Experimental and Finite Element Simulation in Turning Inconel 625 with CNMG Carbide Insert

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Abstract

Nickel based super alloys have found widespread applications in aerospace, nuclear, chemical and petrochemical industries due to their excellent thermo mechanical properties. However, they pose serious challenges to the manufacturing sector due to their difficult to cut nature causing metallurgical damages to the work piece due to the very high cutting forces which leads to work hardening, surface tearing and distortion in final machined components. INCONEL Alloy 625 is a nickel-based super alloy that possesses high strength properties and resistance to elevated temperatures. The present work is focused on investigating the effect of process parameters on machinability performance characteristics and there by optimization of the turning INCONEL Alloy 625 of based on Taguchi-based Grey relational method. The cutting speed, feed and depth of cut were used as the process parameters whereas the cutting force, surface roughness was selected as performance characteristics. DEFORM 3D has been used to simulate the machining of INCONEL 625 to predict the cutting forces. The experimental and simulation results are compared.
Keywords: INCONEL 625 Machining, Taguchi Method, L9 Orthogonal Array, Analysis of Variance (ANOVA), Deform 3D

I. INTRODUCTION

Quality of a product can be described by various quality attributes. The attributes may be quantitative or qualitative. In on-line quality control controller and related equipments are provided with the job under operation and continuously the quality is being monitored. In off-line quality control the method is either to check the quality of few products from a batch or lot (acceptance sampling) or to evaluate the best process environment capable of producing desired quality product. This invites optimization problem which seeks identification of the best process condition or parametric combination for the said manufacturing process. In order to tackle a multi-objective optimization problem, the present study applied used Taguchi method through turning of INCONEL 625 bar using carbide tool. The study aimed at evaluating the best process environment which could simultaneously satisfy requirements of both quality and as well as productivity. Turning modeling procedures in DEFROM-3D software enable to study the process response for any change in process conditions. The effect of process parameters i.e. cutting speed, feed rate and depth of cut on the process response i.e. cutting forces, temperatures or stress etc can be study by it.

A. *Grey Taguchi Method*

The technique of laying out the conditions of experiments involving multiple factors was first proposed by the Englishman, Sir R.A.Fisher. The method is popularly known as the factorial design of experiments. A full factorial design will identify all possible combinations for a given set of factors. The most influential factors for individual quality targets of the turning process were identified by analyzing the Grey relational grade matrix. Furthermore, analysis of variance (ANOVA) was also carried out to examine the most significant factors for the cutting forces Fx, Fy, Fz, and roughness Ra in the turning process. Grey relational analysis is an impacting measurement method in Grey system theory that analyses uncertain relations between one main factor and all other factors in a given system. The use of Taguchi method with Grey relational analysis to optimize the turning operations with multiple performance characteristics includes the following steps:

- Identify the performance characteristics and cutting parameters to be evaluated.
- Determine the number of levels for the process parameters
- Conduct the experiments based on the selection of orthogonal array
- Normalize the experimental results, i.e., measured features of the performance characteristics, ranging from zero to one, which is also known as Grey relational generation.
- Select the appropriate orthogonal array.

- Grey relation coefficient is calculated based on normalized-experimental data.
- Determine the Grey relation grade by averaging the Grey relation coefficient corresponding to selected responses
- Analyze the experimental results using the Grey relation grade and statistical ANOVA
- Select the optimal level of cutting parameters for maximizing the overall Grey relational grade
- Verify the optimal cutting parameters through the confirmation test.

In Grey relational generation, the normalized force (F) and surface roughness (Ra) corresponding to the smaller-the-better (SB) criterion which can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

Alternatively, the original sequence can be simply normalized by the most basic methodology. i.e., the value of original sequence is divided by the first value of sequence

$$x_i(k) = \frac{y_i(k)}{y_i(1)}$$

Where yi(k) is the original sequence, xi(k) is the sequence after data preprocessing, min yi(k) is the smallest value of yi(k) and for the kth response, and max yi(k) is the largest value of yi(k) for the kth response [11]. An ideal sequence is x0(k) (k = 1, 2,…, m) for the responses. The definition of the Grey relational grade in the course of the Grey relational analysis is to reveal the degree of relation between the 9 sequences [x0(k) and xi(k), k = 1, 2, …, m and i = 1, 2, …, 9]. The Grey relational coefficient ξi(k) can be calculated as:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}}$$

After averaging the Grey relational coefficients, the Grey relational grade γi can be computed as:

Where 'n' = number of responses. The higher value of the Grey relational grade represents the stronger relational degree between the reference sequence x0(k) and the given sequence xi(k),which means that the corresponding parameter combination is closer to the optimal.

B. *Finite Element Simulation*

FEM simulation is a means of predicting (and optimizing) the behavior of various complex objects or systems that are often connected - without having to rely on physically existing models, prototypes or measurements. It involves numerically dividing the system being analyzed into a - often very large - number of small (finite) volumes, calculating the physical states (stresses, field strengths, temperatures, etc.) of each individual cell and using an iterative process to approximate the neighboring cells until a physically practical solution is obtained for the overall system. FE methods can be used to examine problems and potential solutions in various physical areas. In recent years the FE method in structural mechanics in particular has become a routine tool in solid-state simulation and is part of the standard repertoire for designing mechanical components. It is also possible for example to simulate temperature distribution and electric or magnetic fields or several factors at the same time with multi parameter simulation. The R&D focus at CTR is on using linked multi-parameter simulation with optimized model approaches, e.g. for simulating the thermal-mechanical behavior of composite materials or crystalline anisotropic high-performance functional materials. Our skills portfolio naturally also includes planning, performing and - depending on requirements - validating classic simulation, for example in the area of structural mechanics.

C. *Deform 3D*

DEFORM-3D is a powerful process simulation system designed to analyze the three-dimensional (3D) flow of complex metal forming processes. DEFORM-3D is a practical and efficient tool to predict the material flow in industrial forming operations without the cost and delay of shop trials. A variety of materials, ranging from carbon steel and aluminum to titanium and nickel-based alloys, can be modeled. The key advantage and benefit of using FE simulation methods is the ability to visualize the distribution of various properties and based on it gain a detailed understanding of the behavior and connections between various factors affecting a system. This enables us to identify a system's most important design factors and (potential) error sources and make the necessary improvements – without time-consuming mass screening of models and reduction of cost instead going for real time experimentation.

II. LITERATURE REVIEW

Lin employed the Taguchi method and the Grey relational analysis to optimize the turning operations with multiple performance characteristics. Tzeng et al. optimized the process parameters for turning operation with multiple performance characteristics using the Taguchi method and Grey relational analysis. However, the change in the S/N ratios of the experimental results obtained with optimal set of process parameters and the initial set of parameters has not been compared. Dattaet .al used Grey-Based Taguchi method for optimization of bead geometry in submerged arc bead-on-plate welding. Yang et al. also applied the Taguchi method and the Grey relational analysis to optimize the dry machining parameters for high-purity graphite in end milling process, etc. In the present study, Taguchi-based Grey relational analysis was used for optimizing turning process with multiple performance characteristics.

III. WORK MATERIAL, TOOL BIT & MACHINE SETUP

A. INCONEL 625

The INCONEL family of alloys was first developed in the 1940s by research teams at Wiggin Alloys (Hereford, England), which has since been acquired by SMC, in support of the development of the Whittle jet engine. INCONEL is a family of austenitic nickel-chromium-based super alloys. INCONEL alloys are oxidation- and corrosion-resistant materials well suited for service in extreme environments subjected to pressure and heat. When heated, INCONEL forms a thick, stable, passivating oxide layer protecting the surface from further attack. INCONEL retains strength over a wide temperature range, attractive for high temperature applications where aluminum and steel would succumb to creep as a result of thermally induced crystal vacancies. INCONEL's high temperature strength is developed by solid solution strengthening or precipitation hardening, depending on the alloy.

1) Chemical composition of INCONEL 625 (percentages)

Cr – 21.73, Ni – 61.47, Mb – 9.62, Co – 0.059, Al – 0.183, Ti – 0.268, C – 0.022, Fe – 2.61, Mn – 0.44, Si – 0.082, Ph – 0.002, S – 0.003

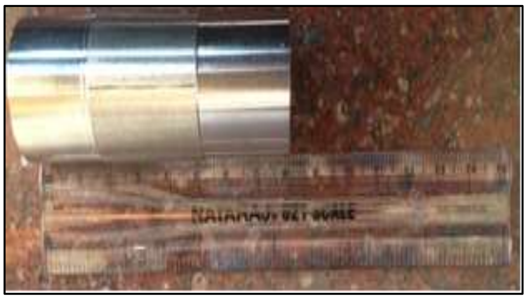

Fig. 1: INCONEL 625

Fig. 2: Precision Lathe Machine

2) Precision Lathe Machine

- Swing over bed 350mm.
- Distance between centers 750mm.
- Swing over carriage 200mm.
- Spindle variable speeds 45-1800 rpm.

B. CNMG 120408

Tungsten carbide inserts, coated with Titanium Aluminum Nitrate using PVD technique, along with the tool holder PCLNR 2020 M12 (Tool geometry: approach angle: 950 and inclination angle: -70)

C - Represents Shape, N - represents Clearance angle, M - represents Tolerance, G - insert type, 12 - cutting edge length, 04 – Thickness, 08 - nose radius

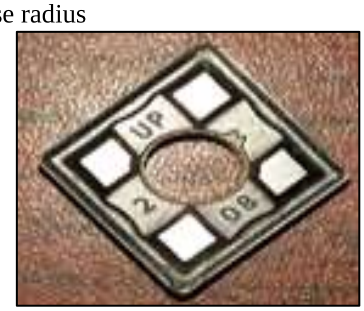

Fig. 3: Carbide Insert

Fig. 4: Tool Holder PCLNR 2020 M12

IV. EXPERIMENTAL PROCEDURE

In the present work 3 parameters cutting speed, feed and depth of cut and 3 levels are considered to conduct the experiment. The values of the 3 parameters are selected accordingly based upon the work compared to few journals. The parameters and variables along with their units are tabulated as shown in the table. Based on Taguchi L9 orthogonal array 9 experiments are performed on precision lathe machine. 3 levels of process variables are selected as process parameters such as speed, feed, and depth of cut. Cutting forces are to be measured during machining with kistler dynamometer. Surface roughness is measured with Talysurf instrument after the machining grey relation analysis is to be done for optimization process parameters.

Table – 1
Process variables and their levels

Symbol	*Parameter*	*Levels*		
		1	*2*	*3*
v	*Speed (rpm)*	*800*	*900*	*1000*
f	*Feed (mm/rev)*	*0.103*	*0.146*	*0.205*
d	*Depth of Cut (mm)*	*0.2*	*0.25*	*0.3*

Table – 2
Layout of an Orthogonal Array: L_9 Orthogonal array

Experiment	*Variable 1 v*	*Variable 2 f*	*Variable 3 d*	*Ra values*
1	*1*	*1*	*1*	*P1*
2	*1*	*2*	*2*	*P2*
3	*1*	*3*	*3*	*P3*
4	*2*	*1*	*2*	*P4*
5	*2*	*2*	*3*	*P5*
6	*2*	*3*	*1*	*P6*
7	*3*	*1*	*3*	*P7*
8	*3*	*2*	*1*	*P8*
9	*3*	*3*	*2*	*P9*

A. Cutting Force Measurement

Kestler cutting force dynamometer mounted on precision lathe machine and calibrated with computer for generation of graphs in x y z directions.

B. Roughness Measurement

Roughness measurement has been done using a portable stylus-type profilometer, Talysurf(Taylor Hobson, Surtronic S128) shown in The Talysurf instrument (Surtronic S128) is a portable, self-contained instrument for the measurement of surface texture. The parameter evaluations are microprocessor based. The measurement results are displayed on an LCD screen and can be output to an optional printer or another computer for further evaluation.

Fig. 5: Dynamometer

Fig. 6: Talysurf Instrument

V. FINITE ELEMENT SIMULATION

DEFORM-3D is an 'open system' that provides incredible flexibility to designers and analysts working on a range of applications, development and research. DEFORM-3D supports user routines and user defined variables. Complex multiple deforming body capability with arbitrary contact allows users to simulate mechanical joining and coupled die stress analysis.

A. Steps Involved in Deform 3D

1) Definition of New Problem Select file-new problem-select machining
2) Working Area Select the unit system as SI
3) Selection of Machining Operation Select the turning operation
4) Selection of Process Parameters
– Input the process parameters
– Speed: 800
– Feed: 0.103
– Depth of cut: 0.2
5) Selection Of Tool And Tool Holder
– Select the tool insert type from tool library or generate the new tool insert with the tool geometry
– Select the tool holder

6) Mesh Generation
– Select the type of mesh generation absolute or relative.
– Select the relative mesh generation which enables automatic remeshing at the machining.
7) Tool
– Tool insert CNMG 120408
– New tool geometry can be generated.
– Tool holder PCLNR 20X20mm
8) Select the Material For Machining
– Select the material from library or generate the new material with necessary properties of the material INCONEL 625
9) Mesh Generation of Work Material
– Relative mesh generation is performed for automatic remeshing during machining operation.
– Material is loaded and relative mesh is generated for surface mesh generation.
10) Simulation Controls
– Select the simulation controls as required for the machining operation
11) Generate the Database for Simulation
– Generate the database for simulation run for definite simulation steps and increment step to save and arc length to cut.

Thus the simulation model is generated for the machining operation and simulation is run for 9 different processes parameters.

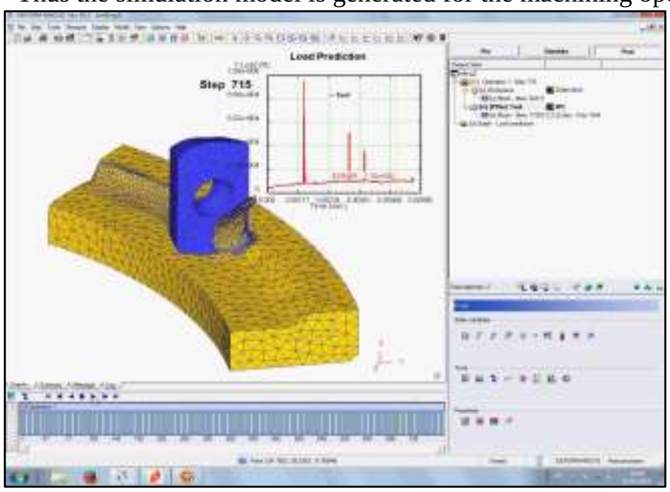

Fig. 7: DEFORM 3D Layout

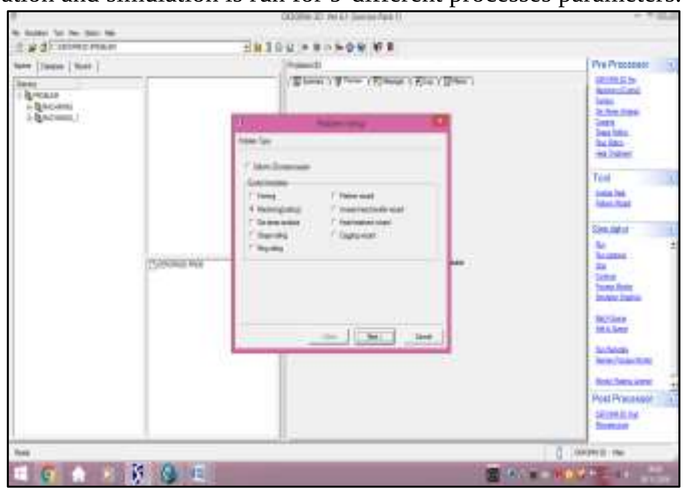
Fig. 8: Problem Definition

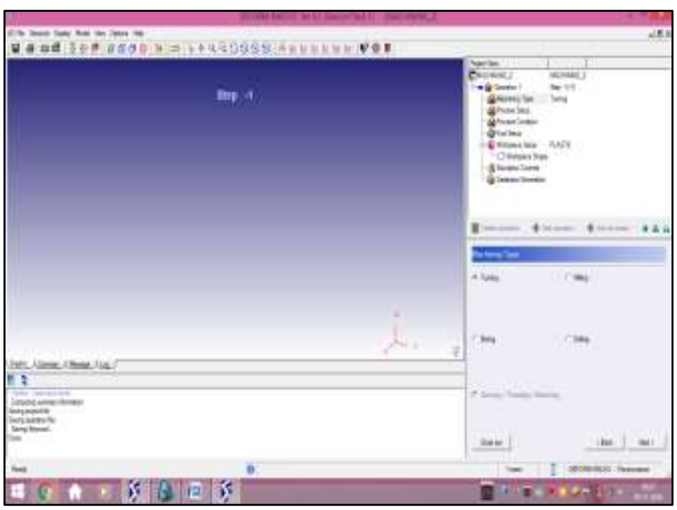
Fig. 9: Selection Of Operation

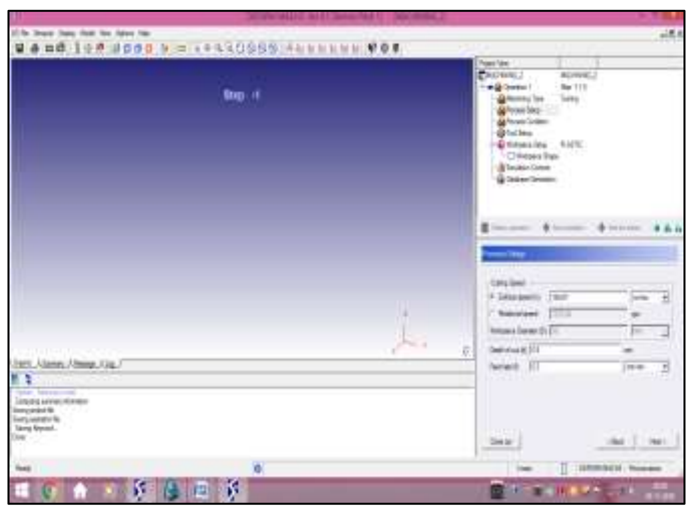
Fig. 10: Input Parameters

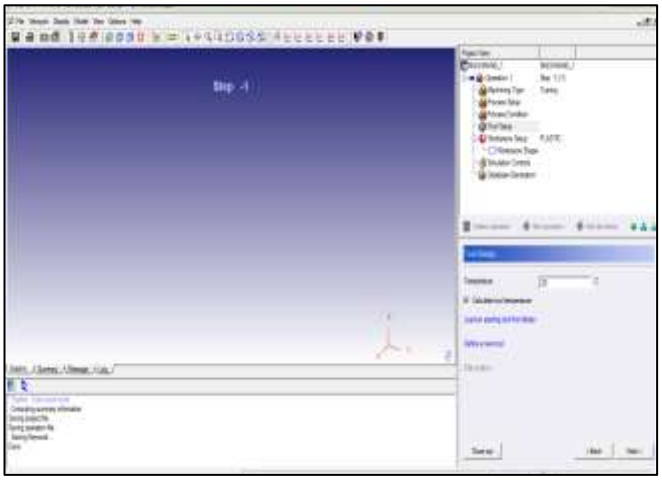

Fig. 11: Defining Tool Geometry

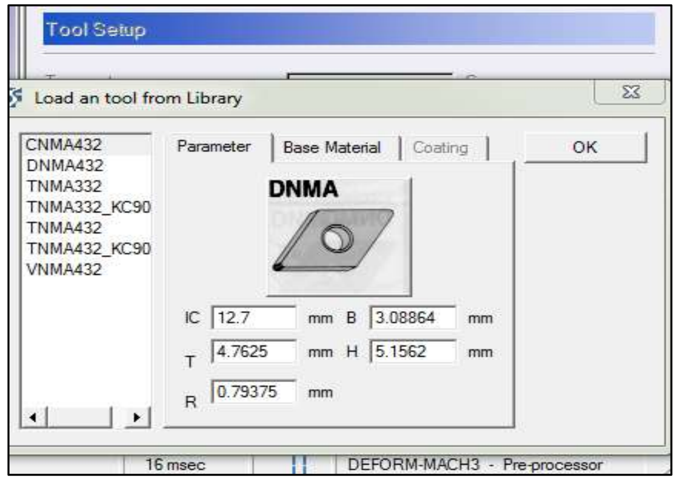

Fig. 12: Tool Setup

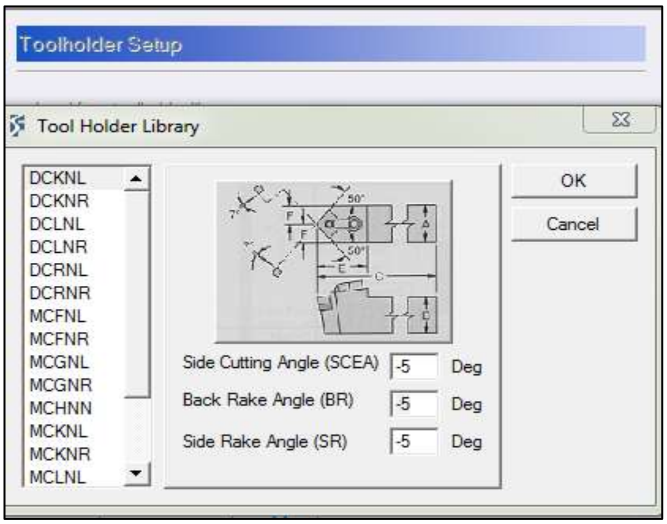

Fig. 13: Tool Holder Setup

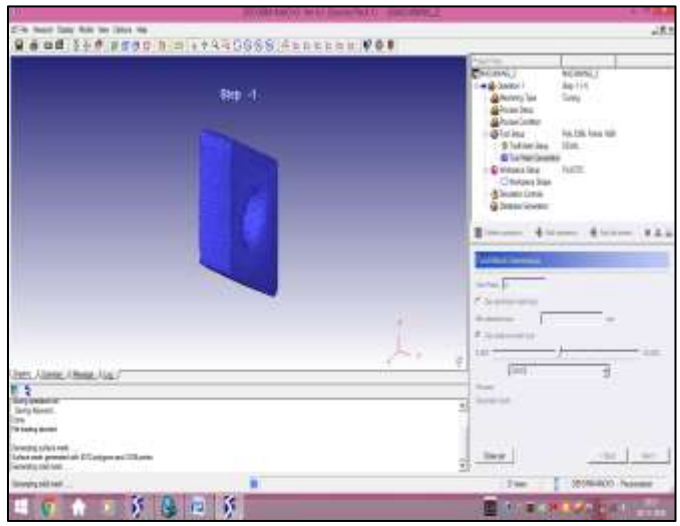

Fig. 14: Mesh Generation Of Tool

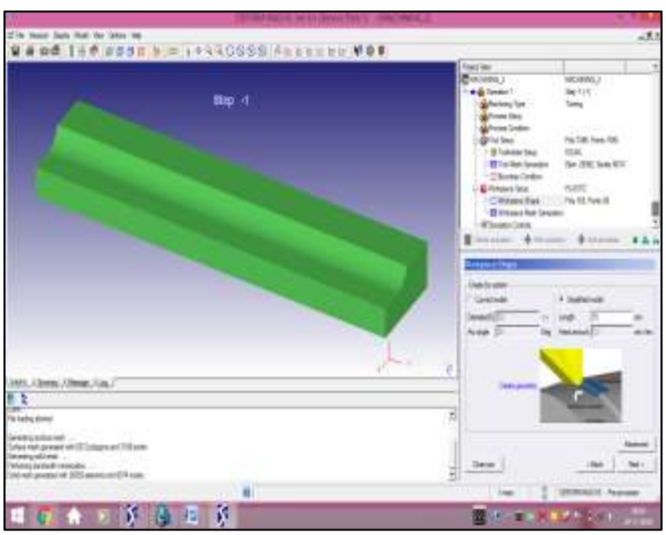

Fig. 15: Definition Of Work Piece

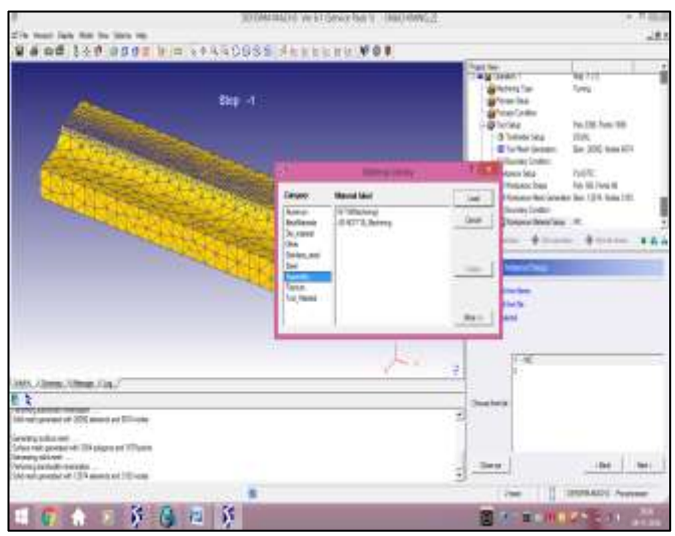

Fig. 16: Mesh Generation Of Work Piece

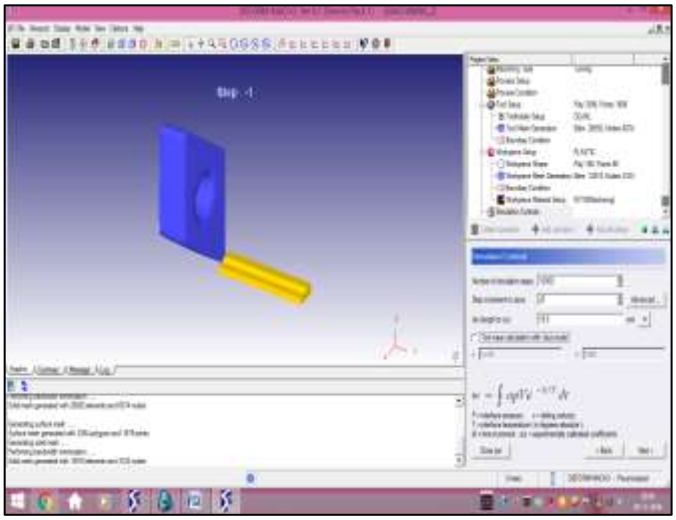

Fig. 17: Simulation Control

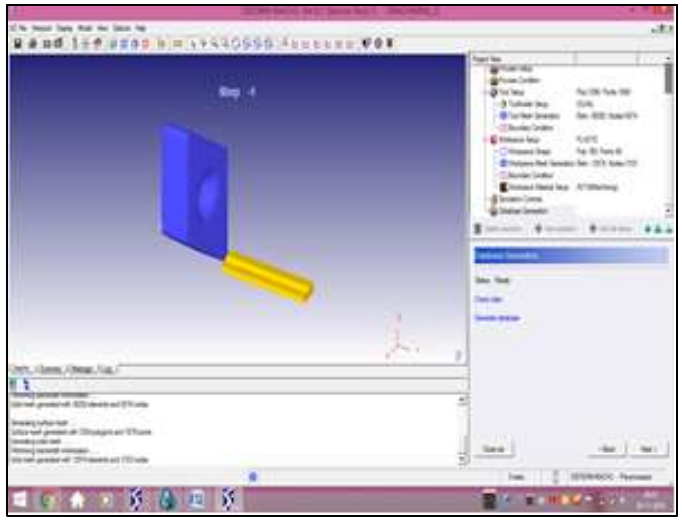

Fig. 18: Database Generation

VI. EXPERIMENTAL RESULTS

Table – 3
Orthogonal Array with Experimental Values

Run no	v (rpm)	f (mm/rev)	d (mm)	Cutting Forces			surface roughness Ra(μm)
				fx (N)	fy (N)	fz (N)	
1	800	0.103	0.2	24	96	61	0.72
2	800	0.146	0.25	74	195	144	0.84
3	800	0.205	0.3	99	269	210	1.80
4	900	0.103	0.25	60	155	111	0.74
5	900	0.146	0.3	96	238	179	0.84
6	900	0.205	0.2	59	232	151	1.41
7	1000	0.103	0.3	110	298	157	1.31
8	1000	0.146	0.2	77	289	122	1.30
9	1000	0.205	0.25	65	252	125	1.48

Table – 4
Grey Relational Grade for Each Performance

Run no	Cutting Forces			Ra	Grey Relational Grade
	fx	fy	fz		
1	1.000	1.000	1.000	1.000	1.000
2	0.570	0.702	0.600	0.814	0.671
3	0.431	0.509	0.333	0.333	0.401
4	0.732	0.881	0.952	0.963	0.882
5	0.466	0.578	0.425	0.814	0.570
6	0.700	0.574	0.553	0.437	0.565
7	0.333	0.333	0.459	0.476	0.400
8	0.566	0.410	0.738	0.481	0.548
9	0.622	0.482	0.515	0.413	0.508

A. Surface Roughness (Ra) Graphs

Fig. 19: Roughness Graphs

Table - 5
Grey Relational Coefficients and Grades for Cutting Forces and Surface Roughness

Response variables	*fx*			*fy*			*fz*			*Ra*		
Factors	*v*	*f*	*d*	*v*	*f*	*d*	*v*	*f*	*d*	*v*	*f*	*d*
Grey relational coefficient	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.53	0.78	0.60	0.67	0.99	0.81	0.61	0.71	0.84	0.81	0.62	0.86
	0.39	0.83	0.48	0.47	0.94	0.62	0.33	0.69	0.33	0.33	0.44	0.33
	0.97	0.73	0.89	0.99	0.88	0.85	0.80	0.55	0.43	0.88	0.93	0.69
	0.46	0.59	0.55	0.59	0.76	0.77	0.48	0.67	0.70	0.94	0.62	0.60
	0.75	0.58	0.62	0.58	0.78	0.50	0.66	0.33	0.34	0.47	0.92	0.34
	0.33	0.33	0.33	0.33	0.33	0.33	0.62	0.39	0.99	0.56	0.33	0.60
	0.64	0.77	0.48	0.42	0.49	0.34	0.80	0.54	0.53	0.57	0.52	0.38
	0.72	0.65	0.69	0.55	0.95	0.47	0.74	0.35	0.54	0.47	0.85	0.38
Grey relational	0.64	0.69	0.62	0.63	0.79	0.63	0.67	0.58	0.63	0.67	0.69	0.57

B. Response Graphs of Cutting Forces

Cutting force graphs from kistler dynoware software

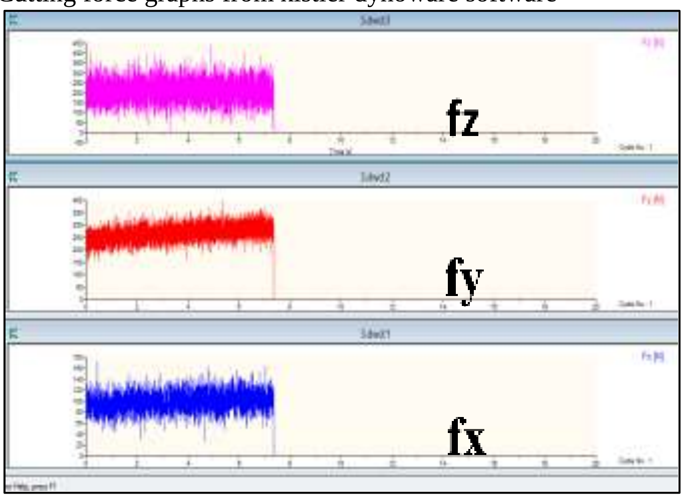

Fig. 20: Experimental Cutting Forces

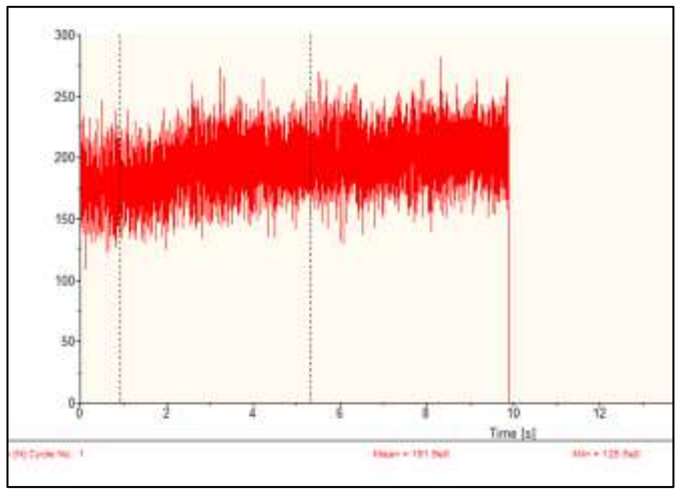

Fig. 21: Main Cutting Force Fy

Table - 6
Response Table for the Mean of Grey Relational Grades

Factors	*Level 1*	*Level 2*	*Level 3*	*Max- min*
v (rpm)	0.690	0.672	0.485	0.205
f (mm/rev)	0.760	0.596	0.491	0.269
d (mm)	0.704	0.687	0.457	0.247

Table - 7
Results of ANOVA

Symbol	*Parameter*	*DOF*	*Sum of squares*	*Mean of squares*	*percentage*
A	*Speed*	*2*	*684.83*	*342.41*	*81.3%*
B	*Feed*	*2*	*82.16*	*41.08*	*9.7%*
C	*Depth of cut*	*2*	*45.45*	*22.12*	*5.38%*
	error	*2*			*3.5%*

VII. SIMULATION RESULTS

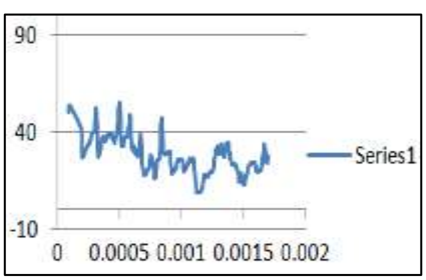

Fig. 22: Simulation Cutting Force Fx

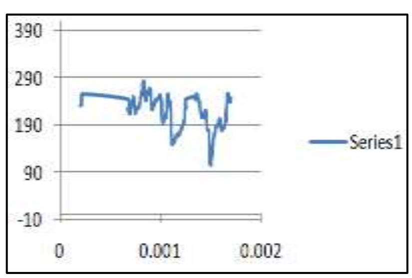

Fig. 23: Simulation Cutting Force Fy

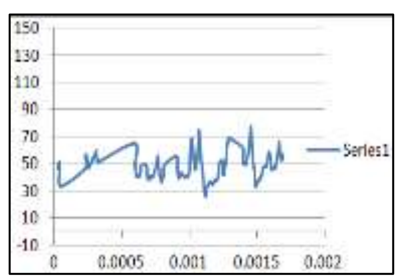

Fig. 24: Simulation Cutting Force Fz

Table - 8
Simulation Cutting Forces

Run no	*v (rpm)*	*f (mm/rev)*	*d (mm)*	*fx (N)*	*fy (N)*	*fz (N)*
1	*800*	*0.103*	*0.2*	*26*	*91*	*56*
2	*800*	*0.146*	*0.25*	*80*	*180*	*132*
3	*800*	*0.205*	*0.3*	*90*	*246*	*198*
4	*800*	*0.103*	*0.25*	*55*	*160*	*121*
5	*900*	*0.146*	*0.3*	*87*	*215*	*162*
6	*900*	*0.205*	*0.2*	*65*	*221*	*142*
7	*1000*	*0.13*	*0.3*	*101*	*274*	*165*
8	*1000*	*0.146*	*0.2*	*70*	*273*	*132*
9	*1000*	*0.205*	*0.25*	*60*	*235*	*135*

VIII. COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

Table - 9
Comparison of Experimental and Simulation Results

Run no	*V (rpm)*	*F (mm/rev)*	*D (mm)*	*Experimental results*			*Simulation results*			*% relative error*		
				FX (N)	*FY (N)*	*FZ (N)*	*FX (N)*	*FY (N)*	*FZ (N)*	*FX (N)*	*FY (N)*	*FZ (N)*
1	*800*	*0.103*	*0.2*	*24*	*96*	*61*	*26*	*91*	*56*	*8.3*	*5.2*	*8.1*
2	*800*	*0.146*	*0.25*	*74*	*195*	*144*	*80*	*180*	*132*	*8.1*	***2.7***	*8.4*
3	*800*	*0.205*	*0.3*	*99*	*269*	*210*	*90*	*246*	*198*	*9.0*	*8.6*	*5.7*
4	*900*	*0.103*	*0.25*	*60*	*155*	*111*	*55*	*160*	*121*	*8.3*	*9.6*	*9.0*
5	*900*	*0.146*	*0.3*	*96*	*238*	*179*	*87*	*215*	*162*	*9.3*	***9.6***	*9.5*
6	*900*	*0.205*	*0.2*	*59*	*232*	*151*	*65*	*221*	*142*	*9.2*	*4.7*	*5.9*
7	*1000*	*0.103*	*0.3*	*110*	*298*	*157*	*101*	*274*	*165*	*8.2*	*8.1*	*5.1*
8	*1000*	*0.146*	*0.2*	*77*	*289*	*122*	*70*	*273*	*132*	*9.1*	*5.5*	*8.2*
9	*1000*	*0.205*	*0.25*	*65*	*252*	*125*	*60*	*235*	*135*	*7.7*	*6.7*	*8.0*

IX. RESULTS AND DISCUSSION

The main objective of the experiment is to optimize the turning parameters (cutting speed, feed rate, depth of cut) to achieve low value of the surface roughness. The experimental data for the surface roughness values and the calculated signal-to-noise ratio are shown in Table 4. The S/N ratio values of the surface roughness are calculated, using the smaller the better characteristics. The effect and contribution of the 3 parameters are identified and ranked according to their percentage. The response table is given as per the average of s/n ratio. Analysis of variance for S/N ratio. Taguchi recommends analyzing data using the S/N ratio that will offer two advantages;

- It provides guidance for selection of the optimum level based on least variation around on the average value, which closest to target, and
- Also it offers objective comparison of two sets of experimental data with respect to deviation of the average from the target.
- The experimental and simulated results of cutting forces along with the percentage relative error were shown in Table 9. It can be observed from the table that the error of simulation for the three force components was found to be within 2.7 to 9.6 of the experimental results.

X. CONCLUSION

The present investigation aimed at optimization of surface roughness and cutting during turning of INCONEL 625 work piece with an coated carbide tool. This analysis was carried out by developing L9 orthogonal array in Taguchi optimization technique. The following are the conclusions drawn based on the tests conducted on turning of INCONEL 625.

1) It is observed through ANOVA that the cutting speed is the most influential control factor among the three turning process parameters investigated in this study when minimization of cutting forces, minimization of surface roughness.
2) The optimal parameter combination for achieving minimum cutting force (Fy) and minimum surface roughness (Ra) is obtained using Grey relational analysis, as v3 f3 d3.
3) The simulation results show a good agreement with that of experimental results. A maximum error of 9.6% was observed between experimental and simulation results.

The methodology proposed, established by the results of validation, promotes the DEFORM 3D simulation for metal cutting experiments and thereby minimizing the cost and time of machining.

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