Taguchi based Optimization of Coated and Uncoated Tool Insert for Turning Ti6Al4V using Grey Relation Analysis

R Ambigai, S Prabhu and Raj Gandhi
Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India
E-mail: ambigair@srmist.edu.in, prabhus@srmist.edu.in

Abstract. The titanium alloy Ti6Al4V has been widely used due to its high strength to weight ratio. The titanium machinability is very troublesome because of its hardness, low elastic modulus at elevated temperature and thermal conductivity, and has high chemical affinity. In this paper we have studied surface roughness, material removal rate for CNC Turning of Ti6Al4V by comparing it with two inserts, one is tungsten carbide coated having a coating of TiAlN and the other is the uncoated tungsten carbide inserts by varying the input parameters such as cutting Speed, feed rate, depth of cut (DOC). These experiments were based on Taguchi’s orthogonal array for three factor and three levels and experiments has been conducted based on L27 orthogonal array for turning operation on computer numerical control machine. Further optimization is done based on multi response optimization-Grey Relational Approach (GRA) to get the optimized parameter for the maximum Material Removal Rate (MRR) and minimum Surface Roughness (Ra). However the surface roughness of the coated insert was found to minimal than the uncoated insert in which the coating just improves the life of the cutting tool.

1. Introduction
Hard material such as titanium is the most widely used in aerospace many precise areas like body implants and hence it is necessary to have a better surface finish with a greater tool life. Specific attention is given for turning of titanium grade 5 alloys (Ti-6Al-4V) and namely the special techniques for cutting improvement, and material removal rate, surface Roughness (Ra) for Ti alloy and flank wear in cutting tools were taken into consideration. The main component of this alloy is that it has 90% of titanium, around 6% of aluminum and around 4%. The machinability of commercial titanium alloy was improved by Laser assisted Machining (LAM) and hybrid machining. It was observed that LAM and hybrid machining can yield to better surface finish and maximize the (MRR) material removal rate and even cost can be saved by 30%-40% for each process[1]. Machinability of titanium alloy Ti-6Al-4V were analysed due to its high hardness, low thermal conductivity(K) and Elastic Modulus at high temperature, and increased chemical reactivity[2]. The processing details for the chips formation, cutting improvement, cutting temperature and the machining forces acting on the tool were analysed. The machinability of titanium alloy with special methods, such as rotary cutting with the ledge tools, has shown good
The machining capability of titanium alloy namely Ti555.3 and Ti-6Al-4V were analyzed and compared for its cutting forces, chips geometry and tool wear. When machining of Ti555.3 more difficulty was observed than the machining of Ti-6Al-4V at higher cutting speeds. A correlation for the mechanical properties of work piece i.e. Ti alloy, component forces and tool wear was developed. The effect of Reed Rate (F), cutting speed (S), and depth of cut (DOC) on machining of hard turning operations were studies. The main focus of the study was on the evolution of the surface roughness (Ra) and component cutting forces on the hard turning of Tool Steel of grade AISI D3 that was cold worked with ceramic tools CC6050 and CC650. Analysis of Variance (ANOVA), the Signal-to-Noise ratio (S/N ratio) and (RSM) Response Surface Methodology were carried out. Results showed that the 1.6 times superior surface finish (Ra) was obtained by means of the ceramic coated insert CC6050 when compared with the uncoated CC650. Uncoated insert showed only positive results in reducing the machining forces.

The mechanism based on which the pattern of saw toothed chips formation on machining of Ti6Al4V were studied. For the specified cutting conditions the combination of adiabatic, primary shear band followed by the crack initiation and propagation of crack were analysed. Taguchi based L9 orthogonal array was used in the dry machining of Al/SiCp-MMC with multilayer TiN coated carbide insert. Abrasive wear was reported to be the most dominant wear. Cutting speed (S) is the most important parameter for the flank wear whereas feed rate (R) has the most influence on the surface roughness. The performance indices for the hard turning of coated ceramic tool insert were studies and machined surface were characterized for the tool nose edge wear, (Ra)surface roughness and cutting forces.

Dry turning of carbon steel grade SAE1045 with cemented carbide uncoated insert and observed that when the cutting speeds is high wear is dominant and that at low cutting speed build up edges (BUE) were visible. In the machining capability of stellite alloy with coated and uncoated carbide tools for turning that the abrasive wear and adhesive wear on the cutting tool insert was predominant for lower cutting speeds while chemical and diffusion wear dominant at high cutting speeds. The performances on turning of Ti-6AL-2Sn-4Zr-6Mo alloy at 150 bar cutting fluid using polycrystalline diamond tools were evaluated. The principle wear modals wear crater formation and work piece adhesion. No major subsurface damage on work piece assessment was observed for the compressive residual stresses of 600MPa. For hard material minimal tool wear was observed for the optimum cutting speeds.

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Taguchi’s based orthogonal array was selected so as to minimize the experiment that needs to be conducted. The optimal cutting condition for getting the minimal tool wear at high cutting speed, minimal (Ra) Surface Roughness for medium depth of cut (DOC) and at low feed rate (R) and least flow of high velocity cutting fluid from the designed levels. Taguchi method was adopted to obtain the optimal (Ra) Surface Roughness on machining of Ti alloy by continuous turning using nano coated carbide inserts. It was observed using analysis of variance the factor that mostly influences the (Ra)surface roughness is (F)Feed Rate than the cutting speed after which the nose radius and then the depth of cut. The chip formation were analysed using SEM for various cutting parameters. For ball burnishing process of Ti-6Al-4V the parameter such as burnishing feed, speed, force & the no. of passes were varied to obtain minimal surface roughness (Ra) and maximize the hardness. The experiments were designed as per the L25 orthogonal array and the optimization of the result as done based on the signal to noise ratio. Grey Relational Approach (GRA) was used for multi-response optimization of electrical process parameter in Electrical Discharge Machining (EDM). The process parameter such as peak current (I), gap voltage (V)
and duty factor were selected and the most influencing electric process parameter was peak current for the (EDM) electric discharge machining process [17]. Not much work has been reported on the (Ra) surface roughness and (MRR) material removal rate of titanium alloy and being turned with two different insert. Hence, this paper emphasizes on the comparison of two cutting tool insert and finding the optimal value using grey relation approach for the factors such feed rate (R), depth of cut (DOE) and speed (S) and keeping the nose radius constant.

2. Experimental Materials & Methods
The work piece material chosen for the machining is a titanium alloy (Ti6Al4V) having diameter and length of 50mm and 600mm respectively. The various elements and its composition of the material was found using x-ray fluorescence test and are given in Table 1 and the mechanical properties are shown in Table 2.

| Table 1. Elemental composition of Titanium Alloy. |
|----------------------------------|
| Ti     | Cr  | Al  | V    | Fe  | Si  |
| 88.8   | 0.16| 6.06| 4.00 | 0.39| 0.38|

| Table 2. Mechanical Properties of Titanium Alloy. |
|----------------------------------|
| Density                         | 4420 kg/m³ |
| Melting point                   | 1650°C     |
| Coefficient of expansion        | 9 µm/m°C   |
| Hardness (HV20)                 | 600        |
| Modulus of elasticity           | 116 GPa    |

2.1. Cutting Tool Insert
The different set of dry turning experiment is performed using coated and uncoated tungsten carbide inserts. The cutting tool for turning uses uncoated tungsten carbide insert, the standard specification are CNMG 12 04 04 H13A SF and coated tungsten carbide insert, the standard specification are CNMG 12 04 04 GC1105 SF having a coating of TiAlN around 5 microns.

Figure 1. TiAlN Coated tool insert and CNC turning tool holder.
2.2. Experimental Procedure

The experiments were performed in CNC turning lathe and the setup is shown in figure 2. The experiments for machining of titanium alloy were designed based on Taguchi method for optimizing the cutting parameters. This is one of the efficient and attractive methods to deal with responses obtained that is influenced by various input process variables. Main parameters that influence the process results are located at different rows in the designed orthogonal array (L\textsubscript{27}). This method is used for analysing the interaction between the parameters. It is one of the powerful design tool used to determine the optimum cutting parameter in a systematic, simplified, efficient and way.

2.3. Details of Experiments

The experiments were performed for 3 factors and 3 levels and is given in table 3 were fixed for both the coated and the uncoated insert. i.e. 27 experiments using coated insert and 27 experiment using uncoated insert. These experiments were done on CNC turning machine. The levels were chosen based on the CNC Turning machine capability. The experiments were carried out in dry machining condition and the chips were collected to investigate and study the effect of machining parameters. The morphological investigation of the tool wear was carried out using optical microscope.

| Parameters         | Level -1 | Level -2 | Level -3 |
|--------------------|----------|----------|----------|
| Speed – S (m/min)  | 35       | 50       | 65       |
| Feed Rate –R (mm/rev) | 0.05     | 0.1      | 0.15     |
| Depth Of Cut – DOC (mm) | 0.5      | 1.0      | 1.5      |

The stylus type instrument is used to quantify the machined surface waviness of the surface of titanium alloy. Surfcom surface roughness tester was used to evaluate the surface roughness and Olympus make Optical microscope was used to study the microstructure of the specimen. Kroll’s Reagent was as etchant and figure 3 shows the microstructure of the titanium Alloy. FIE make Vickers hardness tester was used to find the hardness of the specimen and was found to be Hv380.
3. Results and Discussion

3.1. Effect of Coated tool insert

In Taguchi method desired value is represented by the term “signal” and the undesired value is represented by the term “noise”. The S/N ratio is the measure of performance used to develop products and process insensitive to disturbance i.e. noise factors. The quality characteristics considered in this investigation is smaller-is-better. The S/N ratio is obtained based on the formulae, \(S/N = -10\log\left[\frac{1}{n} \sum Y_i^2\right]\) where ‘n’ represents the no. of replication for every experiment and \(Y_i\) represents the response value. The degree of performance of the process or product in the presence of noise factors is indicated as S/N. The surface roughness-Ra observed at least speed is better than the surface roughness-Ra obtained at high cutting speed for both the coated and uncoated insert. Based on the experimental results it can be inferred that minimal effect on the surface roughness(Ra) is due to the speed of cutting and DOC-Depth of Cut. Contrary to Cutting Speed(S) and Depth of Cut(DOC), the Feed Rate(R) plays the vital role in the surface roughness-Ra and the material removal rate that is in both the insert the minimal surface roughness was observed at lower cutting speed. Thus it is a fact that as the feed rate increases there is heat generation and wearing of tool is witnessed in the tool inserts leading to higher roughness. The chatter wear, notch wear and flank wear were observed more when machined with the uncoated tool insert and with the coating of the TiAlN the coated insert only plays a role to increase the tool life but does not give a better surface roughness. The surface roughness of the titanium alloy when machined using coated insert is compared by taking feed rate as constant and is compared with the other factors like depth of cut(DOC) and the cutting speed(S). Figure 4 shows the variation of Surface Roughness(Ra) because of the diffusion of Ti on the insert was observed and this may be due to the high chemical affinity of the titanium alloy to tungsten. The image shown figure 6 for tool insert there is no heat affected region as the coating plays the role to protect the tool. Optical Microscope was used to find the tool wear and very less flanks were also observed for the coated insert and the images were taken at 100X. The material removal rate increases as the depth of cut(DOC) and cutting speed(S) increases by keeping constant feed rate(R) and the same can be observed from the figure 5. When the cutting depth is least, speed of cutting and the feed rate(R) has the minimal material removal rate.
Figure 4. Effect of Surface Waviness with Feed, Depth of Cut (DOC) and Speed for Coated Insert.

Figure 5. Effect of Material Removal Rate (MRR) with Feed, DOC and Speed for Coated Insert.
3.2. Effect of uncoated Tool insert

Figure 7 shows that for constant feed rate (R), the Surface Roughness (Ra) increases for both the factors depth of cut (DOC) and cutting speed (S). As the feed rate increases there are lots of tool wear observed due to which the surface roughness is more for the machined Titanium alloy. The thermal effect and flank wear for the feed level 3 i.e. 0.15mm/rev, depth of cut level 3 i.e. 1.5mm and cutting speed level 2 i.e. 50m/min was observed for the uncoated tool insert and is as shown in figure 9. These images were captured at 100X in optical microscope. Figure 8 shows that for constant feed rate (R), the continuous increase in the Material Removal Rate (MRR) was observed with increasing depth of cut (DOC) and cutting speed (S). On machining Titanium alloy with uncoated inserts lots of heat is generated which in turn enhances the Material Removal Rate (MRR). Whereas for coated insert the coating acts as heat bearing member and protects the tool enhancing the tool life. The same can be inferred for the optical microscope images obtained which shows more heat affected region and there is more diffusion of Ti alloy to the tool. Since lots of heat of heat is generated local plasticity take place enhancing the surface finish of the titanium alloy.

Figure 6. Tool Wear on Uncoated and Coated Insert.

Figure 7. Effect of Surface Waviness with Feed, Depth of Cut (DOC) & Speed (S) for Uncoated Insert.
Figure 8. Effect of MRR with Feed, Depth of Cut (DOC) and Speed (S) for Uncoated Insert.

Figure 9. Tool Wear on the Uncoated Insert

The chips obtained during machining are shown in the figure 10 and these images were captured at 100X using optical microscope. The chips were chosen for the feed-level 3 i.e. 0.15m/rev and for the cutting speed-level 1 i.e. 35m/min and for varying depth of cut (DOC) of 0.5mm to 1.5mm with an increment of 0.5mm.
3.3. Grey Relation analysis

In the present study there are 3 input parameters and 2 output parameters, there should be one optimal machining parameter to get better output parameter i.e. Good surface finish and maximize material removal rate. To get can optimal value, multi response optimization grey relational approach was carried out to identify the optimal depth of cut(DOC), feed rate(R) and cutting speed(S) for both coated insert and the uncoated insert.  Signal to Noise ratio obtained has to be normalized in the range of 0 to 1. The normalization can be done using the following formula:

For larger the better MRR,

\[ x_{ij} = \frac{(y_{ij} - \min(y_{ij}))}{(\max(y_{ij}) - \min(y_{ij}))} \] (1)

For smaller the better Surface roughness,

\[ x_{ij} = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \] (2)

Then Grey relation co-efficient has to calculated from the least and the highest absolute difference which is the deviation from the target value. By averaging the grey relation coefficient Grey relation Grade can be calculated and ranking can be given and higher the grey relation grade better the multi response characteristics. The GRA for coated and uncoated tool insert are shown in table 4 and 5. The Hence experiment 7 has the optimal conditions for getting maximum MRR and good surface finish for both the coated and uncoated inert.
Table 4. Grey relation analysis for the coated insert.

| TRIAL | S/N Ra   | S/N MRR  | Normalized S/N Ra | Normalized S/N MRR | GC Ra | GC MRR | Grade | Rank |
|-------|----------|----------|-------------------|--------------------|-------|--------|-------|------|
| 1     | 8.355794 | 28.3338  | 0.1168592         | 0.765447927        | 6     | 0.680687| 0.52109| 6    |
| 4     | 2.676441 | 24.4003  | 0.5298358         | 0.1168592          | 7     | 0.75768 |       | 3    |
| 7     | -3.78937 | 24.8821  | 0.9712679         | 0.9712679          | 1     | 0.945658| 0.97282| 1    |
| 10    | 9.962867 | 30.9775  | 0.607808325       | 0.365208325        | 1     | 0.560418| 0.44687| 9    |
| 13    | 1.616119 | 26.8029  | 0.856734731       | 0.9597634731       | 1     | 0.777284| 0.66857| 5    |
| 16    | -3.18634 | 27.916   | 0.790365379       | 0.790365379        | 1     | 0.704588| 0.81198| 2    |
| 19    | -0.26501 | 41.1708  | 0.7437246         | 0.7437246          | 1     | 0.442626| 0.49723| 7    |
| 22    | 1.82498  | 36.3953  | 0.284759225       | 0.284759225        | 1     | 0.411441| 0.48098| 8    |
| 25    | -3.48578 | 34.9594  | 0.370379015       | 0.370379015        | 1     | 0.442626| 0.70017| 4    |

The total mean grey relational grade for coated cutting tool insert is 0.650826 and the optimal parameters according to grey relational approach are Depth of Cut(DOC)-1.5mm, Feed Rate(R)-0.15mm/rev and Cutting Speed(S) 35m/min. The total mean (GRG)-Grey Relational Grade for uncoated insert is 0.593097 and the optimized parameters according to grey relational approach are Depth of cut(DOC)-1.5mm, Feed Rate(R)-0.15mm/rev and Cutting Speed(S)-35m/min for the coated tungsten carbide insert. Based on the optimal value confirmation test was carried out to validate the machining. The
confirmation test and experiment was conducted for the optimal process parameters. At the optimal settings the response values for coated insert, surface roughness is 1.666µm and material removal rate 0.0595cm³/sec and the grey relational grade value 0.6412018. The Grey Relational Grade(GRA) value was improved by 1.47% from the predicted mean value. The response values for uncoated insert are surface roughness is 1.4118µm and material removal rate 0.0538cm³/second the grey relational grade value 0.59610497. The Grey Relational Grade(GRA) value was improved by 0.51% from the predicted mean value. This shows that the optimal parameters given by the Grey relation analysis give optimal output.

4. Conclusion

The Surface Roughness(Ra) and the Material Removal Rate(MRR) in the turning process of Titanium grade 5 alloys under different cutting condition using coated and uncoated tungsten carbide insert has been investigated based on Taguchi(L27) orthogonal array and using grey relational approach the machining parameters were optimized.

1. The better Surface Roughness was observed when the experiment was conducted using the Tungsten Carbide uncoated insert in comparison to that of the Coated Tungsten Carbide insert.
2. Further it can be stated that the crater wear, flank wear, and notch wear was observed to be much lesser for Coated Tungsten Carbide insert when compared with that of uncoated Tungsten carbide insert.
3. The heat effect zone in case of Coated Tungsten carbide insert is much less due to higher thermal conductivity of Titanium Aluminum Nitride Coating therefore the coating plays a vital role in increasing tool life.
4. The surface roughness for coated tungsten carbide insert for optimized parameter was observed to be 15.18% less as compared to the uncoated tungsten carbide insert.
5. The Material Removal Rate for coated tungsten carbide insert for optimized parameter was observed to be 3.74% less as compared to the uncoated tungsten carbide insert.
6. The Machining Time for coated tungsten carbide insert for optimized parameter was observed to be 5.88% less as compared to the uncoated tungsten carbide insert.

5. References

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