Analysis of Cutting Parameters of AISI 52100 with TiAlN Nano Coated Carbide Cutting Tool by CNC Turning

Mr. Tanpure Sandesh Popat[1]*, Dr. Sunil K. Somani[2], Dr. H. S. Patil[3]

ABSTRACT:

Turning was performed under dry conditions in this work to increase the surface finish or roughness of coated Tungsten Carbide tool. Titanium aluminium nitride (TiAlN) nano coating was added to tungsten carbide tools using the Physical Vapour Deposition (PVD) procedure. Turning necessitates careful consideration of the machining parameters of cutting speed, depth of cut, and feed rate, all of which have a significant impact on the Response variable. The trials are organized using a Taguchi orthogonal array, and any necessary machining is performed. Response variable demonstrates a growing tendency in terms of feed rate, and when cutting speed increases, chatter and vibrations cause the response variable value to slightly increase. By carrying out the subsequent experiments, the sufficiency of the response variable is examined. The cutting force is shown to be strongly influenced by the cutting speed (RPM) and depth of cut (mm) following completion of the DOE analysis for the parameters at levels 2 and 3. The results showed that TiAlN coating provided relatively better performance in terms of tool wear, cutting force, and surface integrity when the coating thickness was 20 micrometres. A good machining coating, their increased hardness and oxidation stability combine to create them. The TiAlN coating showed increased tool life.

KEYWORDS: Physical Vapour Deposition (PVD), DOE, CNC Turning, Titanium Aluminium Nitride (TiAlN), Finite Element Analysis

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1. INTRODUCTION

The machining process of turning is flexible and practical. Due to its capacity to produce complicated geometric surfaces with respectable precision and surface smoothness, it is the most crucial operation and is utilised extensively in the majority of industrial sectors [1]. To successfully respond to intense competition and the rising demand for high-quality products on the market in the current production environment, metal cutting optimization techniques are essential [2]. A high-verity single point cutting tool is safely held in a tool post during a turning operation and passed steadily through a rotating work piece in a direction parallel to the work piece's axis of rotation to remove unwanted material in the form of chips and produce a cylindrical profile [6]. Selecting the cutting settings that would produce optimal cutting performance is a vital phase in a turning process [3]. In a turning operation, the resolution of three cutting parameters—feed rate, cutting speed, and depth of cut—is necessary [4]. The most important factor in the machining process is surface roughness since it is thought to be the foundation of product quality. It assesses the surfaces' subtle deficiencies [5]. Three cutting force components are produced when a turn is made: a thrust force that acts in the direction of the cutting speed, a feed force that acts in the direction of the feed rate, and a radial force that acts in the radial direction and is normal to the cutting speed [7]. In the metalworking

***Corresponding Author:** Mr. Tanpure Sandesh Popat
Address: [1]*Research Scholar, Mechanical Engineering Department, Oriental University, Indore
[2]Vice-Chancellor, Mechanical Engineering Department, Oriental University, Indore
[3]Professor and Faculty, Mechanical Engg, Depart. GIDC Degree Engineering College, Abrama, Navasari University.
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sector, coated and uncoated tools are often utilised and offer the best solution for the majority of turning operations [8]. Improved completed products boost industrial productivity and profitability. Corrosion resistance, fatigue strength, and creep failure are all unquestionably enhanced by a better machined surface [10]. PVD and CVD are the two most widely utilised coating techniques, and they may be employed for both single-layer and multi-layer coatings [12]. The input factors that directly impact the cutting tool's performance are speed, feed, and depth of cut [17]. Factors include tool life and wear, surface polish, cutting pressures, material removal rate, power consumption, and cutting temperature affect productivity, product quality, overall economy of manufacturing via machining, and machining quality [23].

1.1 Hard Turning

The process of turning is one of material removal, in which the rotating pieces are made by removing extra material from the outer diameter. Additionally, turning may be used to make cylindrical out of square workpieces, lower the diameter of cylindrical workpieces, and create a smooth machined surface on the workpiece. On a lathe, the turning procedure is performed as follows:

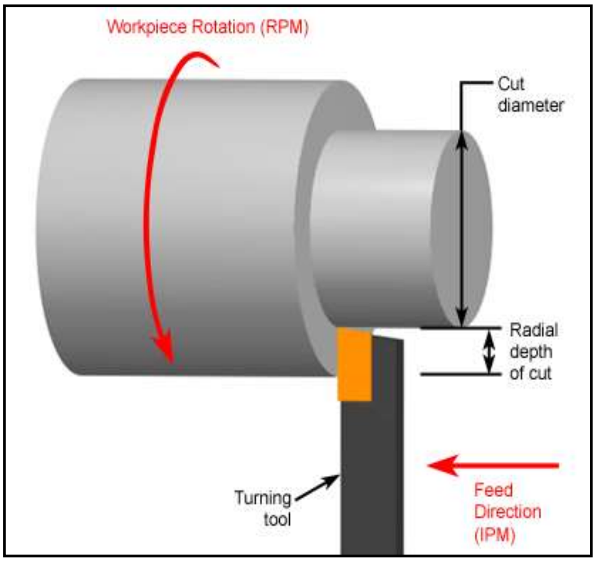

Fig: Turning Opeartion

1.1.1 Tapered turning

A cylindrical form with a steadily shrinking diameter from one end to the other results from tapered turning. This is achievable:

a. The compound slide,
b. The taper turning attachment,
c. A hydraulic copy attachment, respectively
d. Using a form tool;
e. Utilising a C.N.C. lathe;
f. By offsetting the tailstock; this technique works better with shallow tapers.

1.1.2 Spherical generation

By rotating a shape around a predetermined axis of rotation, spherical generation creates a spherical final surface. methods comprise

a. Using a form tool,
b. A hydraulic copy attachment or a C.N.C. (computerised numerically controlled) lathe (a rough and ready method)
c. Making use of a bed jig (need drawing to explain).

1.1.3 Hard turning

A sort of turning known as "hard turning" is performed on materials having a Rockwell C hardness of at least 45. It is usually carried after following heat treatment of the workpiece. The method aims to reduce or eliminate the need for conventional grinding processes. Rough grinding and hard turning are competitive when used just for stock removal. However, grinding is best when used for finishing where shape and dimension are important. Higher roundness and cylindricity dimensional precision is produced by grinding. Additionally, Rz = 0.3–0.8z polished surface finishes cannot be achieved by hard turning alone. Items requiring a surface roughness of Rz 0.8–7.0 micrometres and/or a roundness accuracy of 0.5–12 micrometres are best suited for hard turning. It is used for gears, injection pump components, and hydraulic components, among other things.

1.2. Theory of metal cutting

Nearly all of the products used in modern society are made either directly or indirectly using the metal cutting process, which is the foundation of the engineering sector. In order to maximise the effectiveness of any metal cutting process, the cutting tool is one of the crucial components. The pressures of economic competitiveness have driven extensive research in the area of metal cutting over the years, which has resulted in the development of novel

tool materials with amazing performance and enormous potential for a striking improvement in productivity. Manufacturers are constantly looking for and using new materials to build products that are lighter, stronger, and therefore more effective, so cutting tools must be developed to process new materials at the highest potential productivity.
Any cutting material must primarily exhibit the following qualities in order to function:
1. Difficulty in overcoming wearing action
2. Hot power to combat the heat present
3. Having enough tenacity to tolerate vibration

Materials in the greater hardness segment of the list will break if used for heavy cuts, especially with work components that have interruption-causing holes or grooves, because increasing hardness often leads in a loss in toughness.

The following qualities must be present in a tool material:

- The capacity to maintain form stability at high temperatures and rapid cutting rates.
- Low cost and simple manufacture;
- High resistance to brittle fracture;
- Resistance to heat and mechanical shock

The materials used to make the cutting tools must be able to bear
- Strong stresses (High strength and wear resistant)
- A hot climate (high hot hardness)
- The shock that is produced as a chip forms (tough)

1.3. Evolution of cutting instruments across time

Cutting tools have advanced to a beautiful degree to keep up with the present advancement of science and technology. The following is a timeline of the materials used to make cutting tools
1. Fast-moving steel
2. Carbonates
3. Tiles
4. UCON
5. Coated Carbides
6. Cubic Boron Nitride (CBN)
7. Diamond
Out of all the materials listed above, coated carbides are the next-generation material that best satisfies the needs of the moment and are the subject of the bulk of study. Between 60 and 80 percent of demands are met by carbides, which have dominated the market for machining, especially of ferrous materials.

1.4 Coatings

1.4.1 Cutting tools – Which is the right coating?

Nowadays, coatings are present on around 95% of the cutting edges of carbide tools. Ultra-smooth surfaces reduce the likelihood for weld build up and the production of built-up edges, and higher elevated-temperature hardness due to the layer's insulating characteristics increases tool wear resistance. As a result, far longer tool lifetimes should be attained.

In essence, two techniques are employed for coating:

1. PVD coating (Physical Vapour Deposition)

Contrary to CVD procedures, PVD processes are only reliant on physical response techniques. It is a material vapour in this instance that condenses on the substrate's surface [27]. To ensure that the vapour particles reach the components and are not lost due to the dispersion of gas molecules, the operation is conducted in a vacuum [23, 25]. Since the PVD manufacturing process occurs at lower temperatures, between 400 and 600 degrees Celsius, the base material's properties are affected less than with the CVD technique. Therefore, particular, fine-grained carbides' degree of hardness is mostly maintained [24].

Evaporation, sputtering, cathodic arc deposition, and ion plating are the four coating types distinguished by PVD coating. Most often, sputtering is employed. Almost all metals, including carbon, may be refined to their purest state thanks to the many PVD versions. Reactive gases like oxygen, nitrogen, or hydrocarbons can be added to the process to refine oxydes, nitrides, and carbonides as well [28].

- PVD properties

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- Any coating materials;
- High purity of coatings;
- Low thermal substrate impact - toughness is kept;
- Exceptional adhesive strength (even across further intermediate layers),
- low layer thickness tolerance, and relatively thin layer thicknesses

- PVD applications

Due to their durable but accurate cutting edges, PVD-coated grades are suggested for sticky materials. The application ranges cover all solid carbide milling cutters, drills, and the majority of milling, thread-cutting, and grooving grades. Additionally, grades with PVD coating are frequently used for finishing tasks and as drilling centre cutting grades [30–32].

2. CVD coating (Chemical Vapour Deposition).

Through different chemical processes, the CVD procedure deposits thin layers on the cutting instruments. Ever since they were introduced in the late 1960s, CVD coated cemented carbides have had tremendous success. Since then, multi-layer variants of chemical vapour deposition methods integrating TiN, TiCN, TiC, and Al2O3 have improved from single-layer versions. Modern CVD coatings combine high temperature and medium temperature procedures in complex cycles to produce good wear-resistant coatings with a total thickness of 4–20 m [33]. However, chemical elements permeate from the carbide substrate to the coating during development due to the high deposition temperature (950–1059°C) encountered during CVD. The main outcome is that the coated edge becomes embrittled. Additionally, the chemistry of the CVD process results in more rapid growth along the cutting edge, producing a uniform coating thickness. It was therefore highly advised to look for coatings that could be applied at lower temperatures in order to cover tools with sharper edges without having any embrittlement consequences. PVD, which enables deposition temperature to be maintained at around 500°C, is the solution [34–36].

1.4.2 TiAlN: titanium aluminium nitride coating

- Titanium, aluminium, and nitrogen chemical compound
- All-purpose coating
- Depending on the application, up to 10 times longer tool life
- High degree of elevated-temperature hardness and oxidation resistance
- High cutting speed
- Nanohardness: 35 gigapascal or more (GPa)
- Application: Steel (N/mm2) 1.100, stainless steel, titanium alloys, cast iron, aluminium, brass, bronze, and plastic.
- Layer thickness: 1-4 m.
- Friction coefficient: 0.5.
- Application temperature: 800 °C.
- Cooling is not necessary

1.5 Optimization Techniques

The art and science of effectively allocating limited resources is known as optimization [4].

1.5.1 Response Surface Methodology (RSM)

The Response Surface Method (RSM), a collection of mathematical and statistical techniques, aims to optimise (minimise or maximise, depending on the circumstance) the response in problem-solving and problem-modelling situations where an important output response is affected by a large number of relevant input variables. [6].

1.5.2 Taguchi's Approach

Parametric design by Taguchi is a useful method for creating strong designs. It provides an affordable qualitative optimum design that is straightforward and methodical. The biggest benefit of this strategy is that it reduces experimental costs and time by identifying the key variables [16].

1.6 Objective of Experimental:

1. To calculate the cutting force based on below control factors:
   a. Cutting Speed (RPM)
   b. Feed Rate (mm/min)
   c. Depth of Cut (mm).
2. Study the impact of coating thickness of cutting force
   a. Coating thickness.
3. Study the impact of control factor on cutting force.

4. Proposed worst case combination to study the impact of coating in FEA.

2. LITERATURE SURVEY

Following this review of the literature, it is evident that several studies have already been conducted using CNC turning machines. Table 1 indicates the varied work that has been done on this issue by various researchers as well as the methodologies utilised for analysis of research work.

Table 1: The Summary of Literature Survey

Objectives	DOE	Used Cutting Tool	Used Dominant Parameter
To maximize the surface roughness [1,2,3,4,5,6,7,8,9,10, 11,12,13,14]	Taguchi/ RSM/ ANN	Multilayered coated and uncoated carbide tool	Cutting speed, Feed rate, Depth of cut
To increase the MRR [15,16,17,18,19,20,21,22]	Taguchi/ RSM	HSS, cobalt, plain carbide, multilayered coated tool	Feed rate, Depth of cut
To minimize the tool wear [23,24,25,26,27,28,29]	Taguchi/ RSM	PVD and CVD coated tool	Cutting speed
To increase the cutting forces [30,31,32,33,34,35,36]	Taguchi/ RSM/Regression analysis	PVD coated, CVD coated tool, uncoated CBN tool	Depth of cut, Feed rate
To minimize the cutting temperature [37,38]	Taguchi/ ANN	Multilayered coated and uncoated	Cutting speed, Feed rate
To minimize the energy consumption [39,40,41,42,43]	Taguchi/ RSM	Ceramic coated tool, uncoated tool	Feed rate, Depth of cut

3. MATERIAL AND TOOL USED

3.1 Material of Work piece

Work piece is made of AISI 52100 steel, and the mechanical qualities (%) and chemical composition are listed below.

Table 2: Chemical composition of Workpiece material

C (Carbon)	Si (Silicon)	Mn (Manganese	P (Phosphorus)	S (Sulfur)	Cr (Chromium)	Mo (Molybdenum)	Ni (Nickel)	Fe (Ferrum)
0.4	0.25	0.7	0.035	0.04	0.8	0.25	1.85	95.675

Table 3: Mechanical Properties of Workpiece

E [Gpa]	Y [Mpa]	H [Gpa]	µ
205	710	0.96	0.29

3.2 Material of Cutting Tool

For the experiment, tungsten carbide with a 5 µm TiAlN covering is taken into consideration. The typical pressing and sintering procedure was used to create the substrate specimens from a Tungsten carbide (WC) powder (93.81%) with Cobalt (Co) binder (6%), and Chromium carbide (Cr_3C_2) additive (0.19%).
After that, a cathodic arc deposition in PVD coating of titanium aluminium nitride (TiAlN) was applied at a temperature of around 5000 C. The same coating parameters were utilised for the whole batch of test tool sample pieces that required to be coated. The variety of coating thicknesses was created by placing the samples on several racks with variable spacing and at varied locations inside the coating chamber.
The mechanical properties of the substrate and coating materials are shown in Table 4 below.

Table 4: The mechanical properties of the substrate and coating materials

Parameters	E [GPa]	Y [GPa]	H [GPa]	μ
Substrate	566	5.817	17.05	0.2
Coating	550	10	29.4	0.3

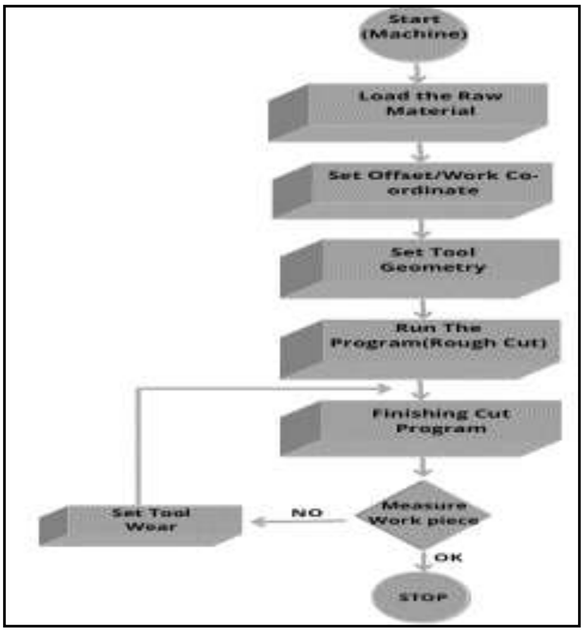
4. METHODOLOGY

Flow chart Explanation step by step:

Steps of Flow chart	Explanation
Start	Start the Machine
Load the raw material	Load the raw material on machine/Hold by chuck.
Set offset/work co-ordinate	Touch the tip of tool (Master tool) on face of the work piece and set the Z value zero. Again touch the tip of the tool on OD of work piece and set X value as OD value.(G54 X_Z_.)
Set tool Geometry	Same like master tool set offset for all other tools. For details of Tool geometry read-Basic of CNC programming.
Run the program	After Offset setting run the program for rough cut with high feed.
Finishing cut program	After rough cut measure the job and give the finishing cut.
Measure Workpiece	After finishing cut measure the workpiece. If the material not removed completely then we have to set Tool wear.
Tool wear	Set tool wear if material not removed completely. After set the tool wear again run finishing cut program.
Stop	Again measure the job and remove from chuck

The most frequent kind of operation on a lathe machine is turning. The task was held between a chuck or the centre while spinning at the desired speed. The tool moves longitudinally to give the feed toward the headstock with the necessary depth of cut. The surface has excellent finishing.

Figure 1: CNC machining process flow chart



5. PERFORMANCE ANALYSIS

5.1 Design of Experiment:

A subset of applied statistics known as "design of experiments" (DOE) focuses on the organising, carrying out, analysing, and interpreting of controlled experiments to identify the factors influencing the value of a parameter or group of parameters. A systematic strategy for determining the relationship between a process's inputs and outcomes is called design of experiments (DOE). In other words, it is used to determine relationships between causes and effects. To control process inputs and maximize output, this information is required.

How to perform a DOE:

1. Specify the DOE's purpose
2. Pick the process parameters (independent and dependent)
3. Choose the DOE design, which relies on your available resources (time, money, and tolerance for Type I and II mistake).
4. Carry out the plan (randomization where possible)
5. Examine outcomes (replicate the tests if practical to help verify results)
6. Explain the findings

5.2 DOE for current study as formulated below:

Level: 2, Factors: 3 & Total Cases with full factorial: 8

The experiment was run with the aforementioned combination, and the results are shown below Table 5 and 6.

Table 5: DOE Setup with 2 level and 3 Factors

Run Order	Input Parameters		
	Cutting Speed (RPM)	Feed Rate (mm/min)	Depth of Cut (mm)
1	1400	200	2
2	1800	100	2
3	1400	100	1
4	1800	200	2
5	1800	100	1
6	1800	200	1
7	1400	200	1
8	1400	100	2

Table 6: Experimental results based on DOE Combinations

Output Parameter			
Cutting Force (N), Fc	Cutting Force (N), Fr	Cutting Force (N), Ff	Resultant Cutting Force (N),F
293	95	154	344
879	227	280	950
160	82	72	194
965	304	352	1071
489	158	116	527
540	207	145	596
171	103	74	213
290	106	152	344

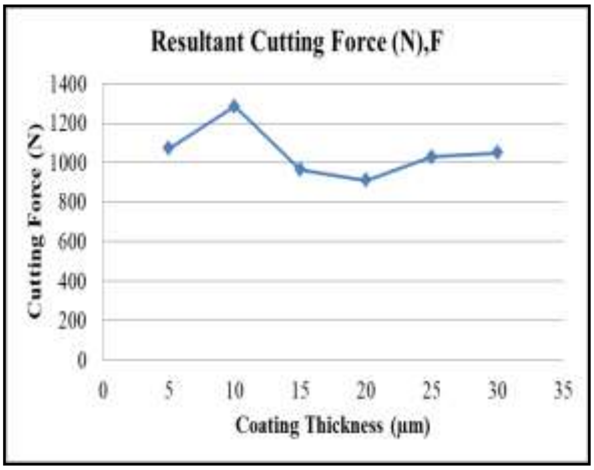
The worst case scenario was taken into consideration while examining the effect of coating on cutting force, with the following findings.

Table 7: impact of coating on cutting force

Trail No.	Coating thickness (μm)	Resultant Cutting Force (N),F
1	5	1071
2	10	1285
3	15	964
4	20	910
5	25	1028
6	30	1049

Table 8: Cutting force vs. Coating thickness results

Trail No.	Cutting Force (N), Fc	Cutting Force (N), Fr	Cutting Force (N), Ff
1	965	304	352
2	1157	365	422
3	868	274	317
4	820	258	299
5	926	292	338
6	945	298	345



Graph 1: Cutting Force vs. Coating thickness

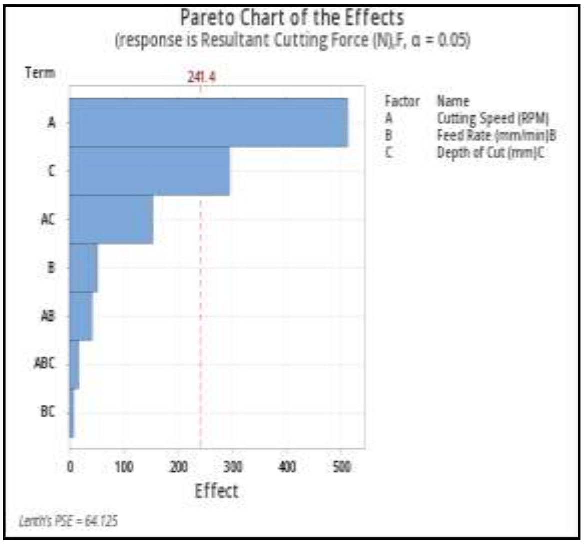
The results force can be considered further to assess the life of tool using finite element analysis (FEA).

6. WORK RESULTS OF DOE ANALYSIS AND DISCUSSION

6.1 Pareto Chart

A graph 2 that displays the frequency of defects and their overall impact is called a Pareto Chart. To find the issues that need to be corrected first in order to get the largest overall improvement, Pareto charts can be employed.

Vilfredo Pareto and his "80/20 rule" are the inspiration behind the naming of the Pareto chart. In other words, 20% of the population may hold 80% of the wealth, 20% of a product line may produce 80% of the trash, or 20% of consumers may be responsible for 80% of the complaints.

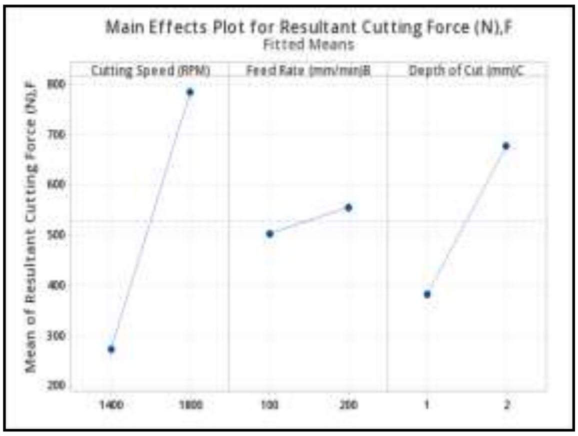


Graph 2: Pareto Chart Plot

Above graph 2 shows the cutting speed (A), depth of cut (C) and its combination (AC) shows in above Graph 2 has highest impact on cutting force.

6.2 Main Effect Plot

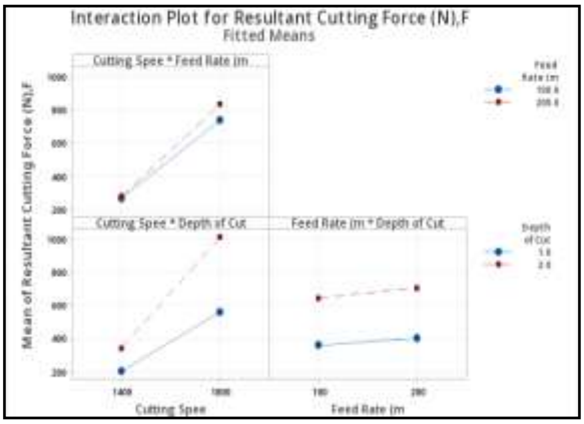
Using a main effects analysis, one may examine differences between level means for one or more factors. Graph 3. There is a big influence when a factor's varying levels have noticeable effects on the reaction. In a main effects plot, the response mean for each level of the factor is graphed and connected by a line. Since the line is not horizontal, it appears that both the depth of the cut (C) and cutting speed (A) have an effect on the cutting force. Cutting speed has a greater impact on cutting force than cut depth (C). The reference line shows the overall average.



Graph 3: Main Effect Plot for Resultant Cutting Force

6.3 Interaction Plot

For each of the three control parameters, the interaction plot displays the mean strength versus sintering time. On the interaction Graph 3, the nonparallel lines denote the effects of the interaction between cutting speed and depth of cut. This interaction effect shows that cutting power has a bearing on the link between cutting speed and depth of cut.



Graph 4: Interaction Plot for Resultant Cutting Force

7. RESEARCH CONCLUSION

1. An experiment to determine the effects of the following factors has been successfully performed.
a. Cutting Speed (RPM)
b. Feed Rate (mm/min)
c. Depth of Cut (mm).
2. After completing the DOE analysis for the parameters at level 2 and level 3, it is found that the cutting force is greatly impacted by the cutting speed (RPM) and depth of cut (mm).
3. For the worst case scenario of cutting speed: 1800RPM, DOC: 2mm, and Feed rate: 200 mm/min, a maximum resulting cutting force of 1071N is recorded, and this may be utilised in FEA to evaluate the life of tools with various coatings and their thickness.
4. The cutting force of a tool coated with Titanium Aluminium Nitride (TiAlN) on a tungsten carbide was calculated. Results show that the cutting force is lowest when the coating thickness is 20 micrometres.

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