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STUDY ON STRATEGIES TO RESOLVE DIMENSIONAL ERRORS OF CRITICAL THIN WALLED AERONAUTIC COMPONENTS

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Abstract : Post machining geometric distortion is the key problem in critical structural aerospace parts under the category of thin walled components**.** The distribution of stresses induced by machining causes dimensional and geometric deviations and impacts the capacity of the components to withstand its designed loading and assembly requirements. It also leads to increased scrap volumes and problems associated with quality during assembly of components. One of the greatest challenges in the aeronautical industry is machining the component shapes from axisymmetric and prismatic bars into part features with wall and floor thickness respectively and they are very similar to sheet metal components. Much study has gone and is still going on in the process of machining thin walled components. The present work involves the investigation of the influence of material removal pattern, method of component holding and process parameters of High Speed Machining (HSM) on component dimensional deviation. This paper presents influence of material removal pattern, use of fixtures and high speed machining strategy on machining of aluminum monolithic thin walled critical cylindrical aerospace parts.

***IndexTerms - Thin walled, monolithic components, residual stress, dimensional errors, distortion*.**

I. INTRODUCTION

Since aluminum alloys posses many important properties such as light weight, high strength, corrosion resistance, etc., are widely used in the aerospace applications. Minimizing the fuel consumption is one of the prime factors in the design of modern aircrafts and hence the aircraft weight plays a critical role in fuel efficiency. Supporting structural components are designed to maintain optimum weight for maximum rigidity with minimum material thickness.

During machining of thin walled components, it has been observed that there are situations where it is required to remove more than 90% of the bulk material from the billets. Machining of such thin walled components results in inducing the residual stresses at the boundary of the components**.** In addition to this bulk residual stresses which were within the material before machining will also add to the total residual stresses [1].

Zheng Zhang, et. al studied an accurate cross-sectional residual stress determination method for minimizing machining distortion. This methodology has been applied to prevent or reduce parts twisting in advance by adapting machining strategies or process conditions [1].

The manufacturing cost of the aircraft structures and aerospace components can be minimized considerably by designing and producing integral metallic structures by eliminating costly, time-consuming, multi-part manufacturing and the assembling of parts together into a finished sub assembly. These Monolithic designs are quickly substituting sheet metal and multi – part assemblies because of their excellent strength to weight ratios and reduced assembly costs. This method of design and machining of these intricate parts has eliminated thousands of hours required for mechanical assembly processes with lots of benefits [2].

Residual stress distribution in the part based on the entire manufacturing history is needed order to minimize, distortion [3]. Initial residual stress in the blank is the main effect element of machining distortion for aluminum alloy aircraft monolithic component, while cutting loads (including cutting force and temperature) are the main effect element of machining distortion for titanium alloy aircraft monolithic component [4] [5]. Residual stresses and machining process conditions are influences significantly on distortion of thin walled components [6]. The cutting parameters in turning that have the highest influence on the dimensional changes are the feed rate and the depth of cut [7]. Garimella Sridhar et. al, presented an overview on various factors which affects the distortion of thin walled components [8].

Qiong Wu et. al, conducted an experiment to measure the deformation of thin walled aeronautical monolithic components machined by CNC machining. They adopted traditional one-side machining and quasi-symmetric machining methods. The maximum deformation value of quasi-symmetric machining method is within 20% of that of the traditional one-side machining method. This result shows the quasi-symmetric machining method is effective in reducing deformation caused by residual stress [9].

Jozef Kuczmaszewski et. al, studied the influence of milling strategies on effectiveness of thin-walled elements production made of aluminum alloy EN AW-2024. The three milling strategies i.e.: high performance cutting (HPC), HPC combined with conventional finishing operation and HPC combined HSC were analyzed. Two factors are used to measure the effectiveness i.e. machining time and deformation (after removal of samples from clamping fixture). On the basis of results obtained, it has been noted that all three strategies have an impact on the deformation. Minimum deformation value is obtained for HPC combined with conventional finishing operation strategy and best machining time is obtained for HPC strategy [10].

Sridhar G et. al, studied to determine the influence of size of the cutter on distortion, twist and cutting force. Different sizes of milling cutters are used for machining the thin wall thin floor aluminium alloys at constant feed, speed, depth of cut and volume of material removal rate to understand the effect of cutter diameter on distortion. From the experimentation results, it is found that distortion increases with the cutter size at constant feed, speed, depth of cut and material removal rates. It is found from simulations that cutter size increases the forces in z-direction and plays a dominant role in distorting the part and at larger cutter sizes twist in the machined part is more because of increase in cutting torque [11]. The volume of material removal has no significant affect on distortion for thickness more than 3mm but it affects the twisting [12].

The distribution of machining induced stresses can affect the component dimensional and geometrical deviation which leads to high rejection rates and quality-related problems [13] [14]. The cutting parameters in milling that have the highest influence on the dimensional changes are the depth of cut followed by width of cut [15]. The amount of deformation of a thin walled part is mainly dependent on heat and the shape of a component [16] Application of natural seasoning at reducing deformations of thin-walled elements made of aluminium alloys may prove an alternative to the difficult intermediate heat treatment [17].

The various factors that affect the distortion of the thin walled components have been presented in Fig 1. The three factors considered in the present work to study their influence on the dimensional and geometrical deviations are material removal strategy, type of fixture and application of high speed machining. Except these three factors all others are assumed as insignificant**.** The dimensions and geometries are validated using Co-Ordinate Measuring Machine and Ultrasonic testing gauge.

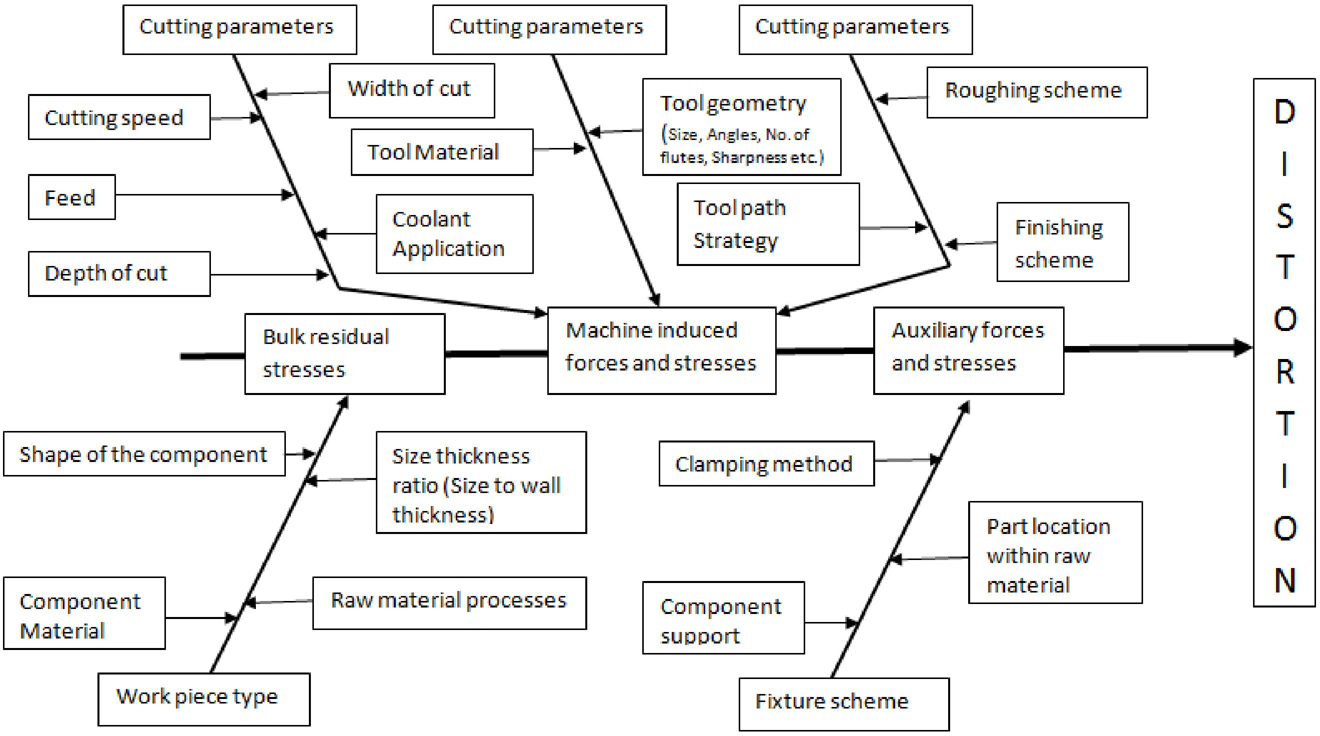

Fig: 1 Parameters affecting the distortion of thin walled components.

II. EXPERIMENTAL METHODOLOGY FOR DIMENSIONAL AND GEOMETRIC ERRORS MINIMIZATION.

The component (ring) considered in the present work has a maximum diameter of 3000mm, height of 100mm and thickness ranging from 6mm to 12mm shown in Fig 02**.**

The manufacturing method followed earlier used eight aluminium blocks as fixture, each of these blocks are to be loaded on machine and trueing was done. Manual machining was carried out to prepare these blocks to receive the part. Part loaded for finishing operation, clamping is done at inner diameter groove and machining is carried out to maintain the height, outer diameter and flange thickness. Than clamps are changed to the flange surface and machining is carried out to maintain the inner diameters and thickness.

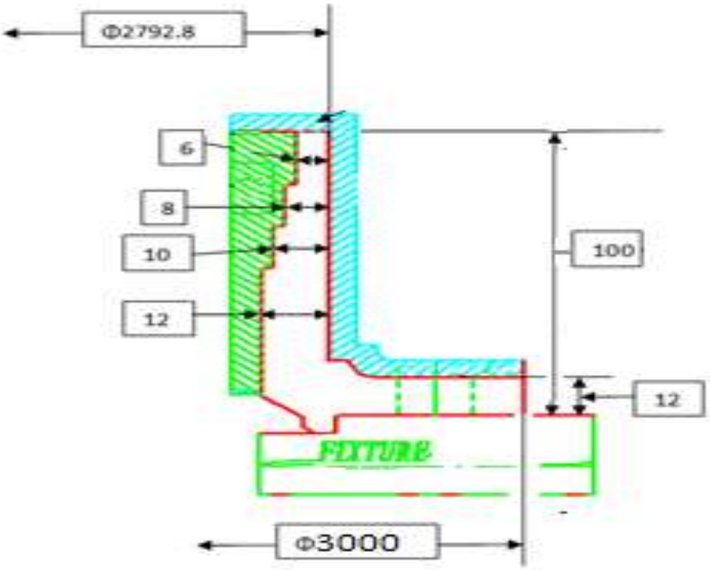

Fig: 2 components considered for the work.

The test samples were fabricated from rolled AA-2014 T652 aluminium alloy bar. The chemical compositions of the alloy are shown in Table 1.

Table 1 Chemical composition of AA2014 T652

Elements	Percentage by Weight
Copper	3.9 to 5%
Silicon	0.5 to 1.2%
Ferrous	0.74%
Manganese	0.4 to 1.2%
Zinc	0.25%
Magnesium	0.22 to 1.8%
Titanium	0.15%
Others	0.15%
Aluminium	remaining

. The rough machining process carried out with a vertical Turn Mill centre COMAU 36H 3 axis turn- mill centre. After rough machining part was kept in laboratory environment to study the natural distortion of the part. Part was kept about two weeks and recorded daily the distortion at the top face perpendicular to the machined surface. From the recorded data it has been found that the maximum distortions noticed for first seven days after which it remained almost constant. Hence it has been suggested that all parts after rough machining are to be kept seven days for natural stress relieving. The residual stresses due to finish machining of the component are not considered as this tends to be very small.

The four methodologies considered in the present work to minimize the dimensional and geometric errors of thin walled aeronautic component are:

1. Modification of material removal strategy (M_1)
2. Change of fixture (M_2):
3. Combination of modification in material removal way and change of fixture (M_3):
4. Change of machining operation from turning to milling (HSM) (M_4):

For methodologies M_1, M_2 and M_3 vertical Turn Mill centre COMAU 36H, 3 axis turn- mill centre and for methodology M4, Lecreno 3 Axis Machining center is used for finish machining operation.

Cutting parameters used for machining are listed in Table 3.

Table 3 cutting parameters for four methodologies

Sl no	Methodology	Tool Material	Cutting speed m/min	Feed mm/rev mm/min	Depth of cut mm	Spindle rev. rpm
1	M_1, M_2, M_3	Carbide	150-400	0.1-0.2	0.25-1	20-100
2	M_4		60-180	2000-3000	0.25-1	12000-15000

1. Modification of material removal strategy (M_1):

During machining common practice is to completely machine one surface before machining the opposite side. However, residual stresses from prior operations such as forging, rolling etc, can significantly affect distortion specifically when machining non-ferrous alloys.

The engagement of the tool varies throughout the tool path during the machining of complex profiles in thin wall thin floor parts. The variation in tool path contributes significantly to variation of cutting forces, influencing the distribution of stresses caused by machining. Thus the strategy of the tool path pattern plays a key role in the distribution of the stresses caused by the machining along the work piece. Choosing the correct method of machining strategy (Roughing scheme, Finishing scheme, tool path approaches such as Zig-Zag, Spiral out etc.) is very vital in minimizing work piece distortion during thin wall thin floor parts machining [8][18].

Mandy S. Younger et. al reported that machining distortion occurs when material is removed asymmetrically with respect to the balanced pattern of residual stresses. Various options for minimizing machining distortion are discussed, including machining strategies to reduce unbalancing the residual stress patterns characteristic of materials with various processing histories [19].

Ivan Baranek et. al studied the influence of material removal way and cutting environment on thin-walled part quality by milling. They had chosen three material removal ways for machining and two cutting environments. Rib parts produced using these three ways of material removal and two cutting environments, different quality of surface was absorbed from visual inspection itself. To quantify the dimensional deviation of parts, these were scanned by 3D scanner and compared with CAD model. From the obtained results they concluded that the surface quality of parts produced by all three ways are worst when cutting is done with air and also produces an unpleasant sound during machining. Surface quality of parts produced from 2SOM and 3SOM is good and worst only for 1SOM when cutting is done with using 5% emulsion Blasocut BC 25 [20].

It has been observed that machining strategy (roughing scheme and finishing scheme) is one of the factor which influence distribution of residual stress and hence on the distortion of the parts. An alternative machining of inner diameter and outer diameter during finishing scheme has been adapted in M_1.

Fig 3 shows the sequence of steps to be followed In M_1 strategy.

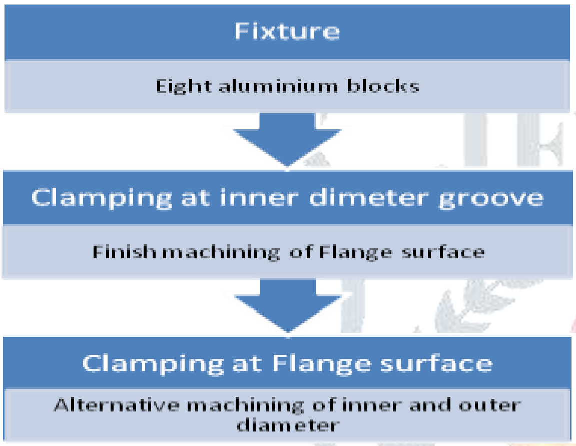

Fig: 3 Machining Procedure for Method 1.

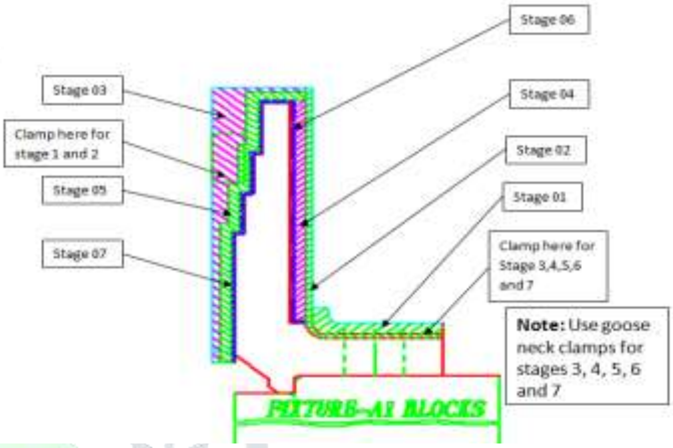

Fig: 4 Operation sketch for method 1(M_1).

The process involved in M_1 strategy is as follows:

a) Cleaning of chuck surface and locators butting face and load the locators (fixture) on to machine chuck and maintain concentricity of each locator with machine axis within limit using dial gauge.

b) Fixture turning operation is carried out to maintain inner diameter and height to receive the part.

c) Load the part on to fixture and Machining is carried out as per operation sketch (figure 4) to maintain the dimensions and geometries.

The dimensional report of this M_1 strategy is presented in Table 2.

2. Change of fixture (M_2):

When large diameter rings (diameter ranges between 2.8m to 3.9m) are to be machined, one serious complication is maintaining the ovality of the ring as well as locating the ring material in symmetry with machine center/chuck.

Adam Patalas et. al, in their study, thin-walled part deformation during finishing turning process caused by gripping force of hydraulic lathe chuck was investigated. Bearing ring was taken as an example of thin-walled part that undergoes finishing turning operation. Finite Element Method (FEM) was used to analyse the deformation of examined part. The aim of this research was to compare the deformation of bearing ring caused by gripping force of hydraulic 3-jaw chuck and 6-jaw chuck for different values of total gripping force. Based on the obtained results, they concluded that application of 6-jaw chuck result in reduction of residual stress and hence deformation of thin-walled parts significantly [21].

L. Nowag et al, studied the effect of clamping technique on the residual stresses and distortion of bearing rings. They considered two different types of clamping mechanisms, a mandrel clamp and segmented jaws. The study showed that the uniform residual stresses were induced in the part which is supported by mandrel. When the part is supported by segmented jaws, residual stresses were induced at 3 real contact locations 120 degrees apart that results in bulging at these locations [22].

Christian Grote et. al, reported that the minimization of the radial deviation and the wall thickness deviation of bearing rings can be done by using standard clamping systems only. Three tests were conducted to minimize the form and wall thickness deviations caused by inhomogeneous material removal. In the first test, hard jaws and segmented jaws are used to clamp the test piece at outer and inner diameter respectively; intention is to minimize the form deviation. In the second test, form locking jaws and mandrels are used to clamp the test piece at outer and inner diameter respectively. The intention is to minimize the form and wall thickness deviation. In the third test form hard jaws are used to clamp the test piece both outer and inner diameter with an intention to minimize the wall thickness deviation. Results concluded that outer form deviation of rings can be minimized by using hard jaws for outer clamping and segment jaws for inner clamping, constant wall thickness of rings is possible with the use of mandrel, clamping force required for form locking jaws is less compared hard jaws, wall thickness deviation can be minimized by using hard jaws only[23].

In M_2 strategy forged ring machined to receive the part is used as fixture. A fixture ring is easier to locate due to ease of trueing comparison to the set of Aluminium blocks. Moreover, the forged ring fixture offers more rigidity to the work piece (ring) during machining, as compared to the Aluminium blocks. Even slightest chance of bending or turning is prohibited. Hence the dimensions may be obtained within acceptable tolerance limit.

Fig 5 shows the sequence of steps to be followed In M_2 strategy.

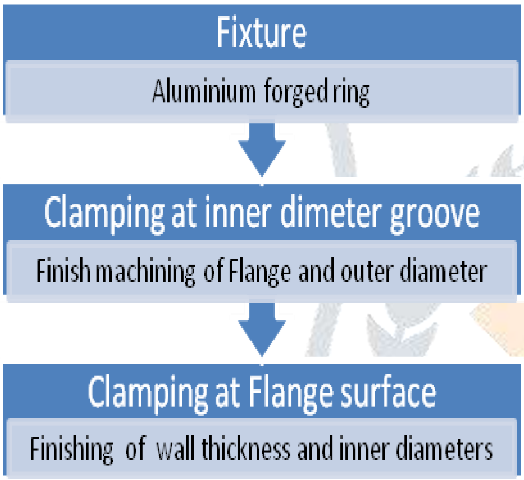

Fig: 5 Machining Procedure for Method 2

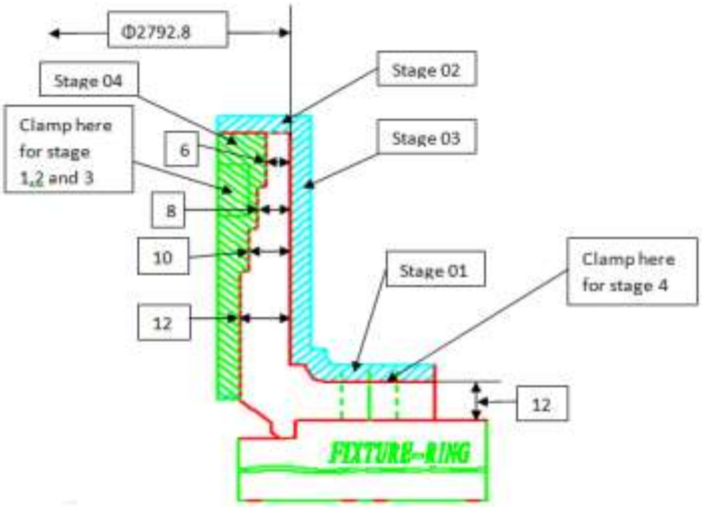

Fig: 6 Operation sketch for method 2 (M_2).

The process involved in M_2 strategy is as follows:

a) Cleaning of chuck surface and aluminium forged ring which is used as fixture and load the fixture on to machine chuck and maintain concentricity of fixture ring with machine axis within limit using dial gauge.

b) Load the part on the fixture and machining is carried out as per operation sketch (Figure 6) to maintain the dimensions and geometries.

The dimension report of this M_2 strategy is presented in Table 2.

3 Combination of modification in material removal way and change of fixture (M_3):

This method is the combination of use of forged rings as fixture (M_2) and modification of material removal strategy (M_1). In this method forged ring is used as fixture in place of aluminium blocks to reduce the set up time and also it gives more rigidity to work piece (ring) and then followed by alternative machining of inside and outside diameter. It takes the advantages of both method M_1 and M_2.

Fig 7 shows the sequence of steps to be followed In M_3 strategy.

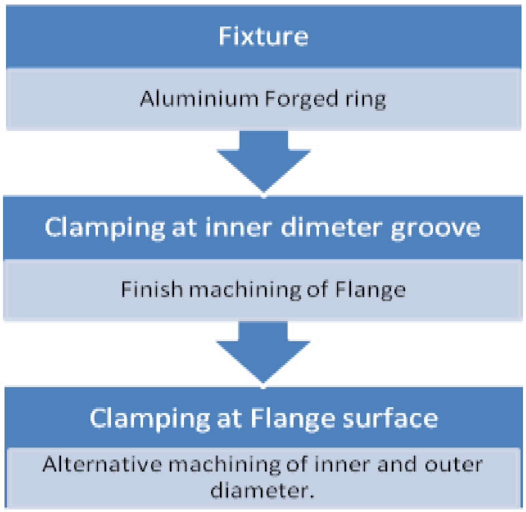

Fig: 7 Machining Procedure for Method 3.

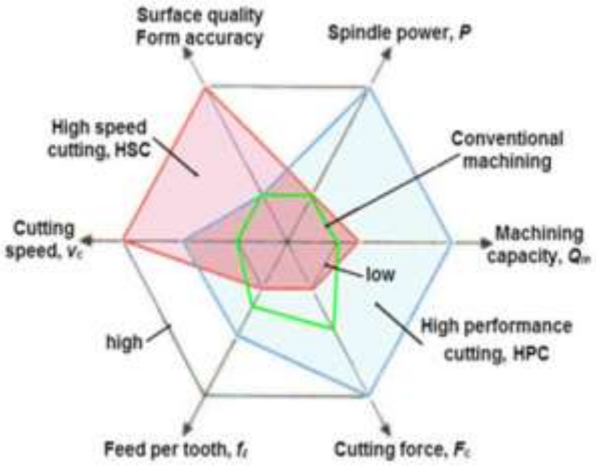

Fig: 8 Comparison of CM to HSM and HPC [26].

The process involved in M_3 strategy is as follows:

a) Cleaning of chuck surface and aluminium forged ring which is used as fixture and load the fixture on to machine chuck and maintain concentricity of fixture ring with machine axis within limit using dial gauge.

b) Load the part on to fixture and machining is carried out as per operation sketch (Figure 4) to maintain the dimensions and geometries.

The dimension report of M_3 strategy is presented in Table 2.

4 Change of machining operation from turning to milling (HSM) (M_4):

Xiaoming Huang et. al, reported that a high-speed milling experiment by means of orthogonal method with four factors was conducted for aluminium alloy AA7050-T7451. The residual stresses (RS) on the surface and subsurface of the work piece were measured using X-ray diffraction technique and electro polishing technology. It has been observed that increase of the cutting speed and decrease of the feed rate lead to significant decrease of machine- induced compressive residual stresses on AA7050-T7451 finished surface. To some extent, the analysis of the machining forces and thermal effects provides explanations for the observed residual stress transformation trends [24].

Paweł Bałon et. al, have highlighted that high speed machining (HSM) or High Speed Cutting (HSC) is currently one of the most important technology used in the aviation industry. The difference between HSM and other milling techniques is the ability to select cutting parameters such as depth of the cut, feed rate and cutting speed. At the same time it ensures high machining efficiency, high quality and precision of the machined surface. Use of high milling speed not only enables economical manufacturing of integral components by reducing machining time but also improves the quality of the machined surface. This happened due to the fact that cutting forces are significantly lower for high cutting speeds than for standard machining techniques [25].

Considering the properties of high speed cutting (HSC) and high performance cutting (HPC), HSC can be defined as machining at high cutting speeds and low machined layer cross-section values. HPC uses moderate cutting speeds at much higher axial and radial traverse (i.e. cutting depth and width values) and feed per tooth values. Figure 8 shows the comparison of conventional machining to high speed machining and high performance cutting.

When machining is carried out at high speed about 15000 rpm, the cutting forces will be reduced and also duration of the tool contact with the part is minimum and hence thickness variation and ovality may get within specified limits. This is the unusual method of machining the circular ring on a rectangular bed.

Fig 9 shows the sequence of steps to be followed In M_4 strategy.

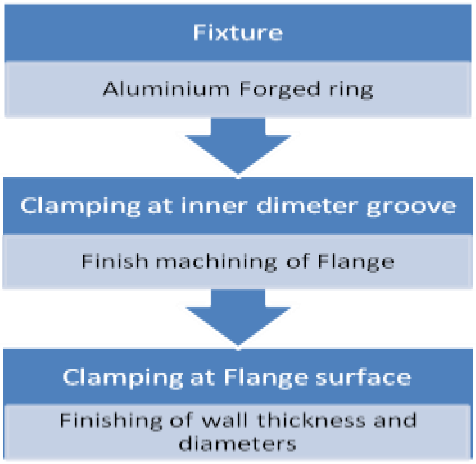

Fig: 9 Machining procedure for Method 4

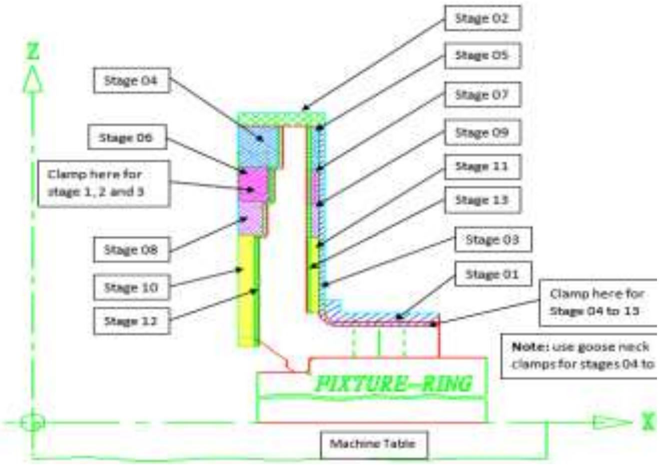

Fig: 10 Operation sketch for method 4.

The process involved in M_4 strategy is as follows:

a) Cleaning of machine table surface and aluminium forged ring which is used as fixture and load the fixture on to machine table.

b) Load the part on to fixture and machining is carried out as per operation sketch (Figure 10) to maintain the dimensions and geometries.

The dimension report of M_4 strategy is presented in Table 2.

III Evaluation of thin-walled part dimensions and geometries.

Once the machining process is completed it is necessary to validate the component as per drawing requirements. For validation LAMBDA model co-ordinate measuring machine and ultrasonic thickness measuring gauge is used. Co-ordinate measuring machine used here is a numerically controlled 3D machine.

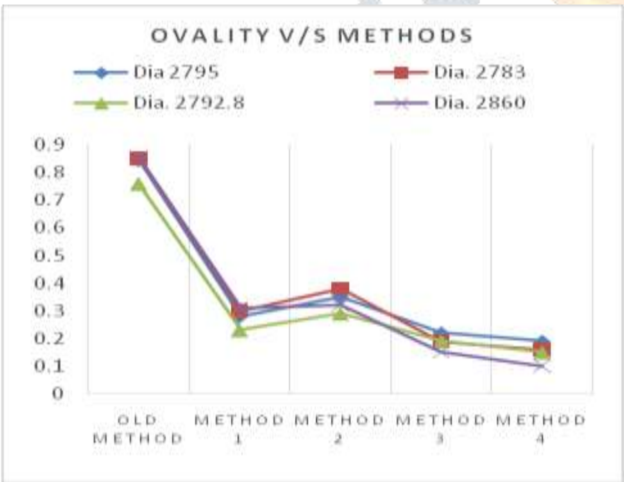

Fig: 11 Ovality Vs Methods

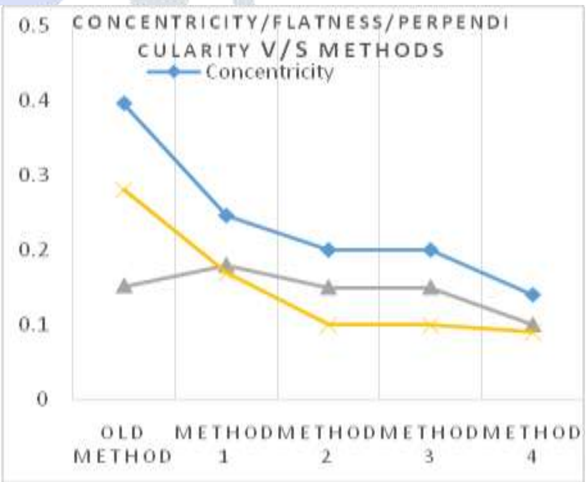

Fig: 12 Concentricity/Flatness/Perpendicularity Vs Methods

The summary of dimensional inspection reports of all four methodologies has been presented in Table2:

Table 2 inspection report of all four methodologies:

Param NO	Nomenclature	Drawing value	Actual measurements					Remarks
			Old method	M_1	M_2	M_3	M_4	
01	Concentricity	0.2	0.396	0.246	0.2	0.2	0.14	
02	Flatness	0.3	0.152	0.18	0.15	0.15	0.10	
03	Thickness	$6^{+/-0.1}$	6.41	6.22	6.29	6.10	6.08	
04	Thickness	$8^{+/-0.2}$	8.36	8.20	8.25	8.18	8.12	
05	Thickness	$10^{+/-0.2}$	10.31	10.15	10.20	10.17	10.10	
06	Thickness	$12^{+/-0.2}$	12.35	12.13	12.20	12.11	12.10	
07	Perpendicularity	0.3	0.281	0.17	0.1	0.1	0.09	
08	Diameter 2795 ovality as per 3D report	0.2	0.846	0.28	0.35	0.25	0.18	
09	Diameter 2783 ovality as per 3D report	0.2	0.851	0.3	0.38	0.19	0.16	
10	Diameter 2792.8 ovality as per 3D report.	0.2	0.758	0.23	0.29	0.19	0.15	
11	Diameter 2860 ovality as per 3D report	0.2	0.854	0.31	0.32	0.15	0.10	

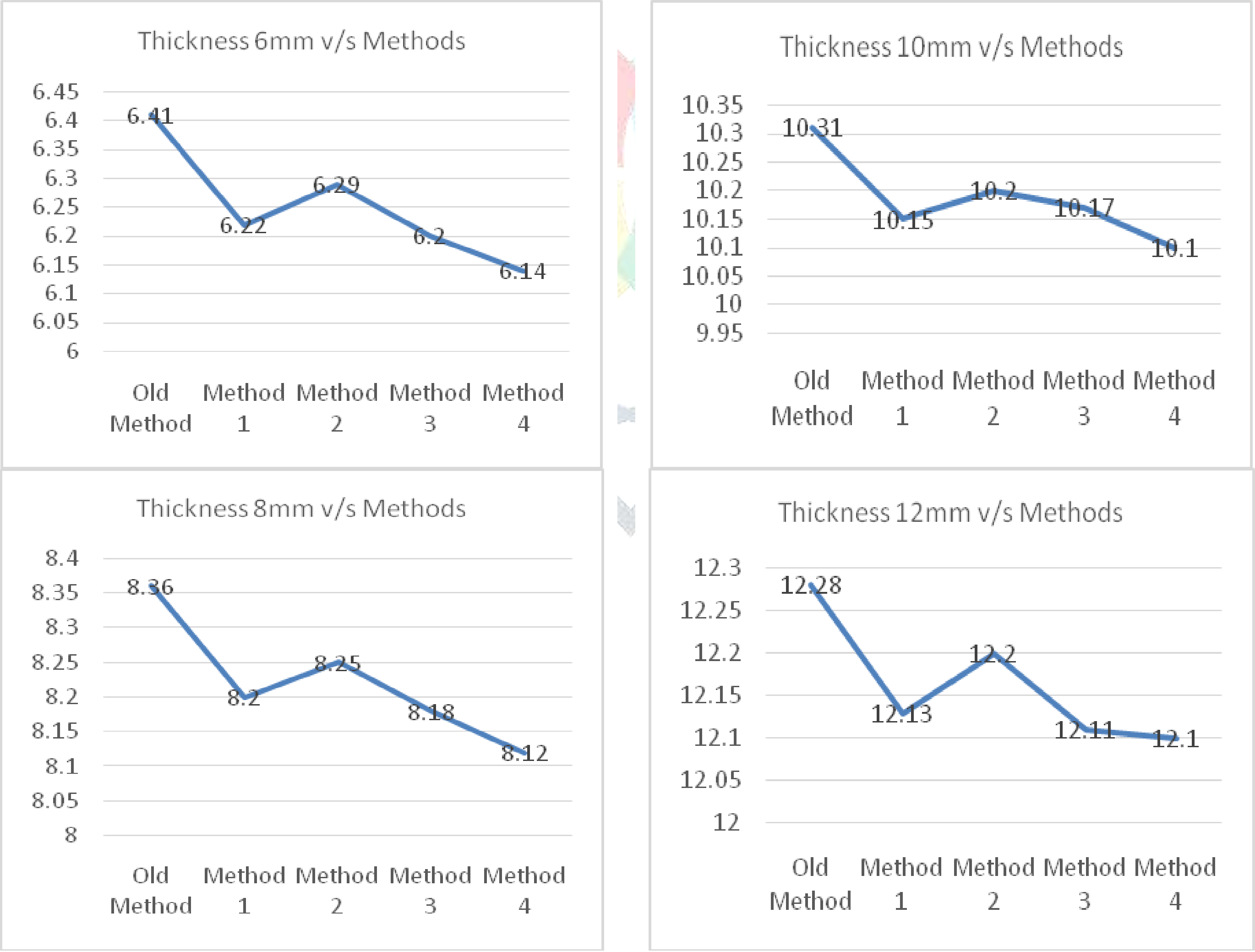

Fig: 13 Thickness vs methods

IV. RESULTS:

The dimensional test results were analyzed starting with effect of material removal strategy, change of fixture, combination of material removal strategy and change of fixture and change of machining operation from turning to milling (HSM) on dimensional and geometric errors.

Summary of Inspection report of all four methodologies are provided in Table 2. From inspection reports of modification of material removal strategy method (M_1), the concentricity reduced from 0.396mm to 0.246mm, flatness increased from 0.152mm to 0.18mm, thickness variation reduced to 6.22mm, 8.20mm, 10.15mm and 12.13mm, perpendicularity reduced from 0.281mm to 0.17mm. Diameter 2795mm ovality reduced from 0.846mm to 0.28mm, Diameter 2783mm ovality reduced from 0.851mm to 0.30mm, Diameter 2792.8mm ovality reduced from 0.758mm to 0.23mm, Diameter 2860mm ovality reduced from 0.854mm to 0.31mm. Total machining time is reduced from170 hours to 161 hours 08 minutes.

From inspection reports of change of fixture method (M_2), the concentricity reduced from 0.396mm to 0.2mm, flatness reduced from 0.152mm to 0.15mm, thickness variation reduced to 6.29mm, 8.25mm, 10.20mm and 12.20mm, perpendicularity reduced from 0.281mm to 0.1mm. Diameter 2795mm ovality reduced from 0.846mm to 0.35mm, Diameter 2783mm ovality reduced from 0.851mm to 0.38mm, Diameter 2792.8mm ovality reduced from 0.758mm to 0.29mm, Diameter 2860mm ovality reduced from 0.854mm to 0.32mm. Total machining time is reduced from170 hours to 158 hours 56 minutes.

From inspection reports of combination of modification of machining strategy and change of fixture method (M_3), the concentricity reduced from 0.396mm to 0.2mm, flatness reduced from 0.152mm to 0.15mm, thickness variation reduced to 6.10mm, 8.18mm, 10.17mm and 12.11mm, perpendicularity reduced from 0.281mm to 0.1mm. Diameter 2795mm ovality reduced from 0.846mm to 0.25mm, Diameter 2783mm ovality reduced from 0.851mm to 0.19mm, Diameter 2792.8mm ovality reduced from 0.758mm to 0.19mm, Diameter 2860mm ovality reduced from 0.854mm to 0.15mm. Total machining time is reduced from170 hours to 149 hours 56 minutes.

From inspection reports of change of machine from turning to high speed milling method (M_4), the concentricity reduced from 0.396mm to 0.14mm, flatness reduced from 0.152mm to 0.10mm, thickness variation reduced to 6.08mm, 8.12mm, 10.10mm and 12.10mm, perpendicularity reduced from 0.281mm to 0.09mm. Diameter 2795mm ovality reduced from 0.846mm to 0.18mm, Diameter 2783mm ovality reduced from 0.851mm to 0.16mm, Diameter 2792.8mm ovality reduced from 0.758mm to 0.15mm, Diameter 2860mm ovality reduced from 0.854mm to 0.10mm. Total machining time is reduced from170 hours to 118 hours 08 minutes.

Table 2 shows the summary of dimensional and geometric deviations of all four components machined from four methodologies. The obtained results from method1 (M_1) revealed that all parameters except concentricity, 6mm thickness and ovality are within the specified limits mentioned in the drawing, method2 (M_2) revealed that all parameters except 6mm thickness, 8mm thickness and ovality are within limit specified in the drawing, method3 (M_3) revealed that all parameters except ovality of diameter 2795mm, are within limit specified in the drawing and method4 (M_4) revealed that all parameters are within limit specified in the drawing. Further analyzed that the total machining time is minimum for fourth (M_4) methodology.

V. CONCLUSION:

The following conclusions can be drawn from present investigation:

- From the analysis it can be concluded that all four machining methodologies have significant effects on the dimensions and geometries of the thin walled components.
- From the summary of inspection report of four components all dimensions and geometries were well within the drawing specified limits for method M_4 where in the component is held using aluminium forged ring as fixture and machined using HSM technology. In other words the cutting forces effects significantly on dimensional and geometrical deviations of thin walled components compared to material removal way and holding method.
- From the results it can also be concluded that the effect of all four methodologies on dimensional and geometrical deviations of thin walled components are in the order of change of machining from turning to milling (HSM) (M_4), Combination of material removal way and change of fixture (M_3), Modification of material removal way (M_1) and change of fixture (M_2).

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