Experimental Study and Optimization of Residual Stresses in Machining of Ti6Al4V Using Titanium and Multi-layered Inserts

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Abstract. Residual stresses are those types of stresses that are preserved in the material even after the applied force has been removed. These stresses have a direct influence in characteristics of superalloy along with the exterior finish of the same which plays a very pivot role in industrial applications especially aerospace. In this paper, the consequence of the residual stress has been given importance alongside the knowledge of machined part finish, tool wear, machining force, the heat generated and chip morphology. Superalloy commonly used aeronautical material Titanium (Ti6Al4V) workpiece has been taken and machined using CNC turning lathe with the help of titanium nitride (TiN) coated insert and multilayer-coated insert. The residual stress is obtained through the use of XRD technique. On the opposite side material removal rate, surface roughness and chip thickness have been also determined using defined machines and compared with various machining constraints like machining speed, depth of cut and feed rate. The tool wear was also interpreted and analysed. The machining parameters has been designated through the use of Taguchi Technique where L4 array have used to define the cutting constraints. Grey relational analysis has also been done to get optimal metal removal constraints and to get the optimal result. ANNOVA analysis is also used in this paper to acknowledge the best optimum result.

1. Introduction

Superalloys of Titanium especially Ti6Al4V is extensively employed in aeronautical, bioengineering and atomic applications because of its tempting properties like extraordinary specific strength, reduced density, outstanding corrosion confrontation, etc. [1]. However, the manufacturing and machining of these alloys is always a more thought-provoking task. The machinability of these superalloys is deprived because of insert attire and reduced tool life which is chiefly because of high machining force and temperature induced in machining [2]. Titanium alloys may exhibit reduced conductivity and improved chemical attraction in the machining region at a raised temperature which central to a larger thermal force shifted into the machining insert interface that additionally puts comparatively a larger thermal force on insert [3]. Apart from this, residual stress is also considered to be a very notable consideration during machining as it determines the excellence of the metal which is going to be employed in aeronautical applications. Removal of residual stresses because of a machining process by
removal of metal may root noteworthy buckles/falsifications on the component [4]. Residual stress may also induce thermal strains which may degrade the tool insert [5] and cause premature failure of parts [6]. Thus, it is recommended by many authors to analyse the effect of these stresses developed in the alloy during machining of superalloys on the machining constraints as it has a direct influence on the behaviour of the same.

Neelesh Kumar Sahu et al. [7] developed forecast model for the residual stress prompted because of metal cutting by considering the impact of the metal cutting constraints differences on the prompted residual stress and studied by revenue of ANNOVA. He also conducted an optimization of the same by using response surface methodology and validated the same with reasonable accuracy.

Zhipeng Pan et al. [8] delivered a detailed thought on the work material residual stress dissemination as inclined by metal microstructural qualities development in the manufacturing. Incorporated a FE model based on adapted Johnson-Cook model to study the same which is authenticated by the cutting forces in changing process parameters. He also showed the understandable grain development on cut material.

Abboud et al. [9] projected the importance of identification of cutting parameters and environment that may create a good mechanical residual stress dissemination in the cut workpiece as only partial data is obtainable in the article for these superalloys, particularly in the finish machining system.

Cotterel et al. [10] explained exact information on the chip development during machining of titanium alloy Ti6Al4V by image examination of the cut chip development procedure of the resulting chip thickness and the concomitant shear strain inside the chips. He also introduced a basic heat model to foresee the regular heat in the chip due to the machining zone.

Jiapeng Lu et al. [11] study delivers a healthier appreciative of chip break development mechanism on the machining interface and optimization of cutting constraints in machining Ti6Al4V. He also elaborated an extra accurate FE model of Ti6Al4V alloy machining plus exit edge defect development. Krishnaraj et al. [12] exhibited the machinability matters related to cutting Ti6Al4V by detailing the observations on the consequence of cutting constraints on machining forces and temperature and consistent to do progression in high speed in machining on turning of superalloys with AdvantEdge. Thus an effort has been done in this paper to analyse with the above-revealed traits through the design of experiments for an assortment of cutting conditions. Residual stress, surface roughness, chip thickness, temperature and tool wear were studied for L4 Taguchi array of experiments and their influence on machining constraints were studied. Grey Relation Analysis is used for the determination of better input conditions and the same through ANNOVA technique. The validation of the optimization is also performed through optimization results.

2. Experiment

Orthogonal machining experiments were carried out on the workpiece of Titanium alloy (Ti6Al4V) of 30mm diameter and 100mm length. The cutting is done CNC lathe machine in non-wet condition without coolants. The commercially available tool insert of tungsten carbide general is used for machining. Two types of coated tungsten carbide tools were used namely titanium nitride (TiN) and multilayer (TiN+Al2O3) dual-layer with each 10µm thickness CVD coated. The tool insert is designated as TNMG160408 with RHS type of tool holder is employed for the experiments. L4 Taguchi Design of Experiments array is castoff for the study by varying the machining constraints in 2 levels with 3 factors. The factors which are meant to machining parameters were selected to be cutting speed, depth of cut and feed rate. The parameter selection and their levels are shown in Table 1. The standard format of design of experiments (L4 array) which used for experiments done on a cylindrical specimen of the selected superalloy is given in Table 2. The experiment methodology used for machining is given in Figure 1.
Table 1. Parameter Selection.

| Parameter            | Level 1 | Level 2 |
|----------------------|---------|---------|
| Cutting Speed (m/min)| 50      | 100     |
| Feed Rate (mm/rev)   | 0.1     | 0.2     |
| Depth of Cut (mm)    | 1       | 2       |

Table 2. Design of Experiments.

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of cut (mm) |
|----------------|-----------------------|--------------------|-------------------|
| 1              | 50                    | 0.1                | 1                 |
| 2              | 50                    | 0.2                | 2                 |
| 3              | 100                   | 0.1                | 2                 |
| 4              | 100                   | 0.2                | 1                 |

Figure 1. Experiment Methodology.

The cutting force which is observed during machining at the interface region is measured using Kistler Piezoelectric Dynamometer. The temperature at the contact area is determined using a non-
contact IR temperature sensor. The arithmetic exterior finish (Ra) value is determined using surface roughness tester and the tool wear is measured using Imager Analyser. The OLM Machine Vision setup is used for the evaluation of chip thickness and Residual stress which is left off in machined workpiece is determined using XRD Analysis Technique.

3. Results and Discussion

3.1. Experimental results

Table 3 displays the experimental results of cutting force, temperature, surface roughness, chip thickness, tool wear and residual stress observed during machining of Ti6Al4V using tungsten carbide insert coated with TiN coated.

Table 3. Experimental Results as per L4 array while machining with TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|---------------------|-------------------|------------------|------------------|------------------------|---------------|--------------------|-----------------------|
| 1                     | 50                  | 0.1               | 1                | 350              | 420                    | 1.3553        | 0.18               | 11.109               | 387.55               |
| 2                     | 50                  | 0.2               | 2                | 415              | 475                    | 0.5819        | 0.31               | 11.139               | 380.74               |
| 3                     | 100                 | 0.1               | 2                | 535              | 620                    | 0.8836        | 0.18               | 10.119               | 376.75               |
| 4                     | 100                 | 0.2               | 1                | 575              | 695                    | 1.2068        | 0.3                | 11.109               | 379.05               |

From the observations, it is apparent that minimum cutting force of 350N, minimum temperature of 450°C, minimum tool wear of 0.18µm and least chip thickness of 11.109mm is recorded at an experimental condition of 50m/min, 0.1mm/rev and 1mm. But to the conflicting, the finest exterior quality and better residual stress do not happen in the same experimental condition. The minimum which is the best surface finish is observed at 50m/min, 0.2mm/rev and 2mm which is observed at a higher feed rate on comparison with the other said output responses because as the velocity at which the cutting insert inside the material increases, the surface finish is ultimately improved. But the reduced residual stress is observed in the condition where the depth of cut and machining speed is high because coverage is more per unit time.

Table 4 shows the experimental results of cutting force, temperature, surface roughness, chip thickness, tool wear and residual stress observed during machining of Ti6Al4V using tungsten carbide insert coated with multilayer (TiN+Al2O3) coated.

Table 4. Experimental Results as per L4 array while machining with multilayer (TiN+Al2O3) Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|---------------------|-------------------|------------------|------------------|------------------------|---------------|--------------------|-----------------------|
| 1                     | 50                  | 0.1               | 1                | 230              | 375                    | 1.2778        | 0.19               | 22.197                | 377.37               |
| 2                     | 50                  | 0.2               | 2                | 275              | 415                    | 1.1137        | 0.32               | 66.825                | 381.04               |
| 3                     | 100                 | 0.1               | 2                | 423              | 575                    | 1.3964        | 0.26               | 10.855                | 381.87               |
| 4                     | 100                 | 0.2               | 1                | 515              | 660                    | 0.707         | 0.19               | 88.931                | 378.43               |

As similar to TiN coated insert, the minimum cutting force, temperature, insert attire is detected in the same condition of 50m/min, 0.1mm/rev and 1mm depth. The minimum values recorded namely 230N, 375°C, 0.19µm is comparatively less than that of the TiN insert because of an additional coating in the insert which reduced the induction of cutting force and its corresponding friction temperature. But because of the same reason extra coating, minimum residual stress of 377.37MPa is observed in
the same experimental condition of 50m/min, 0.1mm/rev and 1mm depth. The minimum surface finish is recorded at high speed and high feed wherein the MRR is comparatively higher than others.

The disparity of cutting force, temperature, chip thickness, surface roughness, tool wear and residual stress with TiN and multilayer insert are shown in figure 2, 3, 4, 5, 6 and 7 respectively. As far as machining load is alarmed, the machining force observed in the multilayer-coated insert is less than that of the TiN insert in all the experiment conditions because of the extra coating load which is required to remove the material is also less. Similarly, as the machining force which is less, the induced temperature on the interface region is also found to be less for all the experiment conditions.
satisfying the same justification. To the contrary, similar variation trends cannot be observed in all experimental conditions in the bags of the remaining output responses. In the instance of chip thickness, it is found that chip thickness is increased for multilayer insert with all conditions except the condition of 100m/min, 0.2mm/rev and 1mm wherein it decreased to the minimum value because, in higher speed and feed, the coating of Al₂O₃ induced to reduce the thickness of the chip. While seeing the surface roughness, the value reduced in the event of small machining penetration and the value enlarged in a situation of great machining penetration because when the machining penetration is more, the MRR is increased and machining time is reduced. But to the contrary of all the output responses, the tool wear is found more drastically increase for the multilayer insert for all the experimental conditions which maybe because of the strain-induced. This may lead to the fact that multilayer insert may not be an economic advantage as the tool wear is more which may reduce the tool life. Similar to the surface roughness and because of the same justification the residual stress value reduced in the case of lesser depth of cut and the residual stress value bigger in case of tall depth of cut because when the depth of cut is more, the material removal rate is increased and machining time is reduced.

The variation of output responses like cutting force, temperature, chip thickness, surface roughness, tool wear and residual stress with respect to other machining constraints for machining with TiN insert are shown in figure 8, 9, 10, 11, 12 and 13 respectively. From figure 8 and 9, it is clear that cutting force and temperature rises with the rise in cutting speed and rise in depth of cut since the material removal rate is more in case of high machining conditions. But the trend is the opposite in the case of temperature with respect to the depth of cut. It is clear that thermal softening of material at a higher feed rate which may induce high cutting. The more cutting force may induce ultimately an increase in

![Figure 8. Variation of Cutting Force (TiN).](image1)

![Figure 9. Variation of Temperature (TiN).](image2)

![Figure 10. Variation of Chip Thickness (TiN).](image3)

![Figure 11. Variation of Surface Roughness (TiN).](image4)
temperature at the machining interface region. The minimum cutting force of 230N is observed at an experiment condition by machining with a multilayer insert.

From figure 10, it is detected that chip thickness is established to rise with the rise in feed rate and rise in depth of cut but the same is found to fall with the rise in machining speed because the rise in the speed in which the cutting insert is fed inside the workpiece rises the chip thickness. But to the exact opposite when chip thickness increased, surface finish is more reduced and with a decrease in chip thickness, surface roughness increased so the thick chip favour better surface finish. The trend is surface finish is abridged with the rise in feed rate and depth but enlarged with fall in cutting speed in figure 11. In figure 12, it is pure that insert attire is said to fall with a rise in speed and rise in depth of cut as the MRR is more which induced less machining time. But with a rise in feed, tool wear is also amplified because the rise of feed of cutter against the workpiece may, fortunately, increase the wear of the tool. From figure 13, the residual stress follows a common trend for all the machining conditions as it falls with a rise in all constraints as MRR is more in high machining conditions, the machining time is reduced which ultimately yields to leave back more stress in the machined workpiece.

The variation of output responses like cutting force, temperature, chip thickness, surface roughness, tool wear and residual stress with respect to other machining constraints for machining with multilayer insert are shown in figure 14, 15, 16, 17, 18 and 19 respectively. The trend observed in cutting force in figure 14 is very similar to that of the TiN insert with respect to machining speed and feed but machining load fall only with the rise in feed rate as the more the cutter feed reduce the load. And a very similar trend in temperature, it is the same trend as the case of TiN insert. The only notable
feature because of the additional coating the values of the output responses were reduced appreciably to a great extent.

![Main Effects Plot for Means - Chip Thickness - Multilayer Coated](image1)

**Figure 16.** Variation of chip thickness (Multilayer).

![Main Effects Plot for Means - Surface Roughness - Multilayer Coated](image2)

**Figure 17.** Variation of surface roughness (Multilayer).

![Main Effects Plot for Means - Tool Wear - Multilayer Coated](image3)

**Figure 18.** Variation of tool wear (Multilayer).

![Main Effects Plot for Means - Residual Stress - Multilayer Coated](image4)

**Figure 19.** Variation of residual stress (Multilayer).

The variation trend detected in chip thickness is exposed in figure 16 is same as that of the TiN insert as the chip thickness is found to grow with rising in feed and rise in depth of cut but the same fall with a rise in speed because of the same justification as above. But from figure 17, it is observed the trend is not the same as in the case of TiN because surface roughness reduced with a rise in cutting speed and rise in feed and surface roughness rose with a rise in depth. This may be because of the properties of additional coating and networking characteristics of the workpiece. From figure 18, tool wear enlarged with a rise in speed and feed because of the same above said characteristics. And the same is said to fall with a rise in depth of cut as more depth wears the insert easily. And to the exact opposite of TiN insert because of the characteristics of additional coating in the multilayer-coated insert, the residual stress rises with the rise in all the cutting parameters.

### 3.2. Taguchi analysis

Taguchi analysis is used to identify the optimum conditions in which the near best output responses can be obtained. This method of analysis is used to elevate the influence of different machining constraints and monitoring the influence of various signal and noise factors. This study aims to optimize the objective function which is the output response. The noise factors which are more common in turning operation are vibration, raw material variation, machine condition, temperature and operator skill. The control factors are cutting speed, feed rate, depth of cut, coolant and nose radius mainly affect the machining of superalloys [13].
3.2.1. Analysis of the S/N ratio. Taguchi practises Signal to Noise S/N ratio to find the feature differing from the desired value. There are numerous S/N ratios obtainable contingent on the type of features i.e., higher-the-better, lower-the-better and nominal-the-better [14].

The S/N ratio is calculated as follows using equation 1,

\[
\frac{S}{N} \text{ ratio} = -10 \log(MSD)
\]  

(1)

Where MSD is the mean square deviation of the output response.

Typically, smaller values of output responses are wanted for any cutting process. Thus, smaller the better standards for output response were designated during the present work. Irrespective of the smaller the better or the larger the better feature, the higher the S/N ratio parallels to the lesser variance of the output response around the wanted value.

The S/N ratio of the experimental results is calculated for the various experiments as it is shown in the graph with respect to process parameters.

![Figure 20. Variation of S/N - Cutting Force (TiN).](image)

![Figure 21. Variation of S/N – Cutting Force (Multilayer).](image)

![Figure 22. Variation of S/N – Temperature (TiN).](image)

![Figure 23. Variation of S/N – Temperature (Multilayer).](image)

The variation of S/N ratio for various output responses are shown in figures 20 to 31. From figure 20, 21, 22 and 23, it is marked that S/N ratio is more in the case of 50m/min, 0.1mm/rev and 1mm depth in case of TiN insert for both output responses of cutting force and temperature. So for TiN insert, it is predicted in the same said experiment condition it is meant to have a better cutting force and temperature. But in the case of multilayer insert, it is found that S/N ratio is higher in the experimental condition of 50m/min, 0.1mm/rev and 2mm depth and so it is predicted to have a better cutting force and temperature.
Figure 24. Variation of S/N – Chip thickness (TiN).

Figure 25. Variation of S/N – Chip thickness (Multilayer).

Figure 26. Variation of S/N – Surface Roughness (TiN).

Figure 27. Variation of S/N – Surface Roughness (Multilayer).

Figure 28. Variation of S/N – Tool wear (TiN).

Figure 29. Variation of S/N – Tool wear (Multilayer).
Figure 30. Variation of S/N – Residual Stress (TiN).

Figure 31. Variation of S/N – Residual Stress (Multilayer).

From figure 24 and 25, it is evident that S/N ratio is high for the experimental condition of 100m/min, 0.1mm/rev and 1mm depth for both TiN and multilayer insert in the case of output response of chip thickness. It is predicted to have a better value in the above-said condition. From figure 26, it is found that better surface finish is predicted at an experiment condition of 50m/min, 0.2mm/rev and 2 mm for machining with a TiN insert but it is predicted to have a better surface finish for machining with multilayer insert in the case of 100m/min, 0.2mm/rev and 1mm because these said cases have high S/N ratio in figure 27. As like chip thickness, the optimum condition for TiN and multilayer insert are the same. From figure 28 and 29, it is found that S/N ratio is high for the experimental condition of 100m/min, 0.1mm/rev and 2mm depth for both TiN and multilayer insert for which it is predicted to have a better value. For figure 30 and 31, it is predicted that better residual stress values will be obtained at high machining levels in TiN inserts and low machining levels in multilayer inserts.

3.2.2. Confirmation tests. A confirmation test is conceded out to verify whether the predicted parameters using Taguchi Analysis are optimum or not. An experiment is performed on the metal using the optimal constraints, for each optimal constraint an average of four cases is taken out to get the predicted value. The confirmation tests conducted for machining with TiN insert and their comparison with predicted and experimental value are revealed in Table 5. Similarly, the confirmation test for multilayer inserts is exposed in Table 6.

| Table 5. Confirmation Tests – TiN Insert. |
|------------------------------------------|
| Response | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Optimal Conditions | Predicted Value | Experimental Value |
|-----------|-----------------------|---------------------|------------------|-------------------|-----------------|-------------------|
| Cutting Force (N) | 50 | 0.1 | 1 | 468.75 | 340 |
| Temperature (°C) | 50 | 0.1 | 1 | 552.5 | 415 |
| Chip Thickness (mm) | 100 | 0.1 | 1 | 1.0069 | 0.57 |
| Surface Roughness (µm) | 50 | 0.2 | 2 | 0.2425 | 0.17 |
| Tool Wear (µm) | 100 | 0.1 | 2 | 10.869 | 10.063 |
| Residual Stress (MPa) | 100 | 0.2 | 2 | 381.02 | 375.85 |
### Table 6. Confirmation Tests – Multilayer Insert.

| Response                      | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Optimal Conditions | Predicted Value | Experimental Value |
|-------------------------------|-----------------------|--------------------|-------------------|--------------------|-----------------|--------------------|
| Cutting Force (N)             | 50                    | 0.1                | 2                 | 360.75             | 225             |
| Temperature (°C)              | 50                    | 0.1                | 2                 | 506.25             | 370             |
| Chip Thickness (mm)           | 100                   | 0.1                | 1                 | 1.1237             | 0.69            |
| Surface Roughness (µm)        | 100                   | 0.2                | 1                 | 0.24               | 0.18            |
| Tool Wear (µm)                | 100                   | 0.1                | 2                 | 47.202             | 19.234          |
| Residual Stress (MPa)         | 50                    | 0.1                | 1                 | 379.67             | 376.23          |

### 3.3. Grey relational analysis

In the multi-output project, the effect and association between various constraints are multifaceted and not vivid. This is called as grey which indicates deprived and inexact data. This planned method (grey relational analysis) examines this complex indecision among the various outputs in a project and optimize it with the aid of grey relational grade. So a multi-output optimization project is abridged to a single output called single grade [15]. The steps involved in the analysis are given below:

- Step 1 – Normalization
- Step 2 – Calculation of Deviation Sequence
- Step 3 – Calculation of Grey Relation Coefficient
- Step 4 – Calculation of Grey Relation Grade (GRG)
- Step 5 – Compute the Rank based on GRG
- Step 6 – Perform the analysis of variance (ANOVA)
- Step 7 – Confirmation Experiment

#### 3.3.1. TiN insert

The grey relational analysis is performed on the experimental values of output responses of TiN Insert in the following steps:

### Table 7. Experimental Values – Input Vs Output Responses – TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|--------------------|-------------------|-------------------|-----------------|------------------------|---------------|-------------------|-----------------------|
| 1                     | 50                 | 0.1               | 1                 | 350             | 420                    | 1.3553        | 0.18              | 11.109                | 387.55                |
| 2                     | 50                 | 0.2               | 2                 | 415             | 475                    | 0.5819        | 0.31              | 11.139                | 380.74                |
| 3                     | 100                | 0.1               | 2                 | 535             | 620                    | 0.8836        | 0.18              | 10.119                | 376.75                |
| 4                     | 100                | 0.2               | 1                 | 575             | 695                    | 1.2068        | 0.3               | 11.109                | 379.05                |
Table 8. Step 1 – Normalization – TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Normalization | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|--------------------|-------------------|---------------|------------------|------------------|-----------------------|----------------|---------------------|---------------------|
| 1                     | 50                 | 0.1               | 1             | 1                | 1                | 1                     | 0              | 1                   | 0.0245              |
| 2                     | 50                 | 0.2               | 2             | 0.7111           | 0.8              | 1                     | 0              | 0                   | 0.6356              |
| 3                     | 100                | 0.1               | 2             | 0.1778           | 0.2773           | 0.6319                | 1              | 1                   | 1                   |
| 4                     | 100                | 0.2               | 1             | 0                | 0                | 0.1931                | 0.0777         | 0.0295              | 0.7837              |

Table 9. Step 2 – Deviation Sequence – TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Deviation Sequence | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|--------------------|-------------------|--------------------|------------------|------------------|-----------------------|----------------|---------------------|---------------------|
| 1                     | 50                 | 0.1               | 1                  | 0                | 0                | 1                     | 0              | 0.9706              | 1                   |
| 2                     | 50                 | 0.2               | 2                  | 0.2889           | 0.2              | 0                     | 1              | 0.3694              | 0                   |
| 3                     | 100                | 0.1               | 2                  | 0.8222           | 0.7273           | 0.3901                | 0              | 0                   | 0                   |
| 4                     | 100                | 0.2               | 1                  | 1                | 1                | 0.8080                | 0.9231         | 0.9706              | 0.2130              |

Table 10. Step 3 – Grey Relation Coefficient – TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Grey Relation Coefficient | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|--------------------|-------------------|----------------------------|------------------|------------------|-----------------------|----------------|---------------------|---------------------|
| 1                     | 50                 | 0.1               | 1                          | 0                | 1                | 0.3333                | 1              | 0.34                | 0.3333              |
| 2                     | 50                 | 0.2               | 2                          | 0.6338           | 0.7143           | 1                     | 0.3333         | 0.3333              | 0.5751              |
| 3                     | 100                | 0.1               | 2                          | 0.3782           | 0.4074           | 0.5617                | 1              | 1                   | 1                   |
| 4                     | 100                | 0.2               | 1                          | 0.3333           | 0.3333           | 0.3823                | 0.3514         | 0.34                | 0.7013              |

Table 11. Step 4 & 5 – Grey Relation Grade and Rank – TiN Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Grey Relation Grade | Rank |
|-----------------------|--------------------|-------------------|---------------------|------|
| 1                     | 50                 | 0.1               | 1                   | 0.66778 | 2     |
| 2                     | 50                 | 0.2               | 2                   | 0.59831 | 3     |
| 3                     | 100                | 0.1               | 2                   | 0.72455 | 1     |
| 4                     | 100                | 0.2               | 1                   | 0.40693 | 4     |

Figure 32. Variation of Mean Effect GRG – TiN.
Table 12. Main Effects on Mean Grey Relational Grade – TiN Coated Insert.

| Level | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|-------|-----------------------|--------------------|------------------|
| 1     | 1                     | 0.6330             | 0.5374           |
| 2     | 2                     | 0.5657             | 0.6614           |
| Min – Max | 0.0673              | 0.1935             | 0.1241           |
| Rank  | 3                     | 1                  | 2                |

Figure 33. Variation of S/N Ratio – GRG – TiN.

Table 13. ANNOVA Analysis – TiN Coated Insert.

| Source              | DF | SeqSS | Contribution | Adj SS | Adj MS |
|---------------------|----|-------|--------------|--------|--------|
| Cutting Speed (m/min) | 1  | 0.0045 | 7.89%        | 0.0045 | 0.0045 |
| Feed Rate (mm/rev)  | 1  | 0.0374 | 65.28%       | 0.0374 | 0.0374 |
| Depth of Cut (mm)   | 1  | 0.0153 | 26.83%       | 0.0153 | 0.0153 |

The input Vs output responses of the experimental values obtained while machining with TiN insert is shown in Table 7. The normalized values of output responses were shown in Table 8 and the deviation sequence is in Table 9. Table 10 shows the grade relation coefficient and Table 11 shows grey relational grade and rank. From Table 11, it is clear that the experiment condition of 100m/min, 0.1mm/rev and 2mm depth showed a better rank and grade out of four experiments. Figure 32 and 33 show the variation of mean GRG values and S/N ratios with respect to process parameters. From table 12, it is vivid that it is predicted that cutting speed at level 1, feed rate at level 1 and depth of cut at level 2 will give near optimum output responses for TiN Insert. From ANNOVA analysis in Table 13, it is very evident that 65.28% of the contribution is from the process parameter of feed rate in the case of machining with TiN insert. The confirmation experiment of the above-predicted condition is given in Table 14.
Table 14. Confirmation Experiment – TiN Coated Insert.

| Level | Prediction | Experiment |
|-------|------------|------------|
|       | Cutting speed at level 1 (50m/min), Feed rate at level 1 (0.1mm/rev) and Depth of cut at level 2 (2mm) | Cutting speed at level 1 (50m/min), Feed rate at level 1 (0.1mm/rev) and Depth of cut at level 2 (2mm) |
|       | Cutting Force (N) | 468.75 | 330 |
|       | Temperature (°C) | 552.5 | 410 |
|       | Chip Thickness (mm) | 1.0069 | 0.56 |
|       | Surface Roughness (µm) | 0.2425 | 0.16 |
|       | Tool Wear (µm) | 10.869 | 10.023 |
|       | Residual Stress (MPa) | 381.02 | 374.021 |

3.3.2. Multilayer insert. The grey relational analysis is performed on the experimental values of output responses of Multilayer Insert in the following steps:

Table 15. Experimental Values – Input Vs Output Responses – Multilayer Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Experimental Values |
|-----------------------|--------------------|-------------------|---------------------|
|           |                   |                   | Cutting Force (N)   |
|           |                   |                   | Temperature (°C)    |
|           |                   |                   | Surface Roughness (µm) |
|           |                   |                   | Tool Wear (µm)      |
|           |                   |                   | Chip Thickness (mm) |
|           |                   |                   | Residual Stress (MPa) |
| 1         | 50                 | 0.1               | 230                 |
| 2         | 50                 | 0.2               | 275                 |
| 3         | 100                | 0.1               | 423                 |
| 4         | 100                | 0.2               | 515                 |

Table 16. Step 1 – Normalization – Multilayer Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Normalization |
|-----------------------|--------------------|-------------------|---------------|
|           |                   |                   | Cutting Force (N)   |
|           |                   |                   | Temperature (°C)    |
|           |                   |                   | Surface Roughness (µm) |
|           |                   |                   | Tool Wear (µm)      |
|           |                   |                   | Chip Thickness (mm) |
|           |                   |                   | Residual Stress (MPa) |
| 1         | 50                 | 0.1               | 1               |
| 2         | 50                 | 0.2               | 0.8421           |
| 3         | 100                | 0.1               | 0.3228           |
| 4         | 100                | 0.2               | 0                |

Table 17. Step 2 – Deviation Sequence – Multilayer Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Deviation Sequence |
|-----------------------|--------------------|-------------------|--------------------|
|           |                   |                   | Cutting Force (N)   |
|           |                   |                   | Temperature (°C)    |
|           |                   |                   | Surface Roughness (µm) |
|           |                   |                   | Tool Wear (µm)      |
|           |                   |                   | Chip Thickness (mm) |
|           |                   |                   | Residual Stress (MPa) |
| 1         | 50                 | 0.1               | 0                 |
| 2         | 50                 | 0.2               | 0.1579            |
| 3         | 100                | 0.1               | 0.6772            |
| 4         | 100                | 0.2               | 1                 |
Table 18. Step 3 – Grey Relation Coefficient – Multilayer Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Cutting Force (N) | Temperature (°C) | Surface Roughness (µm) | Tool Wear (µm) | Chip Thickness (mm) | Residual Stress (MPa) |
|-----------------------|---------------------|------------------|-------------------|------------------|------------------------|---------------|-------------------|----------------------|
| 1                     | 50                  | 0.1              | 1                 | 1                | 0.3765                 | 1             | 0.7749            | 1.0000               |
| 2                     | 50                  | 0.2              | 2                 | 0.7600           | 0.7808                | 0.4587        | 0.3333            | 0.4109               | 0.3801               |
| 3                     | 100                 | 0.1              | 2                 | 0.4247           | 0.4161                | 0.3333        | 0.4815            | 1                    | 0.3333               |
| 4                     | 100                 | 0.2              | 1                 | 0.3333           | 0.3333                | 1.0000        | 1.0000            | 0.3333               | 0.6798               |

Table 19. Step 4 & 5 – Grey Relation Grade and Rank – Multilayer Coated Insert.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Grey Relation Grade | Rank |
|-----------------------|---------------------|------------------|---------------------|------|
| 1                     | 50                  | 0.1              | 1                   | 1    |
| 2                     | 50                  | 0.2              | 2                   | 3    |
| 3                     | 100                 | 0.1              | 2                   | 4    |
| 4                     | 100                 | 0.2              | 1                   | 2    |

Figure 34. Variation of Mean Effect GRG – Multilayer.

Table 20. Main Effects on Mean Grey Relational Grade – Multilayer Coated Insert.

| Level | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|-------|-----------------------|--------------------|-------------------|
| 1     | 1                     | 0.6896             | 0.6784            | 0.7359 |
| 2     | 2                     | 0.5557             | 0.5670            | 0.5094 |
| Min – Max | 0.1339               | 0.1114             | 0.2265            |
| Rank  | 2                     | 3                  | 1                 |
Figure 35. Variation of S/N Ratio – GRG – Multilayer.

Table 21. ANNOVA Analysis – Multilayer Coated Insert.

| Source                          | DF | SeqSS  | Contribution | Adj SS | Adj MS |
|---------------------------------|----|--------|--------------|--------|--------|
| Cutting Speed (m/min)           | 1  | 0.01792| 21.95%       | 0.01792| 0.01792|
| Feed Rate (mm/rev)              | 1  | 0.01241| 15.20%       | 0.01241| 0.01241|
| Depth of Cut (mm)               | 1  | 0.05131| 62.85%       | 0.05131| 0.05131|

Table 22. Confirmation Experiment – Multilayer Coated Insert.

| Level                          | Prediction | Experiment |
|--------------------------------|-------------|------------|
| Cutting Force (N)              | 360.75      | 230        |
| Temperature (°C)               | 506.25      | 375        |
| Chip Thickness (mm)            | 1.1237      | 1.2778     |
| Surface Roughness (µm)         | 0.24        | 0.19       |
| Tool Wear (µm)                 | 47.202      | 22.197     |
| Residual Stress (MPa)          | 379.67      | 377.37     |

The input Vs output responses of the experimental values obtained while machining with multilayer-coated insert is shown in Table 15. The normalized values of output responses were shown in Table 16 and the deviation sequence is in Table 17. Table 18 shows the grade relation coefficient and Table 19 shows grey relational grade and rank. From Table 19, it is clear that the experiment condition of 50m/min, 0.1mm/rev and 1mm depth showed a better rank and grade out of four experiments. Figure 34 and 35 show the variation of mean GRG values and S/N ratios with respect to process parameters. From Table 20, it is vivid that it is predicted that cutting speed at level 1, feed rate at level 1 and depth of cut at level 1 will give near optimum output responses for the multilayer-coated
insert. From ANNOVA analysis in Table 21, it is very evident that 62.85% of the contribution is from the process parameter of the depth of cut in the case of machining with multilayer insert. The confirmation experiment of the above-predicted condition is given in Table 22.

4. Conclusion

The paper is mainly projected on the experimental study on the effect of various constraints like cutting speed, feed rate and depth of cut on the various responses like cutting force, surface roughness, tool wear, temperature, chip morphology and residual stress based L4 Taguchi array.

- Cutting force and temperature is found to rise with the rise in machining speed and feed rate and the least machining force and the temperature is found to be 230N and 375°C respectively with multilayer inserts
- Surface roughness is comparatively better for the titanium inserts than the multilayer inserts and surface roughness is found to drop with the rise in depth of cut. Chip thickness is found to rise with the rise in depth of cut and feed rate
- Multilayer insert has undergone huge wear for the process second and fourth experiments. Again here it proves that feed rate has played a major role in the overall process. More the feed rate more the tool wear has undergone which concludes that multilayer insert is not durable for the process and will eventually wear off early stage leading to more expensive process. On the other hand, titanium insert is hard enough to machine and does not undergo much wear off
- The specimen cut by titanium insert has more influence with respect to speed, as speed is low, higher the residual stress was observed. But the same is not true in case of specimen cut by multilayer insert where the process mainly depends on the depth of cut that creates more impact on the crystal structure
- Taguchi analysis is carried out to find the optimum conditions for which the output responses are near optimum or optimum. Confirmation experiments were conducted to validate the predicted to optimum parameters
- From Grey Relational Analysis, it is predicted that cutting speed at level 1, feed rate at level 1 and depth of cut at level 2 will give near optimum output responses for TiN Insert and cutting speed at level 1, feed rate at level 1 and depth of cut at level 1 will give near optimum output responses for multilayer-coated insert and confirmation experiments were conducted to validate the same
- From ANNOVA analysis, 65.28% of the contribution is from the process parameter of feed rate in the case of machining with TiN insert and 62.85% of the contribution is from the process parameter of the depth of cut in the case of machining with multilayer insert

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