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Influence of Tool Coatings on Distortion of 2014A T651 Aluminum Alloy during Machining

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ABSTRACT: This paper investigates the influence of coated and uncoated H.S.S and Carbide endmills on machining induced distortion in milling thin-wall, thin-floor components. The endmills are coated with Titanium Nitride (TiN), Titanium Aluminum Nitride (TiAlN), and Diamond like Carbon (DLC). The effect of each of the coated H.S.S and carbide end mills is studied by calculating residual stresses using indentation method. The present article also suggests the optimum coating and the tool material for minimizing distortion. Results show that coatings on the tool has significant effect on the residual stress distribution and distortion of components. It is also observed that machining induced stresses by using DLC coating are minimum leading to minimum distortion.

KEYWORDS: Machining, Distortion, Residual stress, Indentation Method, Aluminum Alloy, TiN, TiAlN, DLC, H.S.S, Carbide.

I. INTRODUCTION

Dimensional and form accuracy of machined component in aerospace industry is one of the challenging tasks for manufacturer. In the aerospace industry, machining process is widely used for fabrication of monolithic component that contains a thin-walled structure. Stresses and part distortion have a major cost impact in many machining applications since they can affect scrap rates and processing times. For example, in Avionic monolithic components they may produce distortions which hamper assembly operations. Stresses in machined parts could be either bulk residual stresses from primary processes such as rolling or forging or the stresses induced by the machining process, which are a result from differential plastic deformation and surface temperature gradients [1]. During machining, the cutting forces create thermal and mechanical stresses causing deflection to the thin-wall section, leading to dimensional form errors. Most of the existing research for machining thin-wall component and its correlation to distortion, concentrated on the process parameters (speed, feed, depth of cut, width of cut, material removal rate, volume of material removal, type of cutting fluid, tool path layout, etc) [2,3,4,5] and tool parameters (axial and radial rake angles, helix angle, gash angle, dish angle and clearance angles)[6,7,8,9,10]. The effects of coatings on the tool are often neglected. Coating on the cutting tool has a direct influence on the cutting performance and stress induced and hence should not be neglected in the machining consideration.

High Speed Steel is a high carbon tool steel, containing a large dose of tungsten. A typical HSS composition is 18% tungsten, 4% Chromium, 1% Vanadium, 0.7% carbon and the rest, Iron. HSS tools have a hardness of 62-64 Rc. The addition of 5 to 8% cobalt to HSS imparts higher strength and wear resistance. The advantage of HSS over carbide is its strength to withstand cutting forces and the low cost of the tools. From the tool life point of view, HSS performs very well at intermittent cutting applications. But the greatest limitation of HSS is that its usable cutting speed range is far lower when compared to Carbide. For enhancement in productivity, carbide tools are generally preferred to H.S.S tools in machining. Carbides have high hardness over a wide range of temperatures, high thermal conductivity, high Young's

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modulus making them effective tool and die materials for a range of applications. But higher feed rates and higher material removal rate with an objective to enhance productivity can probably have a negative influence on induced machining stresses and distortion. The major challenge in machining aluminum is chip material adhering to the tool, leading to surface quality deterioration and tool wear. Adhesion of aluminum to the tool creates a built up edge (BUE) at lower cutting speed and built up layer (BUL) at higher cutting speed. Adhesion takes place at wider range of temperature. Material adhesion is a combined effect of work and tool materials, feed rate, rake angle and lubrication [11]. It was found that material adhesion is a major wear mechanism of carbide tools at lower cutting speed while machining aluminum [12]. The absence of lubrication increases the friction and temperature thereby accelerates the material adhesion [13]. Lubricity has a greater impact than thermal dissipation in reducing the machining induced residual stresses at lower cutting speed [4]. Initiation, growth and breaking phases of the adhered material on the cutting tool alter the geometry of the tool continuously. This variation of geometry leads to fluctuation of cutting force and variation in surface generated in the work piece. The nitride, carbide based transition metals and layered MoS_2 coated tools were reported as susceptible to BUE under dry machining and at relatively low cutting speeds [14]. The right surface treatment on the tools can increase overall life of the tool, decrease cycle time and promote better surface finishes on the work piece. Selecting the correct coating on the tool material and its attributes can mean the difference between a successful operation and one that shows little to no difference. The desirable properties of a coated tool during machining are a) Hardness b) Abrasive resistance c) Surface Lubricity d) Oxidation temperature and e) Anti seizure, which in turn increase in Tool life and enhancement in productivity. The commonly used tool materials in machining aluminum are H.S.S and Carbide. The commonly used coatings on tools are TiN(Titanium Nitride), TiAlN(Titanium Aluminum Nitride), Titanium Carbo-Nitride(TiCN), Chromium Nitride (CrN) and DLC(Diamond like Carbon) of which only TiN, TiAlN, and DLC are considered in this article.

Titanium Nitride (TiN) coating increases hardness and has a high oxidation temperature. The addition of carbon in Titanium Carbo-Nitride (TiCN) adds more hardness and better surface lubricity. A formed layer of aluminum oxide in Titanium Aluminum Nitride (TiAlN) gives this tool better life in high heat applications. Chromium Nitride (CrN) has anti-seizure properties and coating makes it preferred coating in situations where BUE is common. Each of the above coatings has a specific characteristic which suits to the specific requirement for reducing the machining induced residual stresses. DLC has a combination of properties of the above coatings and possibly is a promising solution to reduce machining induced residual stresses and in turn distortion. DLC increases hardness, has low coefficient of friction and aids in good lubricity, has excellent thermal and electrical conductivity properties. DLC is the amorphous carbon coating containing a combination of sp^2 and sp^3 bonds. DLC can be further divided into hydrogenated and non-hydrogenated one. The performance of hydrogenated and non-hydrogenated were not similar in all environments. It is concluded that hydrogenated DLC exhibits good tribological performance under dry environment whereas non-hydrogenated performed better in oil and water environments [15]. This article confines to influence of coated HSS and carbide cutting tools on machining induced residual stresses leading to distortion of the component. The objective of this article is to evaluate the combination of tool material and tool coating which minimizes distortion of 2014A T651 aluminum alloy material during machining.

II. EXPERIMENTAL PROCEDURE

Materials and equipment:

The work piece material used is aluminum alloy 2014A T651 rolled plate. This material is used in manufacture of avionics components, as it has high strength to weight ratio, better thermal and electrical conductivity when compared to other grades of aluminum alloys. The chemical and mechanical properties of the material under study are mentioned in Table1 and Table2 respectively [16].

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Table 1: Chemical composition of aluminum alloy 2014A T651

| Element | Al | Si | Fe | Cu | Mn | Mg |
|----------|-----|-----------|----------|---------|---------|---------|
| Weight % | Rem | 0.50-0.90 | 0.50 max | 3.9-5.0 | 0.4-1.2 | 0.2-0.8 |

Table2: Mechanical Properties of 2014A T651

| Property | Temper | Yield strength | Tensile strength | Shear Yield Strength | Hardness Rockwell | Density | Poisson's Ratio |
|----------|---------|----------------|------------------|----------------------|-------------------|-----------|-----------------|
| Value | T6 Clad | 380 Mpa | 420 Mpa | 290 Mpa | B 82 | 2.80 g/cc | 0.33 |

The work pieces are held in the shop made vacuum fixture connected to the WITTIE vacuum pump and machining is done on DECKEL FP4A CNC machine. The mineral oil (SERVOCUT 945) is used as the cutting fluid and pocket out tool path is used as machining layout as the machining induced stresses are minimum with the above [4],[5].The machining is done with various coated H.S.S and Carbide end mills but with fixed tool configuration as shown in Table 3.The end mill configuration used generates the minimum machining induced stresses at low to medium cutting speeds [10]. The indents on the work piece are made with the indenter having an included angle of 120°. The measurements are accurately taken with optical measuring equipment Baty Vision Systems - Venture VI-3030 CNC (Figure 1), which has a resolution of 0.5 micron and 40 X magnification. The images of the surface texture of the coated tools are taken by Hitachi S-3700N scanning electron microscope (Figure 2).



Figure 1: Baty Vision System-
Venture VI-3030 CNC



Figure 2: Hitachi S-3700
Scanning Electron Microscope

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Table3: configuration of the End mill used

| Number of flutes | Helix angle(α) | Radial rake angle(β) | Axial Rake angle(γ) | Gash angle(θ) |
|------------------|-------------------------|------------------------------|------------------------------|------------------------|
| 2 | 30 deg | 8 deg | 4 deg | 35 deg |

III. EXPERIMENTAL WORK

The dimensions of the samples taken are 5mm x 80mm x 200 mm. Prior to machining, the samples are stress relieved to a temperature of 200°C for 2 hrs so as to ensure that the bulk residual stresses are made minimum. Most of the parts in avionic components are designed to have a base thickness of 1.5mm to 2.0 mm hence the final thickness of the experimental work piece after machining is taken as 1.5 mm. The material is machined from 5mm thick to 1.5 mm thick with different combination of coated and uncoated HSS and carbide end mills using neat oil (mineral oil SERVOCUT 945) as the cutting oil and Pocket out as tool path layout. Without removing the work piece from the fixture the indents are made at a pitch of 30mm along X axis (lengthier side) and at a pitch of 40mm along Y axis (shorter side) as shown in Figure 3.

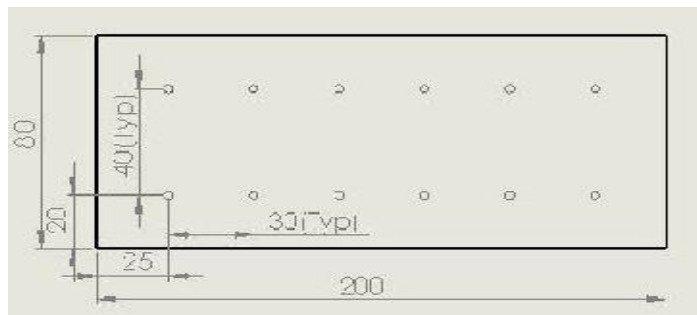


Figure 3: Work piece and indents dimensions

After removal of the work piece from the fixture the shape deviations are measured. The reasons for the shape deviation dominances found are explored by measuring the induced stresses and strains of the work piece during the machining process.

IV. CALCULATION OF STRAIN AND STRESS

The collinear distance between the coordinates of the indents before and after re-equilibration of machining induced stresses are accurately measured. For each of the intended indent it is possible to determine normal components of the residual strain in three directions (ϵ_x , ϵ_y and ϵ_d). Two of these (corresponding to ϵ_x and ϵ_y) are perpendicular and in turn parallel to the sides of the rectangle defined by the indents, as shown in Figure 4, [17] and [18].

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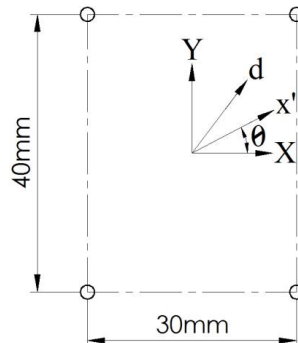


Figure 4: Directions corresponding to ϵ_x , ϵ_y and ϵ_d

The remaining direction (associated to ϵ_d) corresponds to the bisector of the other directions. Such normal components of the residual strain can be expressed as shown in equation 1

$$\epsilon_x = \frac{l_x}{l_x'} - 1 \quad \epsilon_y = \frac{l_y}{l_y'} - 1 \quad \epsilon_d = \frac{l_d}{l_d'} - 1 \quad (1)$$

where l_x and l_x' are the mean values of the horizontal sides of the rectangle defined by the indents and l_y and l_y' are the mean values of the vertical sides, in both cases before and after re-equilibration of stresses (before and after removing from the vacuum fixture). l_d and l_d' correspond to the positive slope diagonal of the aforesaid rectangle, also before and after removing the work piece from the vacuum fixture. Then from the normal components it is possible to obtain the tangential component (γ_{xy}) from equation 2 [19]

$$\gamma_{xy} = 2 \cdot \epsilon_d - \epsilon_x - \epsilon_y \quad (2)$$

As the heat treatment is done below the recrystallization temperature of the material, the dimensional change of the evaluated surface will be caused by the elastic relaxation of the lattice [20], [21]. Therefore if the evaluated surface is considered to be under plane stress conditions the orthogonal components of the residual stress can be expressed for isotropic, linear elastic materials as in equations (3),(4) & (5)

$$\sigma_x = k_1 \cdot \epsilon_x + k_2 \cdot \epsilon_y \quad (3)$$

$$\sigma_y = k_1 \cdot \epsilon_y + k_2 \cdot \epsilon_x \quad (4)$$

Where $k_1 = \frac{E}{1-\nu^2}$ $k_2 = \nu \cdot k_1$ (5)

E is the longitudinal elastic modulus and ν is the poisson's ratio.

Assuming that the generated surface is under a plane stress state and the evaluated material is linearly elastic, homogenous and isotropic, the residual stress components calculated from (6) and (7)

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cdot \cos 2\theta + \tau_{xy} \cdot \sin 2\theta \quad (6)$$

$$\tau_{x'y'} = \frac{\sigma_x - \sigma_y}{2} \cdot \sin 2\theta + \tau_{xy} \cdot \cos 2\theta \quad (7)$$

V. RESULTS AND DISCUSSION

The measured R_a values of each of the coated end mills inside the flute of each of the end mill are listed below in Table 4. The calculated values of maximum value of stress in X, maximum value of stress in Y at centre of the rectangular

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areas defined by the indents in each of the four uncoated and coated H.S.S and Carbide end mills are detailed in Table 5 and Table 6 respectively. The measured maximum values of distortion due to coated and uncoated H.S.S and carbide end mills are detailed in Table 7. The images of the surface texture of the coatings on H.S.S and carbide endmills at 7000X magnification are shown in Figure 5 and Figure 6 respectively.

Table4: R_a Values of the End mills inside the Flute

| S.No | TYPE OF COATING | HSS ENDMILLS R _a VALUE IN | CARBIDE ENDMILLS R _a VALUE |
|------|-----------------|---|--|
| 1 | UNCOATED | 0.25 | 0.238 |
| 2 | TiN | 0.72 | 0.71 |
| 3 | TiAlN | 0.237 | 0.23 |
| 4 | DLC | 0.171 | 0.19 |

Table 5: Stress Range Values Due to different Coatings on H.S.S Endmills

| S.No | TYPE OF TOOL COATING | MAXIMUM STRESS IN X | | MAXIMUM STRESS IN Y | | STRESS RANGE IN X | STRESS RANGE IN Y |
|------|----------------------|---------------------|---------|---------------------|---------|-------------------|-------------------|
| | | Compressive | Tensile | Compressive | Tensile | | |
| 1 | UN COATED | 48.6 | -30.3 | 26 | -27.5 | 76.9 | 54.5 |
| 2 | TiN COATED | 45.6 | -113.3 | 53.4 | -85.5 | 179.9 | 112.9 |
| 3 | TiAlN COATED | 50.2 | -64.8 | 48.8 | -58.9 | 111.6 | 108.7 |
| 4 | DLC COATED | 51.2 | -8.8 | 52 | -36.5 | 59 | 51.5 |

Table 6: Stress Range Values Due to different Coatings on Carbide End mills

| S.No | TYPE OF TOOL COATING | MAXIMUM STRESS IN X | | MAXIMUM STRESS IN Y | | STRESS RANGE IN X | STRESS RANGE IN Y |
|------|----------------------|---------------------|---------|---------------------|---------|-------------------|-------------------|
| | | Compressive | Tensile | Compressive | Tensile | | |
| 1 | UNCOATED | 47.5 | -27.8 | 23.8 | -25.4 | 73.9 | 51.8 |
| 2 | TiN COATED | 43.6 | -110.4 | 53.2 | -81.6 | 170.6 | 108.8 |
| 3 | TiAlN COATED | 41.8 | -59.3 | 42.7 | -47.9 | 103.4 | 99.6 |
| 4 | DLC COATED | 40.2 | -6.6 | 39 | -22.7 | 46.2 | 43.8 |

Table7: Measured Maximum Value of Distortion

| S.No | TYPE OF COATING | MEASURED MAXIMUM VALUE OF DISTORTION IN mm | |
|------|-----------------|--|-----------------|
| | | H.S.S ENDMILL | CARBIDE ENDMILL |
| 1 | UNCOATED | 0.22 | 0.17 |
| 2 | TiN COATED | 0.32 | 0.26 |
| 3 | TiAlN COATED | 0.15 | 0.13 |
| 4 | DLC COATED | 0.12 | 0.09 |

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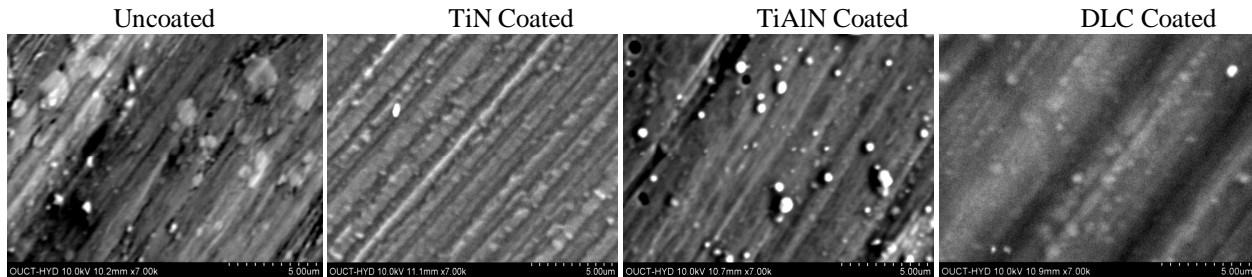


Figure 5: Surface Texture of Coatings on H.S.S endmills

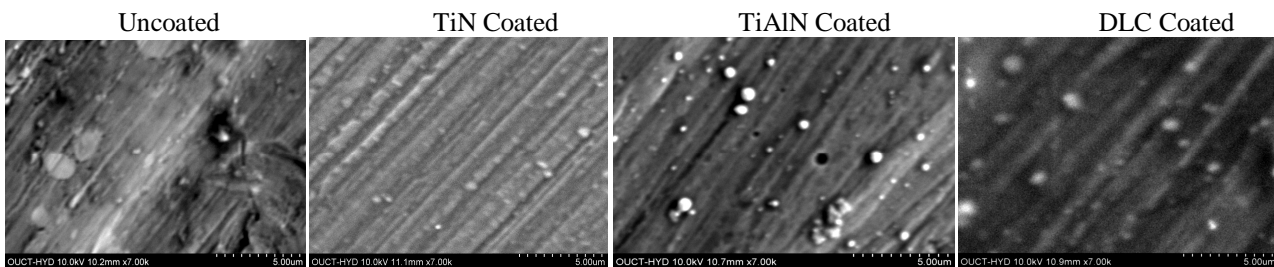


Figure 6: Surface Texture of Coatings on Carbide end mills

The following inferences can be drawn from Table 5,6 and 7 and Figure 5 and 6

- 1) The type of induced stress profile in the work piece due to H.S.S end mill is same as Carbide end mill.
- 2) The induced stress range in the work piece is minimum when DLC coated end mill is used for machining.
- 3) The measured value of maximum distortion in the work piece is minimum when DLC coated carbide end mill is used.
- 4) The surface roughness value (R_a) of end mills in ascending order is $DLC < TiAlN < UNCOATED < TiN$.
- 5) The measured value of distortion in ascending order is $DLC < TiAlN < UNCOATED < TiN$. The above order is observed to be the same in both H.S.S and Carbide end mills but for slight change in magnitude of distortion.
- 6) The machining induced stress range and hence the distortion is having a direct relation to the surface roughness of the end mill in low and medium machining speeds.
- 7) Though the surface hardness of the end mill increases with coating of TiN, the machining induced stresses and hence distortion increases as the surface roughness of the coating increases when compared to uncoated end mill.

VI. CONCLUSION

The machining induced stress range and hence the distortion in machining 2014A T6 51 Aluminum alloy is minimum by using DLC coated carbide end mill.

VII. ACKNOWLEDGEMENT

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