Machinability studies of austenitic stainless steel (AISI 304) using PVD cathodic arc evaporation (CAE) system deposited AlCrN/TiAlN coated carbide inserts

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Abstract

The focus of the paper is on green machining, the environmentally friendly manufacturing (dry machining) which is ecologically desirable and cost effective. The “Cathodic Arc Evaporation Technique (CAE)” is used for depositing AlCrN/TiAlN coating used for dry, high speed turning of AISI 304 austenitic stainless steel. The effect of machining parameters on the cutting force, cutting temperature and surface finish were investigated during the experimentation. It is found that, as feed increases, the radial force increases therefore more friction exists between newly generated surface and the flank face so surface roughness increases. Tool-chip interface temperature increases with increase in cutting speed and it is higher because of low thermal conductivity of the coating as well as AISI 304 work material and AlCrN/TiAlN coating. Thermal stability of the AlCrN/TiAlN coating is good therefore it withstands the high temperature and gives better performance especially in case of dry turning and it also helps in reduction in cutting forces.

The present approach and results will be helpful for understanding the machinability of AISI 304 steel during dry, high speed turning for the manufacturing engineers.

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Keywords: AISI 304, AlCrN/TiAlN coating, CAE, Dry Machining, Adhesion

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1. Introduction

High-speed machining (HSM) is gaining popularity in industry in recent years due to the capability in improving machining performance, reducing cost while achieving reduced lead times, and higher productivity [1]. However, the demand for high quality focuses attention on the surface condition and the quality of the product.

### Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| $R_a$  | Average Surface roughness ($\mu$m) |
| $V_c$  | Cutting speed (m/min)         |
| AISI   | American Iron and Steel Institute |
| ISO    | International Organization of standards |
| CBN    | Cubic Boron Nitride          |

especially the roughness of the machined surface because of its effect on product appearance, function, and reliability. In addition, a good quality machined surface significantly improves fatigue strength, corrosion resistance, and creep life. Dry machining is cost effective and ecologically desirable machining.

The most commonly techniques available for surface modification of the cutting tool substrate are Chemical Vapor Deposition and Physical Vapor Deposition [2]. In the recent years, PVD technology is being preferred to CVD due to the lower process temperature and environment friendly aspect. Titanium nitride (TiN) has been widely used as protective hard coatings for cutting tools [2] where as chromium nitride (CrN) has been successfully applied to the moulding dies, wear components, and cutting tools as well [3]. CrN is known to be superior to TiN in corrosion and wear resistance, friction behavior, and toughness [4]. However, the oxidation resistance of TiN and CrN is limited up to 500 °C and 600 °C respectively [5]. For hard protective coatings, thermal stability is very important because they are exposed to high temperatures during the cutting process. In recent times, various alloying elements such Ti, Si, Al, B, and C have been added into the binary coatings in order to further improve various properties of the coatings [6]. Among these ternary systems, (Ti, Al)N and (Al, Cr)N films showed improved oxidation-resistance up to 900 °C. It is due to the formation of stable oxidation barrier of Al$_2$O$_3$, Cr$_2$O$_3$, and TiO$_2$ layer. It has been reported that (Ti, Al)N films has better abrasive wear resistance whereas (Al, Cr)N films are more thermally stable [7, 8]. Hardness, coefficient of friction, oxidation resistance, chemical stability, and adhesion of the coating play an important role in case of “difficult to cut material” machining in dry environment, whereas toughness, high thermal conductivity of the substrate is desirable to avoid chattering and thermal diffusion.

Austenitic stainless steel is amongst the “difficult to cut material” and the difficulties such as poor surface finish and high tool wear are common.

Ihsan Korkut and Ibrahim Ciftci et al. [9-10,11], reported that during turning of AISI 304 austenitic stainless steel using multilayer (CVD) coated tool, tool flank wear decreases with increasing the cutting speed up to 180 m/min and surface roughness values decreases with increasing the cutting speed. Also, chip curl radii decreases and chip thickness increases in low speed and high speed respectively. As cutting speed increases built up edge decreases with decrease in feed. Zafer Tekiner et al [12], carried out Similar studies and they found that tool chip contact length decreases with the increase of the cutting speed and cutting forces generally decreased with the increase of cutting speed up to certain speed and afterwards it increases in turning [14]. Grzesik et al. [13-14], studied machinability of AISI 304 and C45 steel using CVD TiC, TiN/ TiC and TiN/Al$_2$O$_3$/TiC coated and uncoated (P20) cemented carbide tools used. They found that, in case of TiC and TiN/Al$_2$O$_3$/TiC coating specific cutting pressure decreases and TiC/TiN coating it increases. In another study, they found low value of surface roughness for coating TiC/Al$_2$O$_3$/TiN. In addition, they found that as the cutting speed increases cutting force and contact length decreases.

Temperature measurement in machining is important as the cutting temperature is the key parameter in machining which directly affects the machining efficiency. However, very few researchers have focused on temperature measurement during machining by using tool-work thermocouple method for coated tools. The important methods to predict the cutting temperature during machining (tool-work thermocouple, embedded thermocouple, thin film thermocouple, metallographic method, and thermal radiation method) have been reviewed by Komanduri [15].
Grzesik [13] carried out cutting tests to determine the cutting temperature by using tool-work thermocouple method and found that the average tool–chip interface temperature and the fraction of heat transferred into the tool/chip are influenced by the thermal properties of the work material and the coating.

O’Sullivan et al [16] investigated cutting temperature for six different types of steels by using tool-work thermocouple method and noticed that the variations in temperature were similar for all six materials, and the higher temperature was associated with the finer feeds and lower temperature was associated with the coarse feeds. Embedded thermocouple method is one of the earliest methods, which is used for the estimation of temperatures in various manufacturing and tribological applications.

A good deal of literature on the binary, tertiary nitride coated cutting tools produced by variety of coating techniques is available. In spite of it only (Ti, Al)N and AlCrN tertiary coating shows commercial success in wet environment.

In the present context of sustainable manufacturing, machining of AISI 304 with coated carbide tools have become an economical alternative to costly CBN and ceramic tool material. However, dry machining of AISI 304 puts some restriction on cutting conditions to have the better tool life, dimensional accuracy and surface finish. Therefore, development of the new coating produced by novel coating technique is essential which will serve in extremely hostile environment with good performance. Although, the quaternary coating AlCrN/ TiAlN coating produced by CAE shows excellent properties but it has never been used for machining of AISI 304 in dry environment. Considering all the above facts, the present work aims to study the influence of different machining parameters on the machinability characteristics using AlCrN/ TiAlN hard coating deposited with CAE technique on cemented carbide tools.

2. Experimental Details

The performance of the AlCrN/ TiAlN coated inserts was evaluated in dry turning of AISI 304 austenitic stainless steel. The chemical composition of the work material is shown in Table 1. The length of the material was 300 mm and diameter 90 mm. ACE CNC LATHE JOBBER XL was used for conducting the machining trials. This had continuously variable spindle speed of up to 5000 rpm with maximum power rating of 7.5 KW.

| Table 1 Chemical compositions of the workpiece materials |
|-----------------------------------------------|---------------------------------|------------------|
| CAE Coating | Insert (Substrate) | |
| Composition | AlCrN/ TiAlN | Grade | Grade | |
| Thermal Stability (°C) | 1100 | Thermal Stability °C | 500 |
| Microhardness HV (0.05) | 3500 | Thermal Stability (HRA) | 92.1 |
| Surface Roughness (μm) | 0.3 | T.R.S (Gpa) | 2.06 |
| Coating Thickness (μm) | 4.2 | Thermal conductivity (W/mk) | 85 |

2. Result and Discussion

3.1 Surface Roughness

Surface quality of the machined workpiece surface is dependent on mainly cutting conditions used and it plays vital role in functioning and fatigue life of the component. Fig. 1 shows the graphical representation of surface roughness against the cutting speed and feed. The surface roughness (Ra) is found to be low at high cutting speed because at higher speed continuous chips without built-up edge was obtained which results in improvement of surface finish. Also, The AlCrN/ TiAlN coating demonstrate better thermal stability and chemical inertness at elevated temperature which prevents the formation of built- up edge. Also, it is clearly seen from the experimental values that surface roughness increases with increase in feed which is in line with the classical theory of metal
machining. Also, increase in feed friction between workpiece and tool interface increases, which eventually increases the temperature in the cutting zone. Hence, the shear strength of the material reduces and the material behaves ductile fashion and AISI 304 is sticky in nature, which makes the chips to detach from the workpiece difficult, thereby increasing the surface roughness. In addition, as feed increases, the radial force increases therefore more friction exists between newly generated surface and the flank face so surface roughness increases.

![Variation of Surface roughness with Cutting Speed and Feed at constant depth of cut of 1 mm](image)

Fig. 1. Variation of Surface roughness with (a) Cutting Speed (b) Feed at constant depth of cut of 1 mm

3.2 Cutting Force

In turning operation three force components exists, that are cutting force, feed force and radial force. The cutting force acts along the direction of cutting speed (tangential to turned surface). This is major component of force. The feed force acts along the direction of the tool feed where as radial force acts perpendicular to the turned surface. Cutting force and feed force plays major role in determining the machinability hence, these are discussed. Fig. 2 shows the variation of cutting force and feed force with cutting speed and feed for a constant depth of cut of 1 mm. It indicates that the cutting force component is higher in magnitude than feed force component.

At low cutting speed, the forces are found to be higher. This is because the chip remains for long time in the rake face of the tool and which increases the tool-chip contact length. Thus, it increases the friction between the tool and chip that resulted in higher forces. On the other hand, while turning at higher cutting speed, the temperature generation rate is high which makes the material soft at cutting zone. This helps in removing the material at lower cutting forces. Hence, machining of AISI 304 work material is advisable at higher cutting speed due to this reason. As, the thermal conductivity of the material is very low therefore the heat generated during turning is carried away by the chips. However, the hot hardness and thermal stability of the AlCrN/TiAlN coating is excellent hence, it retains on the tool, which further helps maintain in the temperature and lowering the cutting
force. In addition, the cutting speed increases, the chip gets thinner and forces drops. Therefore, decrease in both cutting force and feed force is due to decrease in contact area and partly by drop in shear strength in the flow zone as the temperature increases with increase in speed. As feed increases the tool wear and temperature in machining increases, therefore the nature of cutting force seems to be increasing. The cutting force seems to be good in the feed of 0.17 mm/rev for all cutting speed.

![Fig. 2 Influence of cutting speed on (a) cutting force and (b) feed force at constant depth of cut 0.75 mm.](image)

### 3.3 Average chip-tool interface Temperature

The cutting temperature during metal cutting processes has been recognized as one of major factors influencing the tool performance and workpiece geometry accuracy. Experiments were conducted at cutting speed, feed and Depth of cut as given in the Table 4. Cutting temperature for the work-tool material combinations (SS304 and AlCrN/ TiAlN Coated insert) was measured by using tool-work thermocouple technique. Schematic experimental set-up is shown in Fig. 4. For each cutting test thermo-electric e.m.f. was measured. The variation of chip-tool interface temperature with cutting speed and feed are shown in Fig. 3. It is seen that the interface temperature increases with the increase in cutting parameters and is higher because of low thermal conductivity of the coating as well as AISI 304 work material and AlCrN/ TiAlN coating. In addition, Shear energy and the frictional energy are directly proportional to the shear velocity and chip velocity respectively. Therefore, increase in the cutting speed reflects straight into the increase in the energy and the temperature. It is clear from the figures that the average tool-chip interface temperature increases with the increase in the feed [17].

At constant cutting speed, with the increase in the feed, material removal rate increases and amount of energy required for shearing also increases and results in more heat formation and finally the cutting temperature [8,17]. In the present combination of work and tool material; the majority of the heat goes along with the chips at constant cutting speed, with the increase in the feed, material removal rate increases and amount of energy required for shearing also increases and results in more heat formation and finally the cutting temperature [8,17]. In the
present combination of work and tool material; the majority of the heat goes along with the chip, which really helps in improving the performance of the tool.

Fig. 3 Variation of Interface Temperature (Experimental) with (a) Cutting Speed (b) Feed at constant depth of cut of 1 mm

Fig. 4. (a) Schematic experimental set-up (b) Experimental set-up
3.4 Regression Modeling

Only performing the experimentation and to obtain the result is not only the objective of this study. The research work findings should also provide useful information and economic machining solution in case of dry, high speed turning of AISI 304 steel. It should also be beneficial for the manufacturing industry and the environment as well. It is done through developing the imperial relation and finding the values of the constant from the experimental results. Many researchers have contributed to the field of machining by developed various relation dedicated for the specific work material and cutting parameters. Some researchers have developed some relations, which are suitable for different material, and cutting conditions e.g. Taylor’s tool life equation and modified tool life equation. The power law based models have proven its significance in the machining. Hence, the power law was used to develop regression models and it is given below:

\[ Y = a V^b f^c \]

where, \( Y \) - response (Surface roughness, Force, Flank Wear, Interface temperature), \( V \) - cutting speed (m/min), \( f \) – feed (mm/rev) and \( a, b, c \) are the constants.

The unknown coefficients were found out using Data Fit software. It uses the following logic for determined the over-determined matrix into the square matrix as described below:

\[ \log Y = \log a + b \log V + c \log f \]

Rearranging the terms,

\[ \begin{bmatrix} \log Y \end{bmatrix} = \begin{bmatrix} \log a & b & c \end{bmatrix} \begin{bmatrix} 1 & \log V & \log f \end{bmatrix}^T \]

writing as,

\[ B = XA \]

\[ X = (A^T A)^{-1}. (A^T B) \]

The value of constant obtained after regression analysis for the different parameters are given in Table 2.

| Sr. No | Parameter          | a     | b     | c     | \( R^2 \) |
|--------|--------------------|-------|-------|-------|-----------|
| 1      | Surface roughness  | 55.73 | -0.37 | 0.71  | 0.98      |
| 2      | Cutting force      | 6771.6| -0.30 | 0.56  | 0.98      |
| 3      | Flank Wear         | 0.43  | 1.06  | 0.27  | 0.97      |
| 4      | Interface temperature | 266  | 0.26  | 0.12  | 0.95      |

The R-squared values of the parameters are given in Table 4, it indicates that the developed models can be used to predict the tool life during turning of AISI 304 steel. However, these equations are valid for flank wear value lower than 0.15 mm and in the feed range of 0.08-0.3 mm/rev, cutting speed in the range of 140-320 m/min for constant depth of cut 1mm.

4. Conclusion

In the machining of AISI 304 austenitic stainless steel using CAE deposited AlCrN/ TiAlN coating tool, important relationship has been observed among the cutting parameters, surface roughness, cutting force and interface temperature. Following conclusions can be drawn from this study:

- With increasing cutting feed, surface roughness values increases whereas as it decreases with cutting speed.
- AlCrN/TiAlN coated cutting tools gave lower cutting forces due to the lower friction coefficient of the coating.
- Tool-chip interface temperature increases with increase in cutting speed and it is higher because of low thermal conductivity of the coating as well as AISI 304 work material and AlCrN/TiAlN coating. Thermal stability of the AlCrN/TiAlN coating is good therefore it withstands the high temperature and gives better performance especially in case of dry turning and it also helps in reduction in cutting forces.
- The developed regression models for different response parameter shows excellent fit and predicted results are very close to the experimental results. It also showed that the developed models are reliable and could be used effectively for predicting the surface roughness, interface temperature and cutting force for the given tool and work material pair and within the domain of the cutting parameters.
• From this study, it is concluded that AlCrN/TiAlN coating produced by CAE technique can be the prominent coating for machining of austenitic stainless steel in today’s demand of Green machining.

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