International Journal of Application or Innovation in Engineering & Management (IJAIEM)
Web Site: www.ijaiem.org Email: editor@ijaiem.org
Volume 5, Issue 7, July 2016 ISSN 2319 - 4847

Impact of Cutting Fluids on distortion of 2014A T6 Aluminum alloy during machining

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ABSTRACT

In this work, influence of different cutting fluids on machining induced residual stresses and in turn on distortion in aluminum alloy 2014 A T6 were studied by calculating residual stresses using indentation method. Results show that cutting fluids has significant effect on the residual stress distribution and distortion of components. It is also observed that machining induced stresses by using Synthetic oil are minimum leading to minimum distortion.

Keywords: Machining, Distortion, Residual stress, Indentation Method, Aluminum Alloy, cutting fluid, Coolant, Lubricant.

1. INTRODUCTION

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 result from two sources. Prior to machining, bulk stresses from primary processes such as rolling or forging may be present in the work piece and the stresses induced by the machining process, which result from differential plastic deformation and surface temperature gradients [1]. This article confines to machining induced residual stresses only.

The basic functions of a cutting fluid are to provide cooling and lubrication and thus reducing the severity of the contact processes at the cutting tool–chip and cutting tool–work piece interfaces. A cutting fluid may significantly affect the tribological conditions at these interfaces by changing the contact temperature, normal and shear stresses and their distributions along the interfaces, the type and/or mechanism of tool wear, machined surface integrity and machining residual stresses induced in the machined parts [2]. Hence selection of cutting fluid during milling is an important issue in machining of thin walled thin floored Avionics components.

In the metal cutting operations work piece geometry is influenced by mechanical, thermal and chemical loads. These loads are responsible for the geometrical and physical properties of the work piece and its boundary layer. The type of cutting fluid used possibly determines the machining induced residual stresses which in turn lead to distortion. There are generally three types of liquids: neat oil, semi-synthetic oil, and synthetic oil. Semi-synthetic and synthetic cutting fluids represent attempts to combine the best properties of oil with the best properties of water by suspending emulsified oil in a water base. These properties include rust inhibition, tolerance of a wide range of water hardness (maintaining pH stability around 9 to 10), ability to work with many metals, resist thermal breakdown, and environmental safety [3]. Although the cutting fluids have diversified roles to play and each fluid having its own advantages and limitations, this article confines to the role of cutting fluid in generating machining induced residual stresses which leads to distortion.

2. RELATED WORK

Lot of research has been done on lubricity and cooling characteristics of cutting fluids and their interaction and influence on tool life. Since the beginning of the 20th century, when F.W. Taylor used water for the first time to cool the machining process and concluded it increased tool life, a large variety of cutting fluids has been used with this and other purposes. Trent [4] says that the lubricant have no access to the seizure zone on the tool rake face. Childs and Rowe [5] also affirms this theory and comments that further studies must be done in the chip-tool interface besides the difficulties encountered to access the seizure zone. Postinikov [6] suggested that the lubricant penetrates against the metal flow, reaching the tool nose, through a capillary action, assuming that the contact in the interface is not total (sliding conditions). Horne [7] in his experiments with transparent sapphire tools demonstrated that the cutting fluid flow reaches the interface by the lateral parts of the contact, instead of moving against the chip flow. No matter the penetration method, cutting fluid, once in the interface, must form the lubricant layer with shearing resistance lower than the material resistance. It may also restrict the chip welding on the tool rake face, if suitable additives are used. The lubrication efficiency will depend on the fluid properties, such as wet ability characteristics, viscosity and layer resistance. These properties may be obtained with a suitable mixture of additives. Shaw has experimentally proved that the cutting fluid efficiency in reducing temperature decreases with the increase of cutting speed and depth of cut [8].Sales developed a method and proved that the cooling ability of the cutting fluids at moderate speeds leading to moderate temperatures in ascending order is dry cutting, neat oil, soluble oil, water and synthetic oil. The cooling efficiency of water at higher speeds leading to higher temperatures reduces to even less than neat oil due to formation of vapor zone which acts a barrier and not allowing the fresh coolant to interact with tool chip interface [9]. Sales proved the fact that the highest convection factor is not the only parameter to decide the cooling efficiency of the fluids in machining at tool chip interface. The Uppsala's pendulum test conducted by Sales revealed that the lubricity of the cutting fluids in the decreasing order of lubricity is Neat oil, emulsion (soluble oil), dry condition, synthetic oil and pure water. It also revealed that the lubricity of the medium is inversely proportional to the mass of the chip [10]. Especially for the machining of thin-walled work pieces, it is important to take the thermo-mechanical loads into account, because of their influence on geometrical shape deviations on the work piece. Due to the slim cross-section of structural components, their transverse rigidity is small and additionally their poor heat dissipation leads to a high temperature level. Such effects have drastic influences on the work piece geometry during the machining process. Weiner investigated the influence of thermal and mechanical loads for the machining of thin-walled light weight components. He found that thermal- induced mechanical stresses had a high influence on shape deviations, than due to the mechanical loads [11, 12].

3. EXPERIMENTAL PROCEDURE

3.1 MATERIALS AND EQUIPMENT

The work piece material used is aluminum alloy 2014A T6 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 [13].

Table 1: Chemical composition of aluminum alloy 2014A T6

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 T6

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 (Figure 2) with constant tool and cutting parameters as mentioned in Table 3.The machining is done with pocket out layout in Dry machining and three different types of cutting fluids. The pocket out machining layout is used in all the experiments as the machining induced stresses in this layout are minimum [14].The different types of cutting fluids used and their significant properties are listed in Table 4.

Table 3: Tool geometry and cutting parameters

Tool Material and Diameter	Helix Angle	No. of Flutes	R.P.M	Feed per Tooth	Depth of cut	Width of Cut
Solid Carbide End mill of 20mm	30 deg	2	2000	0.1	3.5	6mm

Table 4: Cutting fluids and their properties

Sl.No	Cutting Fluid	Make and Grade	Mix ratio	Kinematic Viscosity @ 40^0c
1	Dry Machining	--------	--------	---------
2	Mineral oil	SERVO CUT 945	--------	26-35 cST
3	Soluble oil	Tectyl cool 273	1:8	10-14 cST
4	Synthetic oil	Tectyl 540	1:7	10-12 cST

Figure 1:WITTIE Vacuum pump

Figure 2:DECKEL FP4A CNC machine

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 3), which has a resolution of 0.5 micron and 40 X magnification.

Figure 3: Baty Vision System-Venture VI-3030 CNC

3.2 EXPERIMENTAL WORK

The dimensions of the samples taken are 5mm x 80mm x 200mm.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, new end mills were used for several investigations runs this will reduce the error on evaluation of distortion in the material due to machining induced stresses. Most of the parts in avionic components are designed to have a base thickness of 1.5mm hence the final thickness of the experimental work piece after machining is taken as 1.5mm.The material is machined from 5mm thick to 1.5mm thick with Dry machining, Neat oil, Soluble oil and Synthetic oil in Pocket out tool path layout. Without removing the work piece from the fixture the indents are made at a pitch of 25 mm along X axis (lengthier side) and at a pitch of 40mm along Y axis (shorter side) as shown in Figure 4.

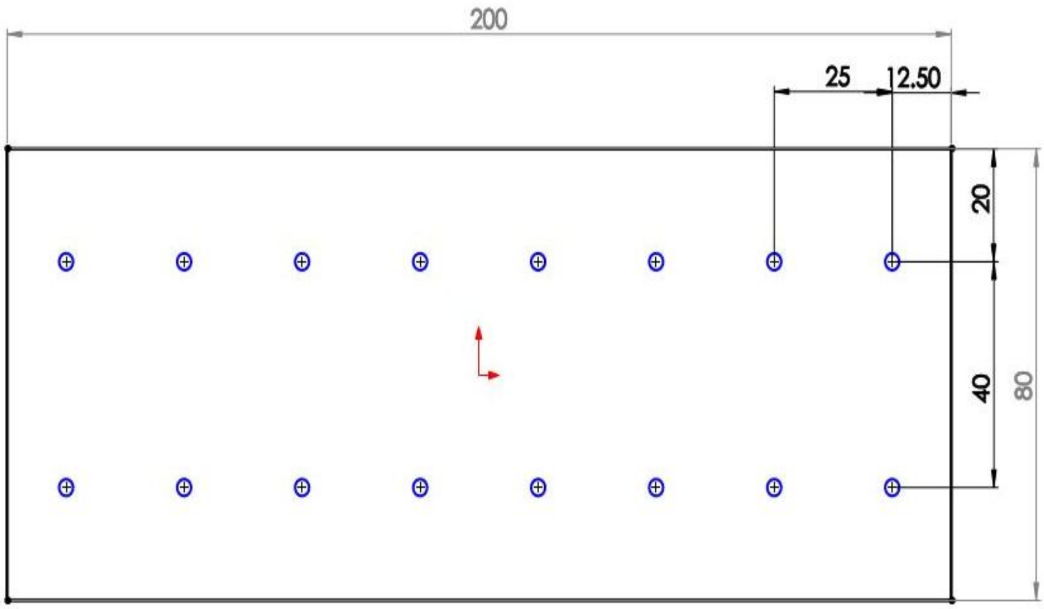


Figure 4: Work piece and indents dimensions

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.

3.3 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 5, [15] and [16].

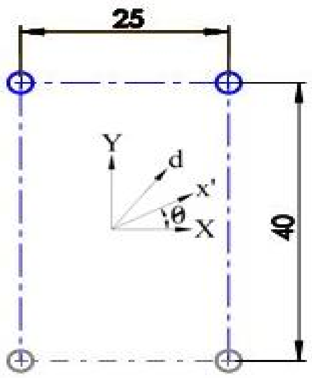


Figure 5: Directions corresponding to ε_x, ε_y and ε_d

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

$$\varepsilon_x = \frac{lx}{lx'} - 1 \qquad \varepsilon_y = \frac{ly}{ly'} - 1 \qquad \varepsilon_d = \frac{ld}{ld'} - 1 \qquad (1)$$

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(Υ_{xy}) from equation 2 [17]

$$\Upsilon_{xy}=2.\varepsilon_d - \varepsilon_x - \varepsilon_y \qquad (2)$$

As the heat treatment is done below the re-crystallization temperature of the material, the dimensional change of the evaluated surface will be caused by the elastic relaxation of the lattice [18], [19]. 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)

$$\sigma_x = k_1.\varepsilon_x + k_2.\varepsilon_y \qquad (3)$$

$$\sigma_y = k_1.\varepsilon_y + k_2.\varepsilon_x \qquad (4)$$

Where

$$k_1 = \frac{E}{1-\nu 2} \qquad k_2 = \nu.k_1. \qquad (5)$$

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 from (6) and (7)

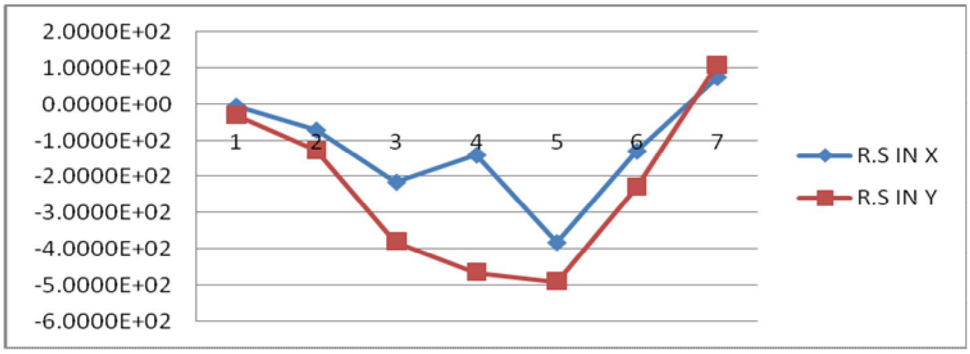
$$\sigma_{x'} = \frac{\sigma x + \sigma y}{2} + \frac{\sigma x - \sigma y}{2}.\cos 2 + \tau xy.\sin 2 \qquad (6)$$

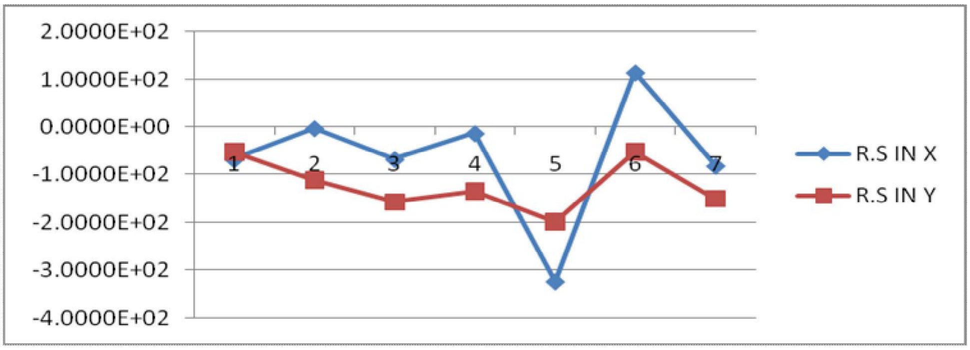
$$\tau x'y' = \frac{\sigma x - \sigma y}{2}.\sin 2 + \tau xy.\cos 2 \qquad (7)$$

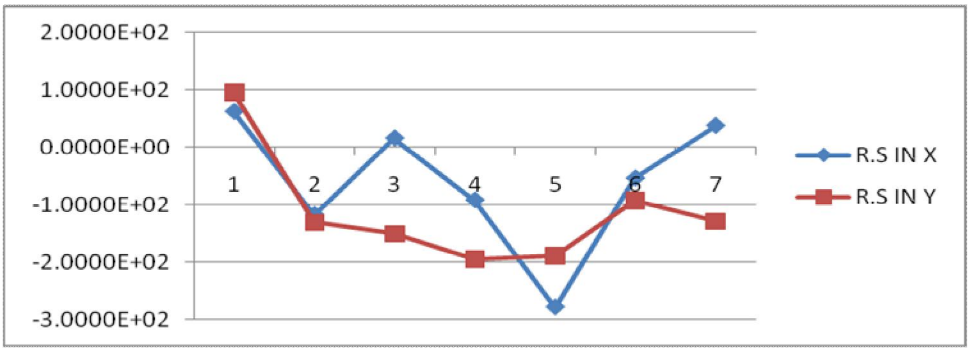
The calculated values of stress in X, and Stress in Y at centre of the rectangular areas defined by the indents with each of the four cutting fluids detailed in Table 5. The magnitude of maximum stress, range of stress and resultant stress are detailed in Table 6. The stress distribution profiles along X-axis and along Y-axis in each of the tool path strategies are shown in Figure 9.

Table 5: STRESS VALUES WITH DIFFERENT COOLANTS

DRY MACHINING			WATER SOLUBLE OIL			NEAT OIL			SYNTHETIC OIL		
S.No	STRESS IN X (MPa)	STRESS IN Y (MPa)	S.No	STRESS IN X (MPa)	STRESS IN Y (MPa)	S.No	STRESS IN X (MPa)	STRESS IN Y (MPa)	S.No	STRESS IN X (MPa)	STRESS IN Y (MPa)
1	-4.240	-30.488	1	-68.217	-52.509	1	62.284	96.110	1	58.139	87.120
2	-71.316	-127.962	2	-3.115	-110.896	2	-117.159	-130.394	2	-110.238	-124.428
3	-215.126	-378.870	3	-67.707	-156.682	3	16.078	-149.866	3	12.524	-132.769
4	-139.995	-463.917	4	-13.768	-134.352	4	-91.829	-194.529	4	-88.735	-176.238
5	-382.139	-489.847	5	-323.580	-198.513	5	-278.216	-188.078	5	-186.543	-173.294
6	-129.230	-228.591	6	113.919	-52.323	6	-53.703	-92.214	6	-48.625	-77.159
7	75.128	108.551	7	-81.629	-150.403	7	37.806	-128.205	7	29.541	-115.106







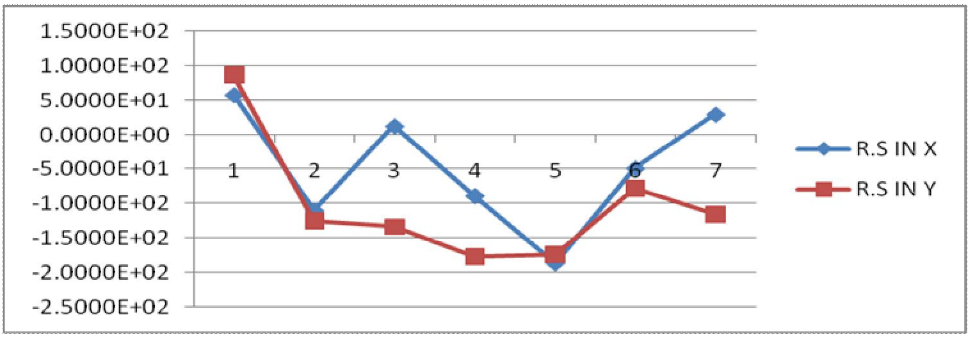


Figure 6: RESIDUAL STRESS PROFILES WITH FOUR DIFFERENT CUTTING FLUIDS.

4.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 7. 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. The 3D geometric profile using the point cloud data is modeled using "SOLIDWORKS 2013" CAD package. The machining is done using "CAMWORKS 2013" CAM package. The calculated values of stress in X, and Stress in Y at centre of the rectangular areas defined by the indents with each of the four cutting fluids are detailed in Table 5. The stress distribution profiles along X-axis and along Y-axis in each of the tool path strategies are shown in Figure 6. The modeled distortion profiles from the measured point cloud after machining is shown in Figure 8.The value in z axis is magnified 50 times to significantly show the distortion profile in machining with each of the cutting fluid. Hence the images are indicative in nature.

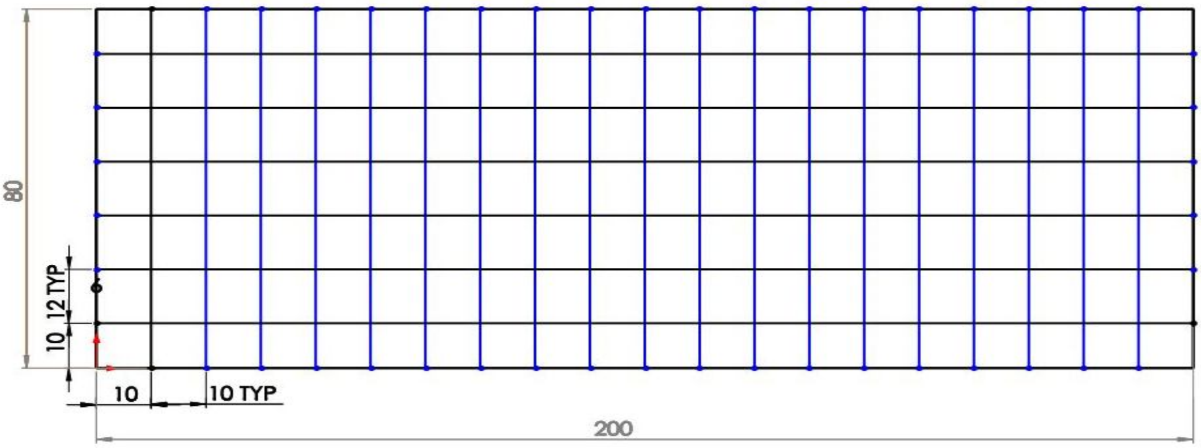


Figure 7: Grid on the work piece for measurement

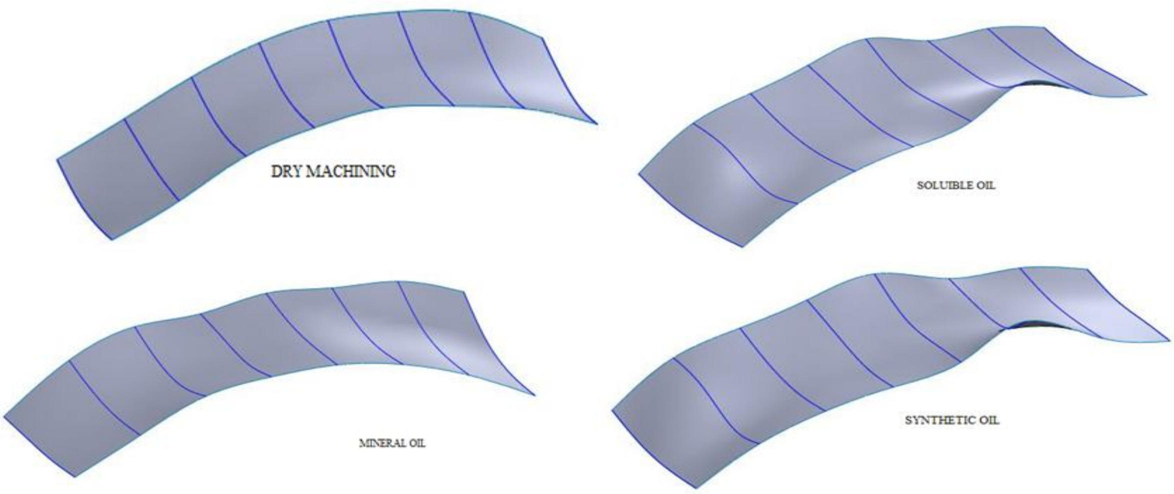


Figure 8: PROFILES OF THE WORK PIECES AFTER MACHINING WITH DIFFERENT CUTTING FLUIDS

5.RESULTS AND DISCUSSION

The total residual stresses in the part after machining are a combination of mechanical and thermal stresses. The characteristics of the cutting fluid which contribute to the distortion of the work piece are viscosity, lubricity and thermal coefficient of the fluid to take away the heat (specific heat of the fluid).

Table 6: MAXIMUM STRESS VALUES WITH DIFFERENT COOLANTS

SL.No	COOLANT TYPE	MAX. MAGNITUDE OF STRESS		MAGNITUDE OF RANGE OF STRESS		MAGNITUDE OF RESULTANT STRESS
		IN X	IN Y	IN X	IN Y	
1	DRY MACHINING	-382.139	-489.847	457.267	598.398	753
2	WATER SOLUBLE	-323.58	-198.513	437.5	146.19	461.27
3	NEAT OIL	-278.216	-194.529	340.5	290.639	447.67
4	SYNTHETIC OIL	-186.543	-179.238	244.682	263.358	359.48

The following inferences are drawn from data in Table 5,Table 6 and its graphical representation in Figure 6.

1. The magnitude of stress induced in machining in descending order is Dry machining > Water soluble > Neat oil > Synthetic oil.
2. The distributions of stresses in both X and Y axes with all the cutting fluids are mostly compressive except for few points at which it is tensile. This can be attributed to the tool path and tool geometry [12].
3. The stress induced is maximum in Dry machining and minimum in machining with Synthetic oil.

In the descending order of viscosity and lubricity the cutting fluids can be arranged as Neat oil > Water soluble oil > Synthetic oil > Dry machining. In the descending order of specific heat the above cutting fluids can be arranged as

Synthetic oil > Water Soluble oil > Neat oil > Dry machining.

From the above inferences it can be concluded that for the evaluated cutting speed the thermal effect is more predominant than the mechanical stress and hence the stresses induced in machining with synthetic oil are minimum. The lubricity plays a significant role in reducing the mechanically induced stresses at low cutting speeds. Hence the stresses induced with neat oil are lesser than the stresses induced with water soluble oil. At low cutting speeds lubrication is important to reduce friction and avoid the formation of built-up-edge. At high cutting speeds, the conditions are not favorable to fluid penetration, to reach the interface and work as a lubricant. In these conditions cooling becomes more important and a water based fluid must be used. The results show that the shape deviation of the work pieces does exist during machining with all the cutting fluids, but the maximum deviation is observed when no cutting fluid is used i.e in Dry machining and minimum deviation is observed with synthetic oil.

6.CONCLUSION

The measured values of distortion indicates that the work piece is twisted in all the X,Y and Z directions which is clearly evident from the stress values in Table 4, its graphical representation in Figure 9 and modeled profiles of the work piece after machining in Figure 10. Though the minimum distortion of the components and stress induced guide the use synthetic oil, the problems encountered in the real time like safe environmental disposal of oil, and white rust formation on specified grade of Aluminum alloy, limit its usage. The second best cutting fluid in terms of distortion and stress for 2014 T6 Aluminum alloy is Neat oil. Hence the combination of Neat cutting oil with oil chillers is used so as to ensure less thermal and mechanical stress in Avionic parts.

7.ACKNOWLEDGEMENT

The authors are thankful to the Head of Department, Osmania University for his constant encouragement and valuable guidance. The authors are also thankful to the management of S.L.R.D.C (H.A.L) for permitting to conduct the experiments.

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