer. The obtained deflection values are compared with the values calculated using the cantilever beam equation. By varying rake angle, cutting feed and tool extension length, experiments were repeated and the degree of influence of these parameters on deflection was studied. In all cases, cutting speed and depth of cut were kept constant. The experiments have been conducted using Taguchi's experimental design technique. Orthogonal arrays of Taguchi, the signal to noise (S/N) ratio, the analysis of variance (ANOVA), and regression analysis are employed to find the optimal process parameter levels to analyse the effect of these parameters on deflection.

## II. EXPERIMENTAL PROCEDURE

### A. *Plan of Experiments*

Taguchi's parameter design is an important tool for robust design, which offers a simple and systematic approach to optimize a design for performance, quality and cost. Taguchi's

**Table 1 Process parameters and their levels**

full factorial design with three parameters each at three levels and $L_{27}$ Orthogonal array (Table 2) was used for this

| Process Parameters | Designation | Level-1 | Level-2 | Level-3 |
|---|---|---|---|---|
| Rake angle (degree) | A | 0 | 10 | 15 |
| Feed (mm/rev) | B | 0.05 | 0.1 | 0.15 |
| Tool extension length(mm) | C | 25 | 30 | 35 |

experiment.

| Experiment Number | Rake Angle(degrees) | Cutting Feed(mm/re) | Tool Extension Length(mm) |
|---|---|---|---|
| 1 | 0 | 0.05 | 25 |
| 2 | 0 | 0.05 | 30 |
| 3 | 0 | 0.05 | 35 |
| 4 | 0 | 0.1 | 25 |
| 5 | 0 | 0.1 | 30 |
| 6 | 0 | 0.1 | 35 |
| 7 | 0 | 0.15 | 25 |
| 8 | 0 | 0.15 | 30 |
| 9 | 0 | 0.15 | 35 |
| 10 | 10 | 0.05 | 25 |
| 11 | 10 | 0.05 | 30 |
| 12 | 10 | 0.05 | 35 |
| 13 | 10 | 0.1 | 25 |
| 14 | 10 | 0.1 | 30 |
| 15 | 10 | 0.1 | 35 |
| 16 | 10 | 0.15 | 25 |
| 17 | 10 | 0.15 | 30 |
| 18 | 10 | 0.15 | 35 |
| 19 | 15 | 0.05 | 25 |
| 20 | 15 | 0.05 | 30 |
| 21 | 15 | 0.05 | 35 |
| 22 | 15 | 0.1 | 25 |
| 23 | 15 | 0.1 | 30 |
| 24 | 15 | 0.1 | 35 |
| 25 | 15 | 0.15 | 25 |
| 27 | 15 | 0.15 | 30 |
| 27 | 15 | 0.15 | 35 |

**Table 2 $L_{27}$ Orthogonal array**

### B. *Work piece Material*

AISI 1060 steel rod is used for machining. It has good machinability, and is the most commonly used material for dies and moulds. Initial work piece diameter is taken as 40 mm, and work piece length as 250 mm (approx.)

### C. *Tool material*

AISI T-42 CT (Cryogenically Treated) H.S.S tools are used for turning operations. Cryogenic treatment is the supplementary process to conventional heat treatment process in H.S.S steels by deep freezing the material to improve the physical and mechanical properties of the material being treated [7]. Rohit EC 500 (T42-CT) single point cutting tool bits used in this work were purchased from their dealers. Chemical composition and properties of T-42 CT H.S.S materials are shown in Table 3

| Chemical composition | | | | | |
|---|---|---|---|---|---|
| C | Cr | Mo | W | V | Co |
| 1.25 | 3.75 | 2.75 | 8.5 | 2.75 | 10.0 |
| Modulus of Elasticity – 217000N/mm² Hardness-67 HRC | | | | | |
| Poisson's ratio – 0.27 Density – 8gm/cc | | | | | |
| Thermal conductivity – 19 W/mK Specific Heat– 460J/kg K | | | | | |

**Table 3 Chemical composition and properties of T-42 H.S.S tool material**

### D. *Tool and cutter grinder*

The purchased T-42 CT H.S.S single point tool bits (12 × 12 × 100 mm) were ground to required tool geometry using BMT-TCG 1 tool and cutter grinding machine. The tools with rake angles of 0°, 10°, 15° were used for turning operation.

Same clearance angle of $12^{\circ}$ and side and end cutting angles of $10^{\circ}$ were selected for all the tools with different rake angles.

### E.  *Centre lathe*

All the 27 experiments were carried out on the precision centre lathe, NAGMATI-175 (Fig. 2) which enables high precision machining and production of jobs. Technical specifications of Centre lathe are, Centre height: 175 mm, Power required: 2.25 KW, Swing over bed: 350 mm. Cutting speed (50 m /min) and depth of cut (1mm) are kept constant throughout the experiments. Before taking the readings, the system was run idle for 30 minutes so that a steady state was reached.



**Fig 2 NAGMATI-175 Centre lathe**

### F.  *Lathe tool force dynamometer*

The instrument used for cutting force measurement was Sharp UIL-15 multi component force indicator. It comprises of three independent digital display calibrated to display force directly using three component tool force dynamometer. Instrument operates on 230 V, 50 Hz AC mains.

## III.   FINITE ELEMENT ANALYSIS

Parallel to the development in computer technology, finite element method (FEM), one of the most accurate numerical solution methods, has been increasingly used for modelling cutting operations [3-6]. It gives accurate results and therefore, it is now a well-accepted numerical method.

Cutting tools were modeled using Autodesk Inventor-2011 as a solid model and deflection  of cutting tools under cutting forces are analysed using ABAQUS/CAE 6.10, finite element program. The created solid model was saved as IGES format and imported to ABAQUS and divided into finite elements.
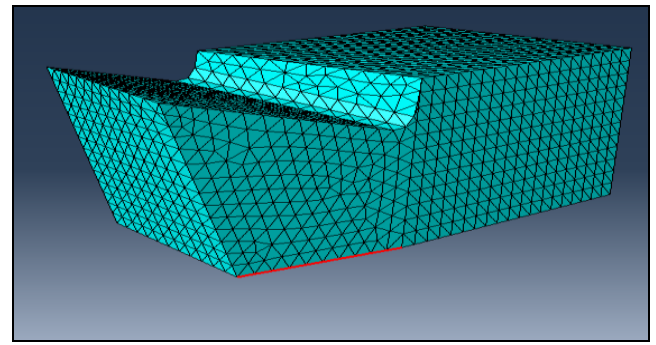


**Fig 3 T42 H.S.S CT cutting tool model after meshing (rake angle $15^{\circ}$)**

Boundary conditions were applied by fixing one end of the beam and cutting forces were applied on the cutting edge as uniform loads along X, Y, Z directions.  The cutting tool material was regarded as having linear elastic isotropic properties and its values were entered through material properties icon. C3D4, 3 dimensional 4 node tetrahedron structural solid element with linear displacement behaviour was used as the element type. A mesh sensitivity study was conducted before selecting the final mesh and element size. A uniform mesh was used throughout the length of cutting tool. A total number of 28000 elements (approx.) have been created in a typical  tool model (Fig. 3).

## IV.   RESULTS AND DISCUSSION

### G. *Influence  of tool rake angle on cutting force components*

Fig. 4 shows the variation of cutting force components with changes in rake angle. The results are shown for a tool extension length of 25 mm and feed of 0.05 mm/rev.

In general, these results show that all the components of cutting force decrease with increase in rake angle. Further while the reduction in the magnitudes of force with rake angle is significant for cutting force ($F_S$) and feed force ($F_V$), it is less pronounced in the case of radial force ($F_P$). This decrease in cutting forces  is attributed to the decrease in  tool/chip contact area and friction force, so that chip will be formed easily [8, 9].
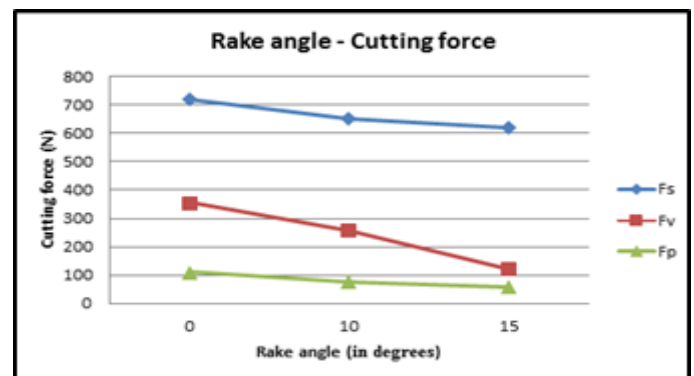


**Fig 4   Rake angle effect on cutting forces**

### H.  *Influence of cutting feed on cutting force components*

Variations of all the cutting force components with cutting feed for $0^{\circ}$ and $15^{\circ}$ rake angled tools are shown in Fig. 5.
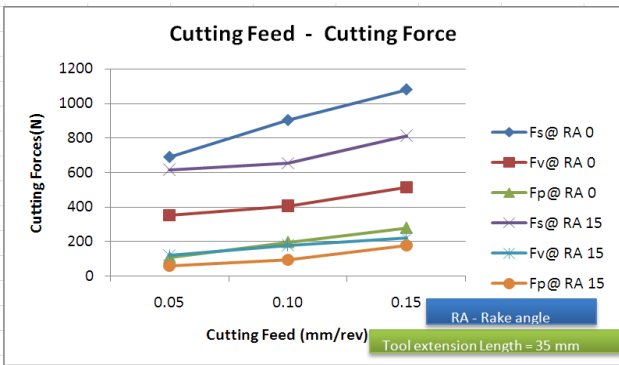
**Fig 5 Influence of cutting feed on cutting forces**

The results show that three components of force i.e. $F_S$, $F_V$, $F_P$ increase as the cutting feed increases in T42 H.S.S single point cutting tools. Further, the above increase is more pronounced for $0°$ rake angled tool compared to that for $15°$ rake angled tool.

### I. *Influence of tool extension length on cutting force components*

The variation of the cutting force components with tool extension length for $0°$ and $15°$ rake angled tools are shown in Fig. 6.

It may be observed from the results that all the component forces decreases slightly with increase in tool extension length. When extension length increases forces applied by work piece on cutting tool decreases and reaction forces i.e. cutting forces also decrease. Cutting force variation is very narrow for feed force ($F_V$) and radial force ($F_P$) as compared to main cutting force ($F_S$).
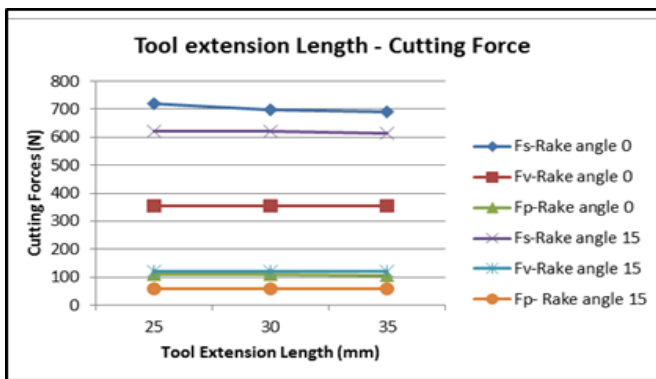


**Fig 6 Effect of tool extension length on cutting forces**

### J. *Deflection analysis*

The deflection values found out by using finite element method are shown in Table 4. It is clear from the results that deflection values increase as cutting feed, tool extension length and cutting feed increases. All the values of deflection obtained were less than 0.1mm, the permitted value in rough turning operation. Whereas, only 14 experiments (Ex No 1, 2, 3, 4, 5, 7, 10, 11, 13, 14, 16, 19, 22, 25 ) can be recommended for finishing operation, since their deflection values are below 0.05 mm.

| Exp. no | Rake Angle (degrees) | Cutting Feed (mm/rev) | Tool Extension Length (mm) | Deflection (mm) |
|---|---|---|---|---|
| 1 | 0 | 0.05 | 25 | 0.0123 |
| 2 | 0 | 0.05 | 30 | 0.03731 |
| 3 | 0 | 0.05 | 35 | 0.04826 |
| 4 | 0 | 0.1 | 25 | 0.01449 |
| 5 | 0 | 0.1 | 30 | 0.04492 |
| 6 | 0 | 0.1 | 35 | 0.05854 |
| 7 | 0 | 0.15 | 25 | 0.01677 |
| 8 | 0 | 0.15 | 30 | 0.05257 |
| 9 | 0 | 0.15 | 35 | 0.06839 |
| 10 | 10 | 0.05 | 25 | 0.01461 |
| 11 | 10 | 0.05 | 30 | 0.04791 |
| 12 | 10 | 0.05 | 35 | 0.05766 |
| 13 | 10 | 0.1 | 25 | 0.01493 |
| 14 | 10 | 0.1 | 30 | 0.04902 |
| 15 | 10 | 0.1 | 35 | 0.05908 |
| 16 | 10 | 0.15 | 25 | 0.0185 |
| 17 | 10 | 0.15 | 30 | 0.0609 |
| 18 | 10 | 0.15 | 35 | 0.0738 |
| 19 | 15 | 0.05 | 25 | 0.0165 |
| 20 | 15 | 0.05 | 30 | 0.05413 |
| 21 | 15 | 0.05 | 35 | 0.06248 |
| 22 | 15 | 0.1 | 25 | 0.01702 |
| 23 | 15 | 0.1 | 30 | 0.05582 |
| 24 | 15 | 0.1 | 35 | 0.06465 |
| 25 | 15 | 0.15 | 25 | 0.01945 |
| 26 | 15 | 0.15 | 30 | 0.06402 |
| 27 | 15 | 0.15 | 35 | 0.07476 |

**Table 4 Deflection values obtained by FEM**

Fig 7 shows the differences between deflection values obtained by beam equation and finite element program, ABAQUS.
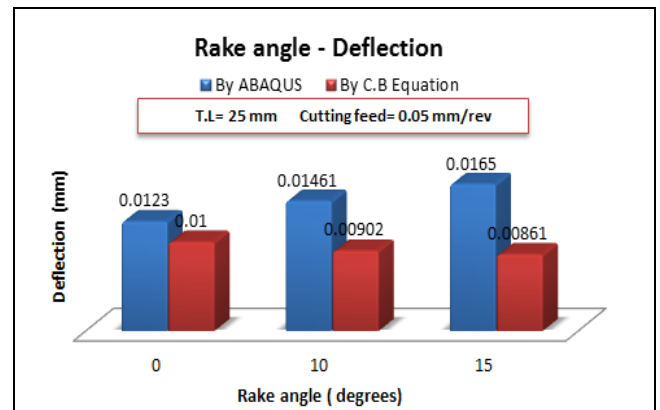


**Fig 7 Comparison of deflection values**

The difference between deflection values is lower at zero rake angle, but it becomes significant as rake angle increases. This is due to the reason that, when we find out the deflection using beams equation, cross section of beam is considered as uniform throughout the length i.e. no consideration is given to the tool geometry. Also deflection is calculated by applying cutting force ($F_S$) at its free end as a point load. Whereas other two components $F_P$ and $F_V$ were neglected due to its low magnitude as compared to main cutting force $F_S$.

### K. *Analysis of S/N ratio*

The standard commercial software package MINITAB was used to optimise the deflection values and study the effect of individual parameters on deflection. In Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value for the output characteristic. Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value [10].

Signal to Noise ratio is found out in each case using the criteria 'lower is better' as deflection is the factor of consideration. The S/N ratio for 'lower is better' is

$$S/N = -10 \log \left[ 1/n \; \Sigma \; (1/y_i^2) \right]$$

where, n is the number of measurements in a trial/row (here n=1) and y is the measured value in a run/row. S/N values for the present study computed using the above equation are given in Table 5. Regardless of the category of the performance characteristics, a greater S/N ratio corresponds to a better performance. Therefore, the optimal level of the machining parameters is the level with the greatest S/N value. From this table it is clear that greatest S/N ratio occurs at experiment number 1. It means that the deflection will be minimum for the parameters corresponding to that particular experiment.

| Experiment Number | S/N Ratio |
|---|---|
| 1 | 38.2019 |
| 2 | 28.5635 |
| 3 | 26.3283 |
| 4 | 36.7786 |
| 5 | 26.9512 |
| 6 | 24.6509 |
| 7 | 35.5093 |
| 8 | 25.5852 |
| 9 | 23.3001 |
| 10 | 36.7070 |
| 11 | 26.3915 |
| 12 | 24.7825 |
| 13 | 36.5188 |
| 14 | 26.1925 |
| 15 | 24.5712 |
| 16 | 34.6566 |
| 17 | 24.3077 |
| 18 | 22.6389 |
| 19 | 35.6503 |
| 20 | 25.3312 |
| 21 | 24.0852 |
| 22 | 35.3808 |
| 23 | 25.0642 |
| 24 | 23.7886 |
| 25 | 34.2216 |
| 26 | 23.8737 |
| 27 | 22.5266 |

**Table 5 S/N ratio**

In order to determine the most significant level as well as parameters, the average deflection values for all the parameters corresponding to different levels are found out and shown in Table 6.

| Level | Rake Angle | Cutting Feed | Tool Extension Length |
|---|---|---|---|
| 1 | 0.04174 | 0.03971 | 0.01606 |
| 2 | 0.04405 | 0.04288 | 0.05184 |
| 3 | 0.04765 | 0.05085 | 0.06553 |
| Delta | 0.00591 | 0.01114 | 0.04946 |
| Rank | 3 | 2 | 1 |

**Table 6 Average deflection values in each level**

From the above table it is clear that all the deflection values are minimum at level 1 (i.e. with rake angle 0°, cutting feed 0.05 mm/rev and tool extension length 25mm). Further, the tool extension length parameter which is ranked as 1, becomes the most significant factor affecting the deflection.
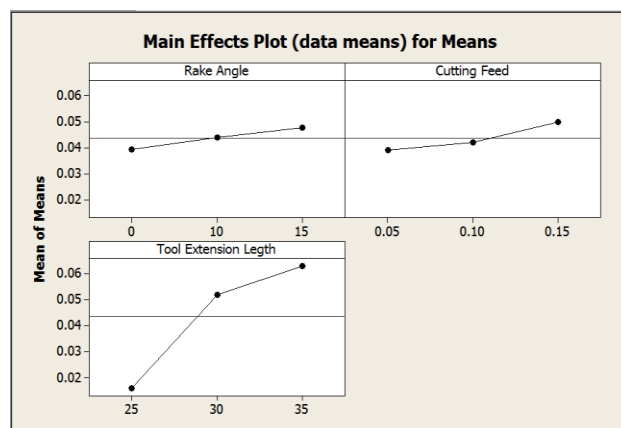


**Fig 8 Response graph of the mean deflection**

Also, the response graphs of the mean deflection corresponding to the data presented in Table 6 are shown in Fig. 8. The graph clearly demonstrates the importance of tool extension length on deflection as compared to other parameters.

L. *Regression analysis*

The correlation connecting different factors (cutting feed, rake angle, tool extension length) with deflection of T42 CT H.S.S single point cutting tool were obtained by multiple linear regression equation. The equation is in the form

$$\text{Deflection} = -0.113 + 0.000546 \; A + 0.109 \; B + 0.00470 \; C$$

$$\text{and} \qquad R^2 = 0.90$$

where, A=rake angle, B=cutting feed, C= tool extension length. Here $R^2$ is the regression coefficient ($R^2$=0.90) for the models, which indicate that the fit of the experimental data is satisfactory [11].

M. *Analysis of Variance*

ANOVA is a statistics based, objective decision making tool used to investigate the significance of each factors on entire process. This analysis was carried out for a level of significance of 5%. Table 7 shows the result of ANOVA.

| Parameter | DOF | SS | MS | F | P | P (%) |
|---|---|---|---|---|---|---|
| Rake Angle | 2 | 0.0003169 | 0.0001584 | 12.37 | 0.000 | 2.64 |
| Cutting Feed | 2 | 0.0005684 | 0.0002842 | 22.18 | 0.000 | 4.74 |
| Tool Extension Length | 2 | 0.0108474 | 0.0054237 | 423.35 | 0.000 | 90.48 |
| Error | 20 | 0.0002562 | 0.0000128 | | | 2.14 |
| Total | 26 | 0.0119889 | | | | 100 |

**Table 7 ANOVA table**

It can be observed from the above table that the percentage influence of tool extension length, cutting feed and rake angle on the deflection of T-42 CT H.S.S single point cutting tool are 90.48 %, 4.74 % and 2.64 % respectively.

## V.  CONFORMATION OF EXPERIMENT

The conformation test is the final step in verifying the results drawn based on Taguchi's design approach. To validate the optimum deflection values a conformation test was done by utilising the levels of optimal process parameters (rake Angle = $0^{\circ}$, cutting feed = 0.05 mm/rev, tool extension length = 25 mm). Confirmation experiment yields a deflection of 0.012 mm, whereas the result obtained using regression modelling equation is 0.011mm, which ascertains the accuracy of the predicted equation.

## VI.  CONCLUSIONS

This paper attempts to conduct a detailed FEM analysis of deflection of T-42 CT H.S.S tools using cutting forces measured by a lathe tool force dynamometer and study the effect of input parameters on cutting forces and deflection. It also formulates an empirical relationship between the deflection values and the input parameters. Based on the analytical and experimental results obtained in this study following conclusions can be drawn.

1. As rake angle and tool extension length increases, all the components of cutting force decreases. Whereas with increase in cutting feed, the cutting force increases.
2. Deflection of cutting tool increases with increase in rake angle, cutting feed and tool extension length.
3. Percentage influence of tool extension length, cutting feed and rake angle on the deflection of T-42 CT H.S.S single point cutting tool is 90.48 %, 4.74 % and 2.64 % respectively.
4. All the components of cutting force slightly decrease with tool extension length. Whereas, tool extension length significantly influences the deflection.
5. Empirical equation relating various process parameters and deflection is formulated.
6. Optimum values of rake angle (0°), cutting feed (0.05 mm/rev) and tool extension length (25 mm) which give minimum deflection are found out using Taguchi optimization technique.

## ACKNOLWLEDGEMENT

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