INFLUENCE OF TOOL ANGLES OF ENDMILL ON DISTORTION OF 2014A T651 ALUMINUM ALLOY DURING MACHINING

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Abstract

The present paper investigates the effects of angles of an end mill viz., Helix angle, Radial rake angle, axial rake angle, and gash angle, on machining induced distortion by performing machining experiments using response surface methodology in milling thin-wall, thin-floor components. Four factor, three level Box-Behnken method is used in optimizing the number of experiments in machining aluminum alloy 2014 T651 with Ø 10 mm two flute solid carbide milling tool. The effect of each of the angles is studied by calculating residual stresses using indentation method. Results show that a combination of (30^0 Helix angle, 8^0 Radial rake angle, 4^0 Axial rake angle, and 35^0 Gash angle) produced minimum stress range and hence minimum distortion in the component.

Keywords: *Machining, Distortion, Residual stress, Indentation Method, Aluminum Alloy, radial rake angle, helix angle, gash angle, axial rake angle, Box-Behnken*

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1. 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. Budak and Altintas [2] used the beam theory to analyze the form errors when milling using slender helical endmill for peripheral milling of a cantilever plate structure. The slender helical endmill is divided into a set of equal element to calculate the form errors acting by the cutting forces on both tool and the wall. Later in their work [3], they proposed a feed rate scheduling strategy to reduce the surface errors produced in milling flexible work piece. However, this approach tends to sacrifice the productivity as reducing the feed rate will increase the machining time. When milling a thin-walled structure, deflection and chatter vibration of the work piece due to low stiffness had a negative effect on the surface integrity and geometric accuracy [4]. Most of the existing research for machining thin-wall component only concentrated on the process planning and the effects of cutter geometric feature is often neglected. Tool geometric feature has a direct influence on the cutting performance and should not be neglected in the machining consideration. This article confines to influence of tool angles on machining induced residual stresses leading to distortion of the component. Hence selection of optimal tool angles for an end mill during milling is important in machining of thin walled thin floored Avionics components. The angles of the cutting tool which are generally considered to have an impact on machining induced stress are Rake angles (Axial and Radial), Relief angles (primary and secondary), Helix angle, Dish angle and Gash. The angles considered in this article are helix angle, Radial rake angle, on the periphery and axial rake, gash angle on the face. The cutting tool's rake angle is the angle between the cutting edge and the cut itself, and it may be positive, negative, or neutral. Positive rake allows lower cutting forces, while the negative rake provides a stronger tool wedge. The rake angle may also affect the quality of the machined surface, and increasing the rake angle improves the overall quality of the machined edge [5]. The helix angle is the angle formed by a line tangent to the helix and a plane through the axis of the cutter. Conventionally lower helix angle end mills are used on more difficult to machine materials where maximum edge strength and rigidity are important. With straight flutes the load builds up almost instantaneously, making the end mills prone to self excited chatter. Generally, end mills with small helix angles develop the greatest cutting force and surface roughness [6]. Helical cutters generate a higher axial force than do straight cutters. Effect of helix angle on thin walled machining was studied by Raja Izamshah and Yuhazri M. Y and concluded that End mills with helix angle ranging from 40^o to 45^o were very effective and would be recommended for the case of milling thin-wall application [7].The gash angle is measured between the tooth face and the back of the tooth immediately ahead.

2. EXPERIMENTAL PROCEDURE

2.1 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 [8].

Fig- 1:WITTIE Vacuum pump

Table 1: Chemical composition of aluminum alloy 2014A T651

Chemical Composition Limits Of 2014A T6	
Element	Weight %
Al	Rem
Si	0.50-0.90
Fe	0.50 max
Cu	3.9-5.0
Mn	0.4-1.2
Mg	0.2-0.8

Table2: Mechanical Properties of 2014A T651

Property	Temper	Yield strength	Tensile strength	Hardness Rockwell	Density	Poisson's Ratio
Value	T6 Clad	380 Mpa	420 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 (Figure 1) 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 [9],[10].The indents on the work piece are made with the indenter having an included angle of 120^o. The measurements are accurately taken with optical measuring equipment Baty Vision Systems - Venture VI-3030 CNC (Figure 2), which has a resolution of 0.5 micron and 40 X magnification.

Fig- 2: Baty Vision System-Venture I-3030 CNC

The configuration of the tool geometry used in the following experiments is shown in Figure 3 and the values of four factors for three levels are tabulated in Table 3.

Table3: Tool configuration values

FACTORS	Helix angle(α)	Radial rake angle(β)	Axial Rake angle(γ)	Gash angle(θ)
LEVEL-1	20 deg	6 deg	2 deg	25 deg
LEVEL-2	30 deg	8 deg	4 deg	35 deg
LEVEL-3	40 deg	10 deg	6 deg	45 deg

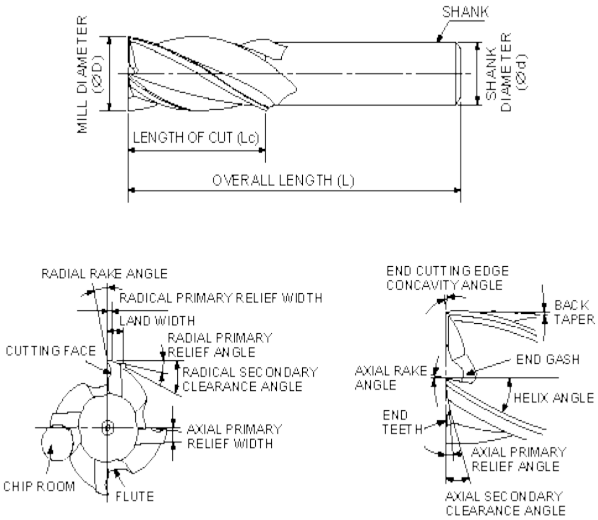

Fig- 3

2.2 Design of Experiments

With an aim to study effect of tool angles viz., Helix angle(α), Radial rake angle(β) on the periphery and axial rake(γ), gash angle(θ) on the face, on machining induced distortion and find optimum parameters to minimize distortion, investigations were done using Box Behnken Design (BBD), one of the Response Surface Method (RSM). RSM is a statistical technique which allows us to investigate relationship and optimize, where several independent variables influence a particular response or dependent variable under study. It gives relationship between independent variables and dependent variables with in response surface. In this study BBD is used for non-sequential experiments performed only once. It provides good estimation of first and second-order coefficients has less design points and is inexpensive to run. All the design points fall within safe operating limits ensuring that all factors are not set at their highest levels simultaneously [11,12]. The BBD design for machining experiments is given in Table 4. MINITAB 16.0 statistical software is used for running the above experiments with BBD. In this study relationship between four factors i.e., helix angle, radial rake angle, axial rake angle, gash angle and output response in terms of induced residual stress (σ) and distortion (D) are measured. The output Y as given in Equation 1 is proposed by nonlinear quadratic equation which is suitable for studying the main and interaction effects on induced residual stress and distortion. The second order mathematical model for four factors is given in Equation 2 [13].

$$Y = F(\alpha,\beta,\gamma,\theta) \text{ -------- } (1)$$

$$Y = A_0 + A_1\,\alpha + A_2\,\beta + A_3\,\gamma + A_4\,\theta + A_{12}\,\alpha\,\beta + A_{13}\,\alpha\,\gamma + A_{14}\,\alpha\,\theta + A_{23}\,\beta\,\gamma + A_{24}\,\beta\,\theta + A_{34}\,\gamma\,\theta + A_{11}\,\alpha^2 + A_{22}\,\beta^2 + A_{33}\,\gamma^2 + A_{44}\,\theta^2 \text{ -------- } (2)$$

Where F is response surface. Xi and Xj are variables or independent factors; A_0 is the constant coefficient; A_1, A_{12} … and A_{44} are interaction coefficients of linear, quadratic, and the second-order terms.

Table 4. Experimental table using BBD with results.

S.No	STD ORDER	RUN ORDER	HELIX ANGLE	RADIAL RAKE ANGLE	AXIAL RAKE ANGLE	GASH ANGLE
1	2	1	40	6	4	35
2	8	2	30	8	6	45
3	7	3	30	8	2	45
4	14	4	30	10	2	35
5	17	5	20	8	2	35
6	22	6	30	10	4	25
7	9	7	20	8	4	25
8	10	8	40	8	4	25
9	20	9	40	8	6	35
10	24	10	30	10	4	45
11	19	11	20	8	6	35
12	25	12	30	8	4	35
13	6	13	30	8	6	25
14	26	14	30	8	4	35
15	13	15	30	6	2	35
16	18	16	40	8	2	35
17	3	17	20	10	4	35
18	15	18	30	6	6	35
19	1	19	20	6	4	35
20	21	20	30	6	4	25
21	4	21	40	10	4	35
22	11	22	20	8	4	45
23	27	23	30	8	4	35
24	23	24	30	6	4	45
25	5	25	30	8	2	25
26	16	26	30	10	6	35
27	12	27	40	8	4	45

2.3 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. To ensure the repeatability of process induced loads to the work piece, and to reduce the error factor, new end mills were used for each investigation separately. 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 1.5mm.The material is machined from 5mm thick to 1.5 mm thick with different combination of tool angles as mentioned in the Table 3 above 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 4.

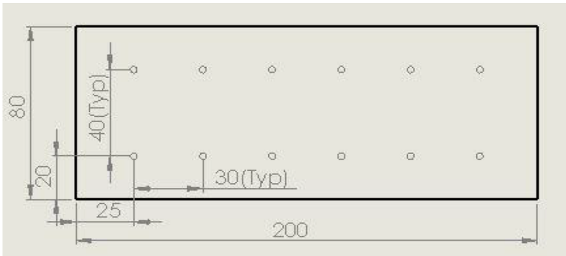

Fig 4: Work piece and indents dimensions

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.

2.4 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 (εx, εy and εd). Two of these (corresponding to εx and εy) are perpendicular and in turn parallel to the sides of the rectangle defined by the indents, as shown in Figure 5, [14] and [15].

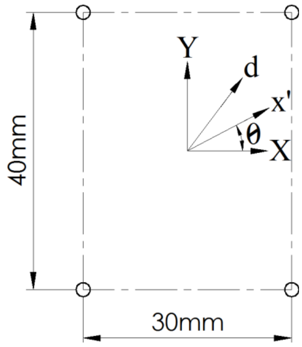

Fig- 5: Directions corresponding to εx, εy and εd

The remaining direction (associated to εd) corresponds to the bisector of the other directions. Such normal components of the residual strain can be expressed as shown in equation 3

$$\varepsilon x = \frac{lx}{lx'} - 1 \ ; \varepsilon y = \frac{ly}{ly'} - 1; \varepsilon d = \frac{ld}{ld'} - 1 \text{ -------- } (3)$$

where lx and lx' are the mean values of the horizontal sides of the rectangle defined by the indents and ly and ly' 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).ld and ld' 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 (ϒxy) from equation 4 [16]

$$\Upsilon xy = 2.\varepsilon d - \varepsilon x - \varepsilon y \text{ ----- } (4)$$

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 [17], [18]. 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 (5),(6) & (7)

$$\sigma x = k1.\varepsilon x + k2.\varepsilon y \text{ ----------- } (5)$$

$$\sigma y = k1.\ \varepsilon y + k2.\varepsilon x \text{--------- } (6)$$

$$\text{Where} \quad k1 = \frac{E}{1-\nu 2} \qquad k2 = \nu.k1. \text{ ---------- } (7)$$

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 from (8) and (9)

$$\sigma x' = \frac{\sigma x + \sigma y}{2} + \frac{\sigma x - \sigma y}{2}.\cos 2\Theta + \tau xy.\sin 2\Theta \text{ ---- } (8)$$

$$\tau x'y' = \frac{\sigma x - \sigma y}{2}.\sin 2\Theta + \tau xy.\cos 2\Theta \text{ ------- } (9)$$

2.5 Modelling of the Workpiece

For measuring the geometry of the work piece before and after machining, a grid of 15 x 7 points with a pitch of 12 x 10 is marked on the backside of each work piece as shown in Figure 6. Each coordinate measurement provided 105 coordinate triplets describing the work piece surface as a point cloud. The geometry is measured opposite the surface machined during the experiments.

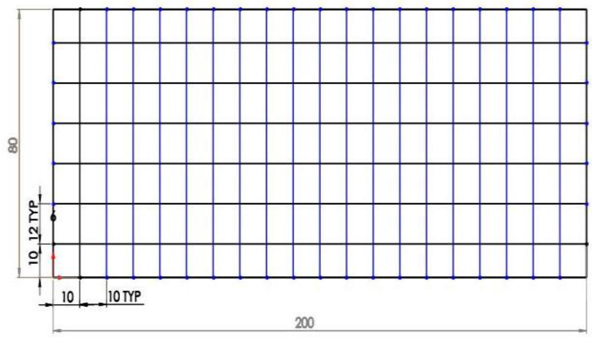

Fig 6: Grid on the work piece for measurement

The 3D geometric profile is modeled using "SOLIDWORKS 2013" CAD package. The machining is done using "CAMWORKS 2013" CAM package.

3. RESULTS AND DISCUSSION

The calculated values of range of stress in the work piece with each of the cutting tool (end mill) are detailed in Table 5. The main effects plot of each of the angles under consideration versus range of stress and interaction plot of combination of each of the angles versus range of stress are shown in Figure 7 and Figure 8 respectively. The derived regression equation from the experimental values and using MINITAB 16 statistical software is given below in equation 10.

Table 5. Range of Stress in the Work piece due to each Tool.

S.No	*TOOL (Helix,Radial rake, Axial rake, Gash angle) in deg*	*Range of stress*
1	TOOL1(20,8,2,35)	-172.02
2	TOOL2(20,8,4,25)	-157.18
3	TOOL3(20,8,6,35)	-181.37
4	TOOL4(20,10,4,35)	-168.38
5	TOOL5(20,6,4,35)	-184.54
6	TOOL6(20,8,4,45)	-643.03
7	TOOL7(30,8,6,45)	-465.73
8	TOOL8(30,8,2,45)	-197.62
9	TOOL9(30,10,2,35)	-169.16
10	TOOL10(30,10,4,25)	-169.36
11	TOOL11(30,10,4,45)	-193.23
12	TOOL12(30,8,4,35)	-322.80
13	TOOL13(30,8,6,25)	-169.23
14	TOOL14(30,8,4,35)	-322.80

15	TOOL15(30,6,2,35)	-197.60
16	TOOL16(30,6,6,35)	-318.51
17	TOOL17(30,6,4,25)	-136.05
18	TOOL18(30,8,4,35)	-60.39
19	TOOL19(30,6,4,45)	-623.80
20	TOOL20(30,8,2,25)	-139.77
21	TOOL21(30,10,6,35)	-91.37
22	TOOL22(40,6,4,35)	-201.39
23	TOOL23(40,8,4,25)	-90.07
24	TOOL24(40,8,6,35)	-367.09
25	TOOL25(40,8,2,35)	-130.45
26	TOOL26(40,10,4,35)	-129.75
27	TOOL27(40,8,4,45)	-100.21

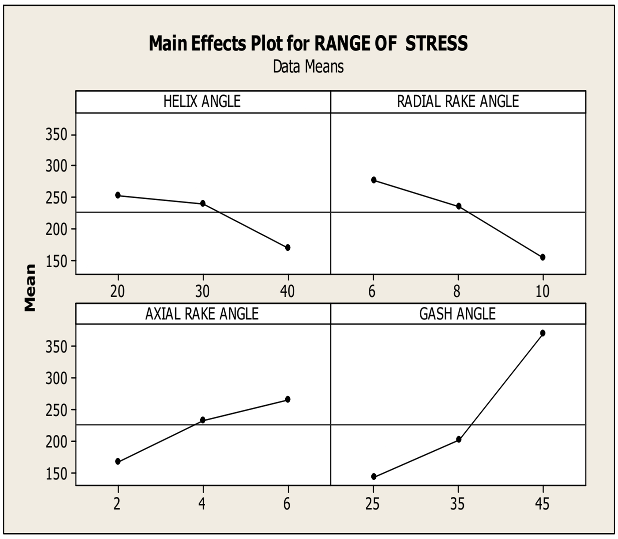

Fig- 7: Main effects plot of Stress versus Tool angles

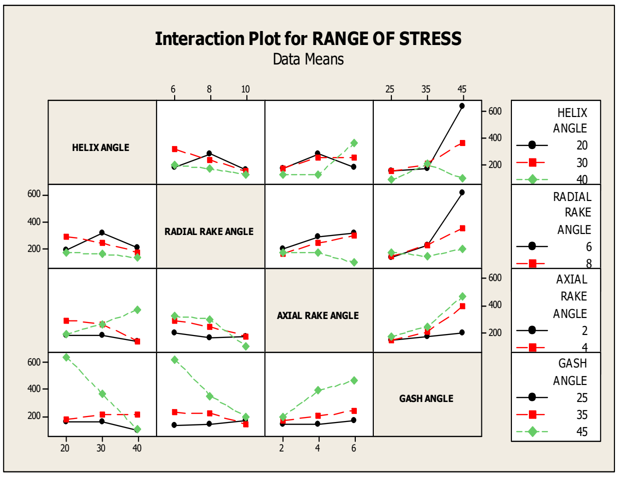

Fig- 8: Interaction Plot of Stress versus Tool angles in combination

The following inferences are drawn from the above

1) The individual effect of Helix angle and Radial rake angle on the magnitude of range of stress is similar and is inversely proportional. Whereas the individual effect of Axial rake and Gash angles on magnitude of range of stress is similar and is directly proportional. However the individual influence of Gash angle on stress is more pronounced than the individual influence of Axial rake angle. Increase in the helix angle increases the effective shearing action thus reducing cutting forces and the amount of heat generated during the milling process. Chip ejection is also improved. With helix angles, chip load is applied to the entire flute length in a progressive siding action similar to that of a snowplow with its blade angled off to one side. This makes the cutting forces much more constant with less chance for chatter. End mills with a higher helix also tend to produce much better work piece finishes.

2) The combination effect of the tool angles is shown in Figure 8 and the magnitude of the range of stress induced is detailed in Table 5. From the stress values it can be concluded that the combination of tool angles mentioned in Tool 18(30, 8, 4, 35), produced minimum compressive stresses under working conditions stated earlier. The maximum distortion produced in the work piece after machining by using the above tool angles is 0.095mm which is minimum among the distortion produced in all the work pieces with other combination of angles.

3) Analysis of variance (ANOVA) was performed for Helix angle, Radial rake angle, Axial rake angle, Gash angle and Range of stress. It can be observed from test of ANOVA and from main effects plot at Figure 7 that there is a decrease in range of stress with increase in Helix angle and Radial rake angles, and there is increase in range of stress with an increase in increase of Axial rake angle and Gash angle. As the p value (0.001) is less than 0.05 for Gash angle only, except for Gash angle the other three angles do not have statistically insignificant effect on range of stress for the given range of angles selected. There is a significant interaction effect of Helix angle and Gash angle on range of stress induced during machining (p value less than 0.05). It can also be seen from ANOVA and interaction plot from Figure 8 that there are no interaction effects of angles except for a combination effect of Helix angle and Gash angle on Range of stress.

4) The presumed second order mathematical model function for Range of stress(Y) in terms of independent parameters i.e Helix angle(α), Radial rake angle(β), Axial rake angle(γ) and Gash angle(θ) is Y = F ($\alpha,\beta,\gamma,\theta$)

Where F is response surface. Xi and Xj are variables or independent factors; A_0 is the constant coefficient; A_1, A_{12} … and A_{44} are interaction coefficients of linear, quadratic, and the second-order terms.

$$Y = A_0 + A_1\,\alpha + A_2\,\beta + A_3\,\gamma + A_4\,\theta + A_{12}\,\alpha\,\beta + A_{13}\,\alpha\,\gamma + A_{14}\,\alpha\,\theta + A_{23}\,\beta\,\gamma + A_{24}\,\beta\,\theta + A_{34}\,\gamma\,\theta + A_{11}\,\alpha^2 + A_{22}\,\beta^2 + A_{33}\,\gamma^2 + A_{44}\,\theta^2$$

The generated regression equation from the experimental values and using MINITAB 16 statistical software is as follows.

$$Y= 235.33 +(-40.63 * \alpha) + (-61.72* \beta) + (48.89 * \gamma) + (113.50 * \theta) + (-13.87 * \alpha* \beta) + (56.82 * \alpha* \gamma) +(-118.93 * \alpha* \theta) + (-49.68 * \beta* \gamma) + (-115.97 * \beta* \theta) +(59.66 * \gamma\, \theta) + (-$$

$$26.85 * \alpha^2) + (-19.64 * \beta^2) + (-17.55 * \gamma^2) + (43.12 * \theta^2) \quad \text{---------} \quad (10)$$

Test of ANOVA for range of stress shows that the regression Equation 10 is significant as the lack of fit (0.427) is insignificant as it is more than 0.01.

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