Static & dynamic performance analysis and modal simulations of single point cutting tool

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Abstract. Tool manufacturers’ aims to produce quality tools to withstand higher cutting forces, thermal resistivity with increased wear resistance to improve tool life and to produce better surface finish maintaining dimensional accuracy of the finished product. The paper analyses the machining performances of single point cutting tool made from high speed steel and tungsten carbide in dry machining of mild steel and aluminium. Varying cutting speeds, feed rates and depth of cuts were taken into consideration for the experimental performance, using lathe tool dynamometer. The data obtained from the experiments are used for the static, modal and steady state dynamic analysis using FEA package ABAQUS solver. From the static analysis, it was found that WC has a higher stiffness and durability as compared to the HSS. The natural frequencies and the mode shapes of the HSS and WC tools were identified and plotted. The analysis showed WC tool has higher natural frequencies as compared to the HSS tool for each of the six mode shapes. The dynamic analysis of the tools showed the deformation was least for WC. The stress induced in WC was found to be around 50% of that of HSS and the factor of safety was almost double to that of HSS. Thus this paper shows that static and dynamic performance analysis of the WC tools is better than the HSS tools.

Key words: cutting tool; ABAQUS; static; modal; dynamic analysis

1. INTRODUCTION

Any machine tool is just as efficient as its cutting tool. Cutting tools are given more thoughtful considerations in any work shop or shop floor. Time is an essential commodity, which can be wasted due to an improperly shaped cutting tool. The shape and positioning of the tool in the tool holding device directly affects the cutting process of the tool. Single point lath cutting tool are considered as wedges in any research and analysis. The wedges are analysed for forces of compression to cause plastic flow or rupture in the materials due to the single point cutting tool. This rupture is known as metal/material cutting. To efficiently and accurately machine metal/materials effectively, it is essential for the single point cutting tool to have appropriate cutting edges for the particular metal/material being machined and the desired type of cut. The commonly used cutting tool materials are High Speed Steel (HSS) and Tungsten Carbide (WC).
Tungsten is used as an alloying element along with vanadium, chromium, or molybdenum in High Speed Steel (HSS) cutting tools to improve its properties. A majority of single point cutting tools are made of HSS due to its hardness retention properties at elevated temperatures, even though their hardness is lower compared to tempered carbon steel. Metal/material cutters made from HSS have a tendency to remove material with ease without self damage at high speed and feed rates, which could heat the cutting edges. Tungsten carbide (WC) is employed in tool inserts at high speed which require maximum efficiency is required for materials which are difficult to machine. These cutting tool inserts are highly efficient in machining of metals/ materials such as copper, bronze, brass, cast iron, alloyed cast iron, aluminum, and its alloys as well as nonmetallic materials such as fiber, hard rubber, and Bakelite.

2. LITERATURE

J.A. Ghani et al. [1,11] evaluated the TiN-coated carbide and uncoated cermet tools for the mechanism of wear mechanism at varying combinations of cutting speed, feed rate, and depth of cut for machining hardened AISI H13 tool steel. It was noticed that the time consumed for initiating the cracking and fracturing which was found to longer in TiN-coated carbide tools as compared to uncoated cermet tools, specifically at combinations of high & low cutting speed, feed rate, and depth of cut. The research concluded the uncoated cermets tools show more uniform and gradual wear on the flank face than that of the TiN-coated carbide tools. Yong Huang et al. [2] have investigated the performance of the tool based on the tool life with respect to flank wear criterion which was a function of cutting parameters such as, cutting speed, feed, and depth of cut. It was observed that the cutting speed played a dominant role in evaluating the performance of the tool in terms of tool life as well as feed and depth of cut. The overall experimental observations and evaluations agreed with predictions from the general Taylor tool life equation.

Schulz et al. [3] stated that cutting edges of cemented carbide tools coated with TiC, TiN or(Ti, Al)N by Physical Vapour Deposition (PVD) and/or Chemical Vapour Deposition (CVD) techniques showed an enhanced service life of tools by a factor of ten as compared to uncoated tools. It is found by F. Akbar et al. [4] that the application of TiN coatings on the cutting tools triggered a reduction in heat penetration into the cutting tool as compared to the uncoated tool with 17% at standard cutting speed and 60% in the HSM zone. According to RAMAMOORTHY et al. [5] the sputter deposition parameters for DLC/TiN/Ti/Cu/Ni multi-layer coatings are recognized to attain enhanced quality with specific reference to surface finish and adhesion. K. Subramanyam et al. [6] examined the coated tools performance of machining hardening steel under dry conditions. The experimental results showed with increase in feed the surface roughness observed is very poor. The outcome of cutting velocity on surface roughness is relatively low when compared to feed rate. With increase in depth of cut the surface roughness is increased. Here experimental results shows by selecting the proper cutting parameters the coated tools are suitable to produce fine surface finished components.

As per L.B. Abhang et al. [7] it has been undertaken into measuring the temperatures generated during cutting operations. The main techniques used to evaluate the cutting temperature during machining are tool-chip thermocouple, embedded thermocouple, and thermal radiation method. Tool-work thermocouple has become a popular tool to be used in temperature measurements during metal cutting. In this paper the tool-work thermo couple technique was used to measure the chip-tool interface temperature during machining of EN-31 steel alloy. M.B.Silva and Wall Bank J. [8] stated the improvement of cutting performance, the knowledge of temperature at the tool-work interface with good accuracy is essential. Numerous analytical and experimental methods have been developed for measuring the rise in temperatures in the cutting tools generated during the cutting processes.

Shreedhar Bhattarai [8] investigated the performance of single point cutting tool coated with metal (Nickel and Zinc) in the turning operation of Aluminum. The single point cutting tool is used for machining cylindrical shaped specimen of Aluminum. A number of tests are performed with different
cutting speeds, feed rates and depth of cuts. The temperature in the chip-tool interface and surface roughness is measured and material removal rate is calculated. These data helped in analyzing the performance of cutting process. A. Nagarajan [9] investigated tool wear characterization of single point cutting tool inserts coated with titanium nitride (Tin) and Al₂O₃. The single point cutting tool of material SAE-AISI 1037 carbon steel is selected. The coated tools exhibited superior wear resistance over the uncoated tool. The Al₂O₃/Tin coated tool had the lowest flank wear due to the high abrasive resistance. The coating is done according to the boundary conditions of the existing cutting tool as we selected, more than one layer are coated. The analysis of coated cutting tool is reported. Modeling of a cutting tool is designed by existing dimension. Feed force and cutting force are Analysis induced in the coated tool material. Subsequent to which the FEA is accomplished to evaluate the total deformation in the existing single point cutting tool for the given loading conditions using Finite Element Analysis software ANSYS workbench. In the first part of the study, the static loads acting on the cutting tool.

Sanjeev Sharma [10] explained measurement of metal machining process factors and on the promotion of adaptive control, demonstrates that the performance of machine, tool material selections and work-piece, tool life, surface finish, dimensions of cutting tool edges, and cutting specifications are intimately associated to the cutting forces. The paper deals with checking the design of lathe tool dynamometer under the capacity of 500 kg and optimization of their cutting force measurement. The data is obtained using technique of force measurement in metal machining processes. In particular for turning process the results are analyzed, leading to an appraisal of the current status of the cutting force measurements with respect to feed rate, depth of cut and feed/revolution. The high speed steel (or HSS) which has over 30 grades of high-speed steel, categorized into tungsten, molybdenum, and molybdenum cobalt based grades. Carbide tools are preferred in the industries because of their abilities to cut faster than other tools and longer life cycles. The major categories of hard carbide include tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide. Tungsten Carbide (TC) is used in solid round tools or in the form of replaceable inserts. HSS has a lower working range speed as compared to TC.

3. OBJECTIVES AND METHODOLOGY:

From the literature review it is found that greatest limitation of high speed steel (HSS) is that its usable cutting speed range is far lower when compared to Tungsten Carbide (TC). To validate this phenomenon, experiments of turning operation were conducted with different cutting speeds of aluminum as a work piece and high speed steel (HSS) as cutting tool mounted in dynamometer. From dynamometer will get the individual cutting speed’s reaction forces like Feed Force, (Fₓ) and Cutting/ Tangential Force, (Fᵧ) these forces will take into consideration for the finite element analysis to draw a comparison study of high speed steel (HSS) and Tungsten Carbide (TC). Reaction forces from experimental data are use to carry out the static, modal and steady state dynamic analysis. From above analysis the comparison on the deformation, stress and factor of safety (FOS) of high speed steel (HSS) and tungsten carbide (TC) single point cutting tool.

The methodology followed for the research is shown in the Flow chart in Figure 1.
4. EXPERIMENTAL PROCEDURE

Aluminium rods of 25 mm diameter and 100 mm long were chosen for the experimental machining procedure. The aluminum rod is cut into 10 cm pieces with the help of hand saw. The aluminum rod is held in vice. The cut aluminum work pieces ready for facing and turning operation areas shown in Figure 2. The tool selected for our experimental purpose is high speed steel Figure 3. The aluminium rods are turned using HSS single point cutting tool. When tool steels contain a combination of more than 7% molybdenum, tungsten and vanadium, and more than 0.60% carbon, they are referred to as high speed steels. The cut piece of aluminum was fitted to the head stock in the lathe machine and subsequently, facing operation was executed to provide a smooth face. The faced work piece is turned as shown in Figure 4, in lathe machine and 0.5mm thickness is reduced. During the turning process lathe tool dynamometer shown in Figure 5 and Lathe Tool Force Indicator as shown in Figure 6, is used to measure the axial or feed force (F_X), radial or thrust force (F_Y) and cutting or tangential force (F_Z) recorded values is noted. In the following table the experimental result of turning aluminum work piece with various cutting speed t in dry environment is shown in Table 1.

Table 1. Experimental result for turning of aluminum with different cutting speed

| Sr. No | Speed, N (rpm) | Diameter of work piece, D (mm) | Depth of cut (mm) | Feed (mm/rev) | Cutting speed \( V_c = \frac{\pi D N}{60000} \) (mm/Sec) | Machining Time (Sec) | Force(N) |
|--------|----------------|-------------------------------|-------------------|--------------|-----------------------------------------------|---------------------|----------|
|        |                |                               |                   |              |                                               |                     | Feed Force, F_X, (N) | Cutting/Tangential Force, F_Z, (N) | Resultant Force, F_R, (N) |
| 1      | 260            | 25                            | 0.5               | 0.83         | 0.34                                          | 20                  | 19.62    | 58.86   | 62.04    |
| 2      | 400            | 24.5                          | 0.5               | 0.83         | 0.51                                          | 13                  | 29.43    | 127.53  | 130.88   |
| 3      | 610            | 24                            | 0.5               | 0.83         | 0.76                                          | 8                   | 39.24    | 137.34  | 142.83   |
| 4      | 905            | 23.5                          | 0.5               | 0.83         | 1.11                                          | 5                   | 49.05    | 156.96  | 164.44   |
5. FINITE ELEMENT ANALYSIS PROCEDURE AND SIMULATIONS

Static and dynamic analysis of all the configurations was carried out for obtaining the Stress and deformation of the structure. The finite element analysis was carried out by using the analysis software Abaqus. The solution procedure is described in the flow chart in Figure 7. The three dimensional (3D) model of the Lathe Tool Dynamometer Single Point Cutting Tool (HSS) was done using Abaqus/CAE software. The meshed fig is shown in Figure 8.
The 3D tool is meshed with tetrahedron quadratic (2\textsuperscript{nd} order) element. Cutting edge area meshed with finer mesh element and tool holding area meshed with coarser mesh element. To avoid huge analysis solving time above meshing concepts have been adopted. The terminology C3D10M means Continuum 3 dimensional 10 node Modified formulation. Modified formulation method gives the good contact pressure in the parts.

Quadratic (2\textsuperscript{nd} order) tetrahedron element used because, if we select linear element it makes the model more stiffness and it won’t give exact result. By selecting quadratic element we can achieve good results. Highlighted red color region fixed in X, Y and Z translations directions as shown in Figure 8. As component is modeled in solid element rotational degrees of freedom are ignored. The loading conditions are taken from Table 1 as obtained from the experimental set up. The mechanical properties considered for the tool made of HSS and TC is shown Table 2 and Table 3.

For the static and dynamic analysis different loading conditions are considered and these are explained in detailed way in the static and dynamic analysis.

![Figure 7. FEA Methodology flow chart](image_url)

![Figure 8. Meshed tool with boundary Conditions Details](image_url)
Table 2. Mechanical Properties of High Speed Steel (HSS)

| Properties | Density   | Elastic Modulus | Poisson’s Ratio | Yield Stress | Ultimate Stress |
|------------|-----------|-----------------|-----------------|--------------|-----------------|
| Values     | 7.87e-9 Tonn/mm³ | 240GPa          | 0.30            | 280MPa       | 450MPa          |

Table 3. Mechanical Properties of Tungsten Carbide (TC)

| Properties | Density   | Elastic Modulus | Poisson’s Ratio | Yield Stress | Ultimate Stress |
|------------|-----------|-----------------|-----------------|--------------|-----------------|
| Values     | 1.58e-8 Tonn/mm³ | 640GPa          | 0.22            | 335MPa       | 530MPa          |

5.1 STATIC ANALYSIS:
Static analysis is used to determine displacements, stresses, etc. under static loading conditions, both linear and nonlinear static analyses. Nonlinearities can include material non-linearity, geometry non-linearity and boundary non-linearity. The material non-linearity details of both HSS and TC are shown in Figure 9 and Figure 10. Geometric non-linearity means large deflection and large strain observed in the analysis. In Abaqus Standard Solver, if Nlgeom = off means geometric non-linearity not considered in analysis and if Nlgeom = On means geometric non-linearity considered in analysis. Material Plasticity Card Details of High Speed Steel (HSS) Tool and TC tool are shown in Table 4 and Table 5. Boundary non-linearity means considering the contact surfaces in analysis. Resultant forces are applied to single point cutting tool edge through the rigid body element. The following four cases are considered for static force analysis.

Case 1: For the 260 rpm cutting speed, 62 N resultant force applied.
Case 2: For the 400 rpm cutting speed, 131 N resultant force applied.
Case 3: For the 610 rpm cutting speed, 143 N resultant force applied.
Case 4: For the 905 rpm cutting speed, 165 N resultant force applied.

For the Case 1, For the 260 rpm cutting speed, 62 N resultant force result plots for High Speed Steel (HSS) material Single Point Cutting Tool. Similarly, For the Case 1, for the 260 rpm cutting speed, 62 N resultant force result plots for TC material Single Point Cutting Tool. Similar analysis is conducted for the remaining cases. The static analysis of HSS and TC Tool is shown Figure 11 and Figure 12 for Case 1.

Figure 9. Material Non-Linearity Details of High Speed Steel (HSS) Tool
Figure 10. Material Non-Linearity Details of Tungsten Carbide (TC) Tool
Table 4. Material Plasticity Card Details of High Speed Steel (HSS) Tool

| Data | Yield Stress | Plastic Strain |
|------|--------------|----------------|
| 1    | 249          | 0              |
| 2    | 251          | 0.002          |
| 3    | 554          | 0.275          |

Table 5. Material Plasticity Card Details of TC Tool

| Data | Yield Stress | Plastic Strain |
|------|--------------|----------------|
| 1    | 333          | 0              |
| 2    | 336          | 0.002          |
| 3    | 636          | 0.1813         |

Figure 11. Static Analysis Load Case-1 Deformation Plot for HSS Tool

Figure 12. Static Analysis Load Case-1 Deformation Plot for TC Tool

Figure 13. Static Analysis Load Case-1 Stress Plot for HSS Tool

Figure 14. Static Analysis Load Case-1 Stress Plot for HC tool
A sample stress plots for static loads is shown in Figures 13 and Figure 14 for HSS and TC tool respectively for case 1 conditions. Similarly, the stresses were plotted for the other cases. The Table 6 shows the static analysis results condition for the different load cases. A plot of the stresses versus cutting speeds is shown in Figure 15.

Table 6. Static Analysis Results Comparison Table

| Load Case | Cutting Speed, N (rpm) | Resultant Force, F_k(N) | Deformation, (mm) | Stress, (MPa) | FOS |
|-----------|-----------------------|-------------------------|-------------------|--------------|-----|
|           |                       |                         | HSS               | TC           |     |
| 1         | 260                   | 61                      | 0.078             | 0.063        |     |
|           |                       |                         | 252.2             | 450          |     |
| 2         | 400                   | 131                     | 0.103             | 0.076        |     |
|           |                       |                         | 292               | 450          |     |
| 3         | 610                   | 143                     | 0.125             | 0.077        |     |
|           |                       |                         | 316.3             | 450          |     |
| 4         | 905                   | 165                     | 0.159             | 0.08         |     |
|           |                       |                         | 373.1             | 450          |     |
|           |                       |                         | 288.72            | 530          | 1.78|
|           |                       |                         |                    |              | 3.31|
|           |                       |                         |                    |              | 1.54|
|           |                       |                         |                    |              | 2.50|
|           |                       |                         |                    |              | 1.42|
|           |                       |                         |                    |              | 2.37|
|           |                       |                         |                    |              | 1.20|
|           |                       |                         |                    |              | 1.83|

Figure 15. Static Analysis Result Comparison Graph

5.2 DYNAMIC ANALYSIS:
For case 1 at 260 rpm cutting speed, 62 N resultant force result plots for High Speed Steel (HSS) material Single Point Cutting Tool. The deformation and stress plots for HSS tool is shown in Figure 16 and Figure 17 respectively. For case 1, at 260 rpm cutting speed, 62 N resultant force result plots for TC material Single Point Cutting Tool. The deformation and stress plots for TC tool is shown in Figure 18 and Figure 19 respectively. Similar analysis is conducted for the remaining cases.
Figure 16. Dynamics Analysis Load Case-1 Deformation Plot for HSS Tool

Figure 17. Dynamics Analysis Load Case-1 Stress Plot for HSS Tool

Figure 18. Dynamics Analysis Load Case-1 Deformation Plot for TC Tool

Figure 19. Dynamics Analysis Load Case-1 Stress Plot for TC Tool

The Table 7 shows the dynamic analysis results condition for the different load cases. A plot of the stresses versus cutting speeds is shown in Figure 20.

Table 7. Dynamic Analysis Results Comparison Table

| Load Cases | Cutting Speed, N (rpm) | Resultant Force, FR(N) | Deformation, mm | Stress, MPa | FOS |
|------------|------------------------|------------------------|-----------------|-------------|-----|
|            | HSS                    | TC                     |                 | HSS         | TC  | HSS | TC  |
| 1          | 260                    | 61                     | 0.0018          | 19.00       | 450 | 530 | 23.68 |
| 2          | 400                    | 131                    | 0.0037          | 40.15       | 450 | 530 | 11.20 |
| 3          | 610                    | 143                    | 0.0041          | 43.83       | 450 | 530 | 10.20 |
| 4          | 905                    | 165                    | 0.0047          | 50.57       | 450 | 530 | 8.89  |

The Table 7 shows the dynamic analysis results condition for the different load cases. A plot of the stresses versus cutting speeds is shown in Figure 20.
5.3 MODAL ANALYSIS:
Natural frequencies and mode shapes of the Lathe Tool Dynamometer Single Point Cutting Tool was conducted. For the HSS tool, Mode-1 having the natural frequency of 23262 Hz and tool is subjected to Y-axis bending shown in Figure 21. For the TC tool Mode-1 having the natural frequency of 28526 Hz and tool is subjected to Y-axis bending shown in Figure 22. Mode shapes and deformation scale factor set to value 10 for the better visualization. Similarly, the different modes were simulated X-axis bending, Z-axis bending, Z-axis torsion, X-axis torsion, Y-axis torsion for both HSS and TC tool. Natural frequencies of the Single Point Cutting High Speed Steel (HSS) and Tungsten Carbide (TC) tool.

The natural frequencies of both the HSS and TC tools are determined using the simulations. The modal analysis is shown in Table 8 and the plot of natural frequencies versus the mode numbers are shown in Figure 23.

| Mode Number | Natural Frequency, (Hz) | As Tungsten Carbide tool improved Natural Frequency, (Hz) |
|-------------|-------------------------|--------------------------------------------------|
| HSS tool    | TC tool                 |
| 1           | 23262                   | 28526 |
| 2           | 25787                   | 319193 |
| 3           | 35420                   | 45313 |
| 4           | 55842                   | 65140 |
| 5           | 61729                   | 77581 |
| 6           | 64281                   | 80756 |

Figure 21. Mode-1 shape of the HSS tool

Figure 22. Mode-1 shape of the TC tool
6. RESULTS & DISCUSSIONS

It is observed that in static analysis, for the cutting speed of 260 rpm and resultant force of 61 N the high speed steel tool has stress of 252.20 MPa and FOS of 1.78. Whereas tungsten carbide tool has stress of 159.75 MPa and FOS of 3.31. Considering these parameters tungsten carbide tool is stiffer and durable than high speed steel tool. Similar results can be observed for the increasing cutting speeds. It is observed that in dynamic analysis, for the cutting speed of 260 rpm and resultant force of 61 N the high speed steel tool has stress of 19 MPa and FOS of 23.68, whereas tungsten carbide tool has stress of 10.15 MPa and FOS of 52.21. Considering these parameters tungsten carbide tool is stiffer and durable than high speed steel tool. Similar results can be observed for the increasing cutting speeds. As observed in the modal analysis, the natural frequencies of the TC tool are higher than that of HSS tool for the different modes simulated.

By considering these parameters, it has been concluded that the tungsten carbide (TC) single point cutting tool is stiffer and durable, when tool is subjected to high cutting speed rather than high speed steel (HSS) tool.

7. CONCLUSIONS AND SCOPE FOR FUTURE:

Based on the investigations carried out in static analysis, modal analysis and steady state dynamic analysis tungsten carbide (TC) single point cutting tool withstand more strength during high cutting or machining speed rather than high speed steel (HSS) single point cutting tool. Hence the Tungsten Carbide (TC) single point cutting tool performs better as compared to High Speed Steel (HSS) single point cutting tool.

The further research can be carried out by random vibration or Power Spectral Density (PSD) in single point cutting tool. Accelerometer is required for the random vibration, this accelerometer need be fixing in different location of lathe tool dynamometer single point cutting tool and measure the vibration on it. Depending on different cutting or machining speed for the turning process, in random vibration analysis gives predict the exact life of the tool.
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