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Distortion Analysis of Arc Shaped Workpiece in NC Machining

Mei Zhongyi, Wang Yunqiao, and Amir Saleem

Abstract—**The objective of this study is to simulate and analyze the effect of residual stress on NC machining distortion. NC machining distortion theory is studied by analyzing the typical aircraft arc shaped workpiece. The causes which lead to machining distortion are analyzed. It indicates that induced residual stress developed at the material manufacturing state is the main source of post machining distortion. The direct coupled field analysis is adopted to develop a quenching induced residual stress field in the workpiece. The contacting analysis technique is used to predict the machining residual stresses developing. Square shaped plates with different thickness are selected to simulating the distortion generated by machining induced residual stresses and quenching induced residual stresses after material removal. A comparison of the distortions generated by two kinds of residual stresses is also presented. Several arc shaped workpieces are adopted to establish initial residual stress fields and simulate the distortion in different cutting quantity and cutting sequence. The simulating results are compared with the actual machining data. It presents that both distortion trends are consistent. The validity of the analysis method is verified. Finally, some suggestions and conclusions are proposed.**

Index Terms—**distortion, residual stress, NC machining, arc shaped workpiece, simulation**

I. Introduction

Aircraft structures are generally large thin walled components. Parts are often machined to spars, ribs, stringers, and frames from large blank. Metal material removal is around 90-95%. The machined aircraft structures include ribs, frames and spars in a civil aircraft manufacture company. Most of these thin walled components are machined by CNC milling machine. Deflection and distortion can immensely enhance for thicknesses around 1.5 to 3 mm as the structure rigidity lessens. Thin walled arc shaped workpieces (Fig.1) suffer more seriously distortions as comparing to other components. Therefore, in order to attain the accuracy of these parts, it is imperative to adopt the distortion control strategies and remedial measures during the machining operations.

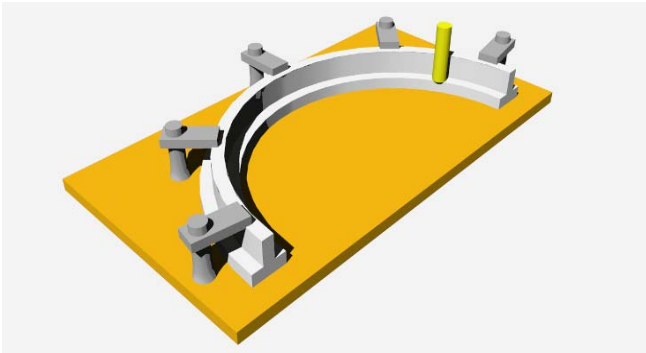

Fig. 1. Thin walled arc shaped workpiece

The performance of aircraft components is extremely sensitive to the final part quality and dimensional accuracy. Induced residual stresses or strains developed at the material manufacturing state are the main source of post machining distortions [1]. So the influence of residual stresses on machining distortions is mainly discussed in this paper. The other sources of machining distortion include cutting and clamping [2]. Another important factor causing the distortions is the material removal volume. In case of aircraft components, an approximately 90% volume is removed from the blank in order to reduce the weight. This increases the distortion potential to a great extent because of weakened rigidity and the release of excessive residual stresses. For example, in manufacturing of large aluminum aircraft thin walled arc shaped workpieces, machining is quite difficult and obviously a tedious task to control the resulting distortions. Therefore, an early prediction of post machining distortions via CAE simulations helps to manufacture such components precisely [3-6]. Some layout optimization models which are developed and carried out by FEM are adopted to improve the overall workpiece deformation and distribution condition [7]. An integrated design and optimization approach is developed to find the optimal manufacturing configuration designs [8-11]. This approach incorporates the non-parametric optimization and CAE manufacturing simulations at an early design stage. Topology optimization is executed to find the optimum material distribution (initial structural layout) of the initial design space. The manufacturability is predicted through CAE cutting simulation techniques. CAE software is used to simulate the post machining distortions and dimensional accuracies. This paper also adopts CAE manufacturing simulation to analyze residual stress effects on NC machining

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distortion of arc shaped workpiece.

II. Analyzing Residual Stresses

Manufacturing operations can generate residual stresses in most of the engineering materials, which may lead to plastic distortions. For example, parts manufactured from die forgings, rolled sheet material, welded products and quenched forgings are likely to contain residual stresses. The NC machining also creates residual stresses. The induced residual stress generates the detrimental effects on the manufactured components. These not only affect the material stability and dimensional accuracy of the finished parts, but also deteriorate their mechanical characteristic like corrosion, fatigue, stiffness, stress corrosion cracking due to surface tensile stresses etc.

Until now, various research efforts in the form of experimental findings, analytical modeling, finite element modeling and combinations of these have been carried to estimate, predict and simulate the effects of pre and post machining induced residual stresses. After the material heat treatment, different stress relieving operations are performed to relieve the induced residual stresses, such as pre-stretching and artificial aging. Through these operations, stresses are reduced to satisfactory level but cannot be eliminated completely.

The main residual stresses of aluminum alloy after heat treatment and artificial aging are quenching heat stress. Fig.2 shows the residual stresses distribution of aluminum alloy along the thickness direction after heat treatment. After stress relieving operation by pre-stretching, the stresses were reduced, but the stresses distribution is more complicated.

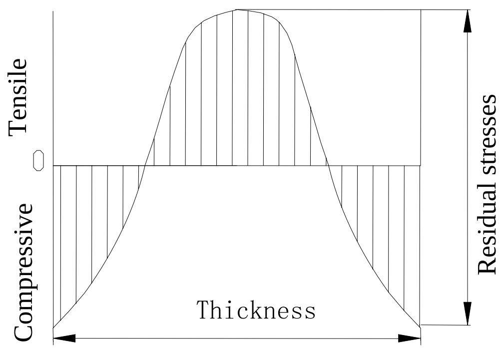

Fig. 2. Residual stresses distribution of aluminum alloy after heat treatment

III. Simulating Residual Stresses

A. Simulating Initial Residual Stresses

Before executing cutting simulation, a direct coupled field analysis is performed to develop an initial residual stress field in the model. Residual stresses are developed in the actual material due to heat treatment processes. Initial residual stress developed during the material processing is the main cause of post machining distortions. Generally, effects of these are not considered at the early design stage. However, through manufacturing simulations, these can be studied and controlled by effective measures like applying an additional stress relieving process etc.

Simulation process can be accomplished in two steps, a thermal analysis followed by a structural analysis. Firstly, a thermal analysis is performed. The thermal parameters are defined and the model is discretized into elements by using an appropriate thermal element type. Temperatures are used approximately same to the actual material heat treatment (quenching, thermal rolling etc). Convection loads are applied to the outer exposed surfaces. Then, the structural analysis is performed by using the result of initial temperature distribution and a residual stress field is generated. The stress values attained are evaluated by comparing with the standard published data. The whole process is explained in the Fig.3.

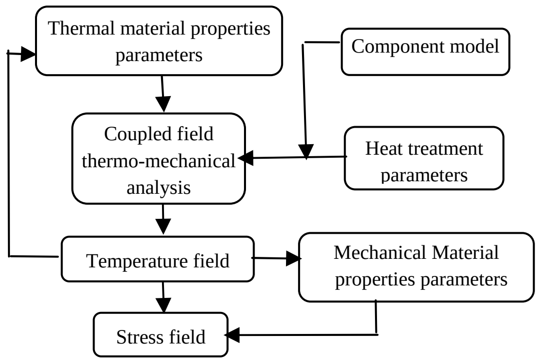

Fig. 3. Process of direct coupled field analysis

B. Simulating Machining Induced Residual Stresses

In the machining process, the causes which lead to residual stresses occurring include the plastic deformation in front field of the cutter, extrusion and smoothing underside the field of the cutter, and the effect of thermal stresses. The residual stresses produced by NC machining are distributed on a slight portion on surface of the component. The machining induced residual stresses are related to machining manner and cutting parameter. Generally， the cutting depth of aircraft component approximates 1 mm. The machining induced residual stresses exist below 0.15mm of the cutting layer.

The contacting analysis technique is used to predict the distortion and the residual stresses developing. An updating lagrangian method is applied to simulate machining process. The emphases is predicting the distribution of the machining and post machining induced residual stresses which distribute in the component surface, and also confirming the effect of milling quantity and sequence on the final magnitude and distribution of residual stresses. The ideal residual stress distribution can be obtained via selecting appropriate cutting parameters and optimizing machining processes.

IV. Distortion Generated by Removing Material

The post machining residual stress field is overlapped by initial residual stresses and machining induced residual stresses. After removing material, the stresses become imbalance which results in distortion, inner stresses releasing and stresses redistributing. The significant difference between initial residual stresses and machining induced residual stresses is the thickness of stress distribution in

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component. Firstly, the effect which two kinds of residual stresses releasing lead to distortion in different thickness components is estimated. Subsequently, the machining distortions of square plates with different thickness is analyzed which is used to determining the sensitivity of different thickness components for two kinds of residual stresses.

The selected blank material is aluminum alloy 2A70. The water temperature of quenching is 75-85℃. In order to confirm the effect of both the quenching induced residual stresses and the machining induced residual stresses on machining distortion, the stress releasing and distortion in square plates with different thickness is simulated. Square plates with blank size 250x250 mm and 5, 15, 25, 35, 50 mm separately in thickness direction are selected as test specimen. The thickness of removed material is one fifth thickness of the square plate, i.e. 1, 3, 5, 7, 10 mm separately. Due to symmetry of the square plate, only one fourth finite element model is selected for simulation.

A. Simulating the Distortion Generated by Machining Induced Residual Stresses

Similar machining induced residual stress field is applied to five test plates with different thickness. Machining induced residual stresses are added to the refined elements at outer layer of test specimen 1 mm in thickness, as shown in Fig.4. The machining processes are simulated through an element deactivation technique (element Birth/Death feature in ANSYS software). The loads are removed once the material removal is finished. In order to simulate the state of removing loads, all additional constraints are removed and the symmetrical section constraint is applied to the component to restricting rigid body motion. The models of machining induced residual stress field are also shown in Fig.4. Only considering the effect of machining induced residual stresses, the distortion distribution after material removed from top layer of the component is shown in Fig.5. In Fig.5, it's clearly shown the perimeter around the component warping upward.

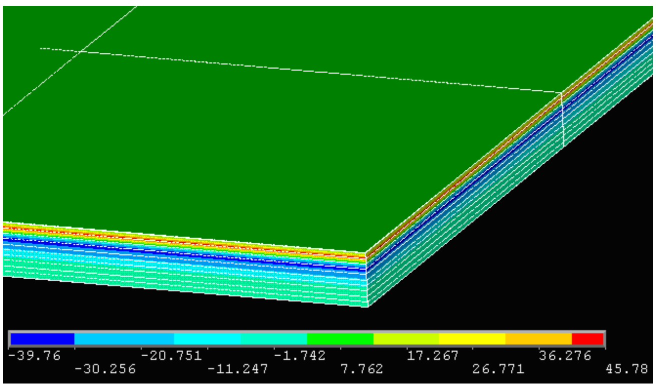

Fig. 4. Machining induced residual stresses are added to plate at outer layer of test specimen 1 mm in thickness

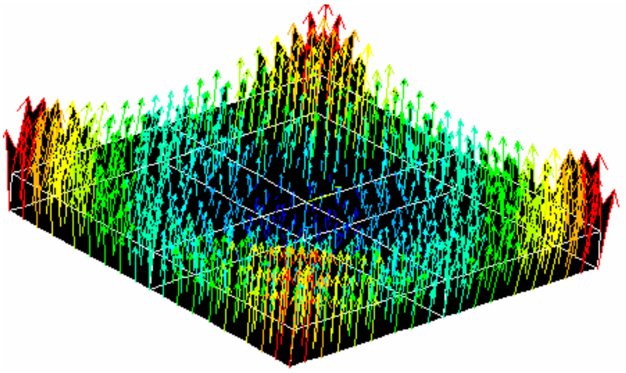

Fig. 5. Vector graph of the distortion after material removed from top layer

B. Simulating the Distortion Generated by Quenching Induced Residual Stresses

The direct coupled field analysis is performed to simulate a quenching induced residual stresses distribution in a square plate, as shown in Fig.6. The residual stresses are distributed in whole thickness direction. Only considering the effect of quenching induced residual stresses, the distortion distribution after material removed from top layer of the component is shown in Fig.7. The distortions tend to the bend downward around the component edges. After distortion, the residual stresses have been relieved, the maximum stress values have reduced greatly and the residual stresses distribution have also tended to more uniform, as shown in Fig.8.

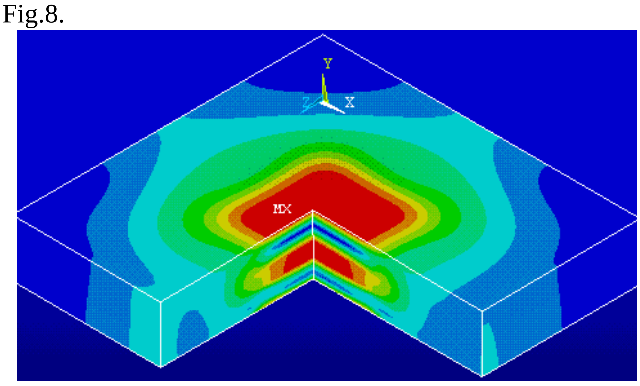

Fig. 6. Quenching induced residual stresses distribution

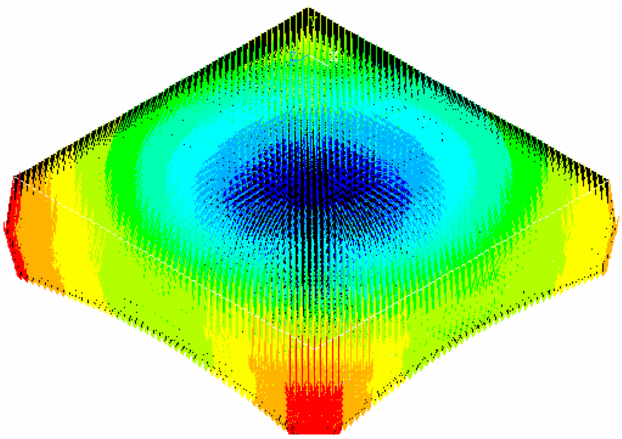

Fig. 7. Distortion distribution created by quenching induced residual stresses

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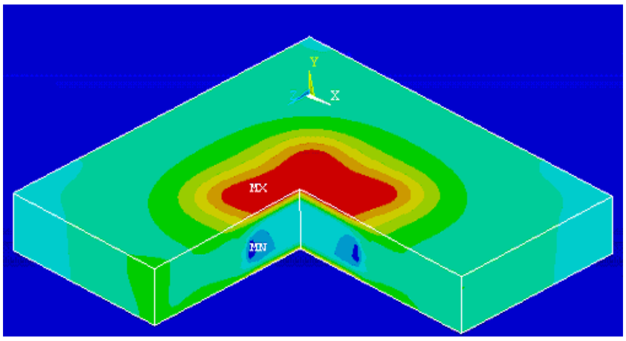

Fig. 8. Residual stresses distribution after material removed from top layer of the component

C. Comparing the Distortion Created by Two Kinds of Residual Stresses

The distortions created by each of the quenching induced residual stresses and the machining induced residual stresses in different thickness are shown in Fig.9. The simulation result reveals that distortion is mainly created by machining induced residual stresses in thin workpiece. For aluminum alloy 2A70, the thickness of thin workpiece is less than 6-7 mm, decreasing the machining induced residual stresses, in the thin walled workpiece during milling operation, is the main measure of controlling distortion. The mentioned cause of distortion can be reduced by improving the rigidity of the machining system and optimizing the cutting parameters. For machining thick workpiece, thickness greater than 10 mm, distortion is mainly created by quenching induced residual stresses which distribute along the entire thickness direction.

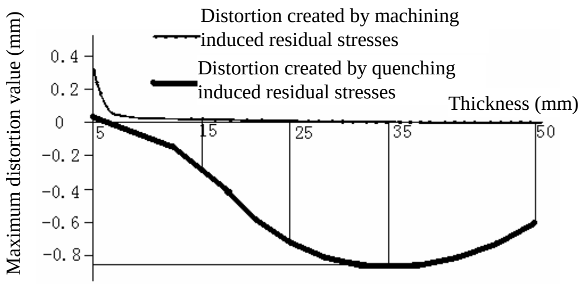

Fig. 9. Distortions created by two kinds of residual stresses in different thickness

V. Machining Distortion of Arc Shaped Workpiece

A. Choosing Machining Scheme of Arc Shaped Workpiece

Via analyzing the shape and thickness of the arc shaped workpiece, quenching induced residual stresses field is the main cause of machining distortion. So machining simulation of arc shaped workpiece mainly considers the effect of quenching induced residual stresses. In order to simplify the calculation and simulation, the initial model of arc shaped workpiece is designed to square section with size 60×60 mm and radius 600 mm. The element Birth/Death technique in ANSYS software is adopted for cutting simulation. A hexahedron element can satisfy the simulation requirements. Due to initial residual stresses are created by material heat treatment, the direct coupled field thermo-mechanical analysis is performed to develop an initial residual stress field in the initial model. For arc shaped workpiece with material of aluminum alloy 2A70, the heat treatment induced residual stresses distribute as follows, tensile stress distribute in the center of the workpiece, compressive stress distribute in the exterior of the workpiece, the stress values reduce gradually from inner to outer side. These are shown in Fig.10.

The distortion caused by material removal on inner and outer sides of the ring is simulated by using FEM. The thickness of removed material every times can be 6 mm, 12 mm or 18 mm. Optimal sequence of thickness and location of material removed from workpiece can reduce distortion. After removing material 6 mm in inner side of the ring and the workpiece has been released, the maximum radial distortion is 1.126 mm and the distortion direction is stretching outward, as shown in Fig.11. Distortion increases to 3.291 mm with one more cut of 6 mm in inner side of the ring for the same workpiec. In contrast to two 6 mm cut, a single 12 mm cut in inner side generates a maximum radial distortion of 3.834 mm.

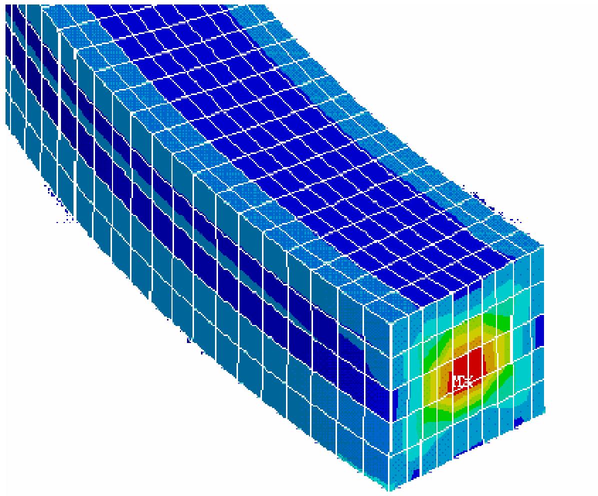

Fig. 10. Initial residual stress field in the model

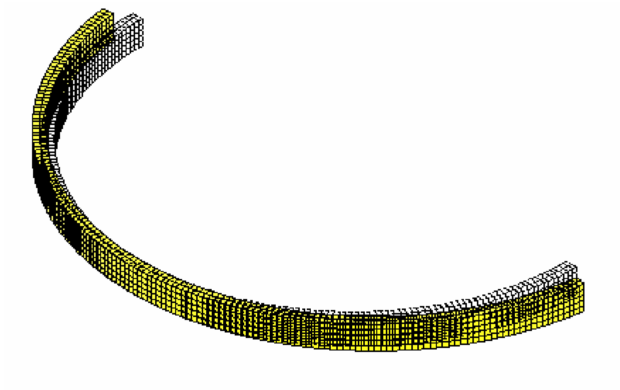

Fig. 11. After removing material in inner ring, the distortion direction is stretching outward

Along with material removed, the stresses release gradually, stresses tend to reducing and distributing uniformly. The rigidity of the workpiece also reduces gradually. But the distortion increases with the rigidity reducing. After removing first layer of material in inner ring, the stress distribution is shown in Fig.12.

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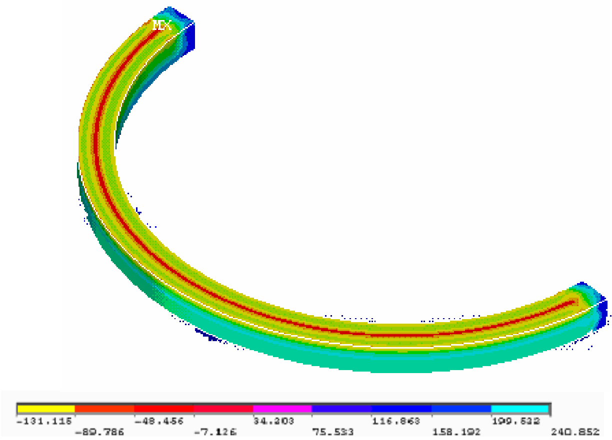

Fig. 12. Stress distribution after removing first layer of material in inner ring

According to actual design, 18mm and 6mm material should be removed from inner and outer ring respectively. Considering all possible machining sequence, all cutting processes are simulated. The distortion and stress distribution are recorded and presented in Table I.

TABLE I
DISTORTIONS AND STRESSES OBTAINED BY 12 POSSIBLE MACHINING PLANS

Num	The methods of removing material	Maximum radial distortion (mm)	The level of tensile stress (MPa)	The level of compressive stress (MPa)
1	S+S+ W+S	1.221	48	73
2	S+ W+S+S	1.252	54	35
3	S+W+M	1.267	46	83
4	M+W+S	1.273	48	60
5	W+L	1.281	47	116
6	L+W	1.228	46	128
7	S+M+W	1.241	47	110
8	M+S+W	1.243	48	75
9	S+S+S+W	1.257	51	50
10	W+S+S+S	1.170	53	50
11	W+S+M	1.190	48	71
12	W+M+S	1.205	54	50

In the second column of Table I, S denotes removing material with 6 mm in thickness in inner ring at one times, M denotes removing material with 12 mm in thickness in inner ring at one times, L denotes removing material with 18 mm in thickness in inner ring at one times, W denotes removing material with 6 mm in thickness in outer ring at one times, S+S+S denotes removing material with 18 mm in thickness in inner ring at three times, and so on.

It can be seen in Table I, the distortion created by the scheme 10 which removing material at W+S+S+S manner is minimum. But the machining cost is higher than the cost of the scheme 11 and scheme 12. Choosing the optimized cutting sequence can reduce the distortion by 10 %.

Some intermediate data which come from the machining simulation in Table I are recorded in Table Ⅱ, Table Ⅲ, and Table Ⅳ. These intermediate data are used as reference data to analyze the distortion. Nine possible machining plans which are adopted for removing material 18 mm in thickness (at most 6 mm in outer ring) are recorded in Table Ⅱ. Four possible machining plans which are adopted for removing material 12 mm in thickness (at most 6 mm in outer ring) are recorded in Table Ⅲ. Two possible machining plans which are adopted for removing material 6 mm in thickness (only one layer) are recorded in Table Ⅳ.

TABLE Ⅱ
NINE POSSIBLE MACHINING PLANS FOR REMOVING MATERIAL 18 MM IN THICKNESS

Num	The methods of removing material	Maximum radial distortion (mm)	The level of tensile stress (MPa)	The level of compressive stress (MPa)
13	S+S+S	4.023	120	108
14	M+S	5.746	108	124
15	S+M	4.374	112	119
16	L	5.365	97	140
17	S+S+W	2.002	171	118
18	W+S+S	2.109	222	89
19	S+W+S	2.087	204	104
20	M+W	2.292	146	113
21	W+M	2.365	195	95

TABLE Ⅲ
FOUR POSSIBLE MACHINING PLANS FOR REMOVING MATERIAL 12 MM IN THICKNESS

Num	The methods of removing material	Maximum radial distortion (mm)	The level of tensile stress (MPa)	The level of compressive stress (MPa)
22	S+W	-0.265	219	135
23	W+S	-0.306	212	105
24	S+S	3.291	174	123
25	M	3.834	172	112

TABLE Ⅳ
TWO POSSIBLE MACHINING PLANS FOR REMOVING MATERIAL 6 MM IN THICKNESS

Num	The methods of removing material	Maximum radial distortion (mm)	The level of tensile stress (MPa)	The level of compressive stress (MPa)
26	S	1.126	240	107
27	W	-1.314	235	119

In Table Ⅲ and Table Ⅳ, positive values in table means distortion stretching outwards and negative values means distortion shrinking inwards.

From Table Ⅱ to Table Ⅳ, it shows the machining scheme 13, 14, 15, 16, 24 and 25 which remove material only in one side (only in inner ring) generate more distortion. If adding cutting material in outer ring, the distortions decrease greatly. These can be seen in the scheme 22 and scheme 23. In scheme 22 and scheme 23, because of removing material symmetrically in inner ring and outer ring, the maximum distortion values decrease to the smallest and the distortions also shrink inwards.

B. Simulating Results Compare with Actual Machining Results

For actual machining, some locating holes are added in the workpiece. The finished section of the workpiece looks like the shape of T, as shown in Fig.13. Because of the limitation of machining cost, only the scheme 9 and scheme 10 in Table I are actually machined. Some intermediate data which correspond to the scheme 13 and scheme 27 are also recorded. These are presented in Table Ⅴ. The distortions created by machining simulation and actual machining present consistency in magnitude and direction. The distortion values created by machining simulation are higher than the values

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created by actual machining. The reason is that quenching induced residual stresses in machining simulation have not undergone the process of artificial aging.

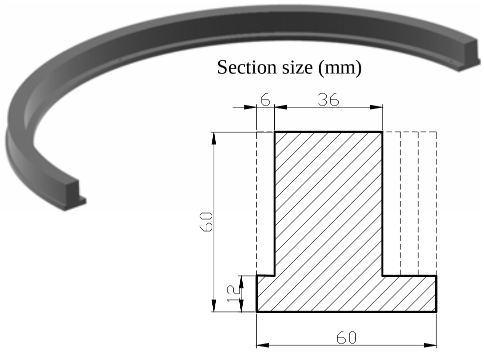

Fig. 13. Structure of actual machined arc shaped workpiece

TABLE V
MAXIMUM RADIAL DISTORTIONS COMPARED BETWEEN MACHINING SIMULATION AND ACTUAL MACHINING (MM)

The methods of removing material	S+S+S+ W	W+S+S+S	S+S+S	W
Simulating results	1.257	1.170	4.023	-1.314
Actual machining results	0.913	0.802	3.262	-0.681

C. *Result and Discussion*

By simulating the machining process of arc shaped workpiece in different machining sequence and actually machining arc shaped workpiece. Some conclusions can be achieved, as follows:

1) The first removing material leads to the high residual stresses released. The following removing material also leads to the residual stresses released. But the decreasing rate becomes slow greatly.
2) Decreasing the cutting quantity can reduce the distortion of the workpiece. The difference of the distortion created by minimum cutting quantity and maximum cutting quantity can reach 10% of the maximum distortion.
3) In rough machining process, removing more material at one times can decreasing the residual stresses greatly. But comparing with the removing material increasing, the distortion increasing is not at the same proportion.
4) Removing material symmetrically in inner ring and outer ring can reduce distortion greatly than only removing material in inner ring or in outer ring.
5) Cutting sequence in inner ring and outer ring can affect the machining distortion.

VI. CONCLUSIONS

The main cause leading to distortion is the residual stresses which distribute in the workpiece. In this paper, the distortions created by machining induced surface residual stresses and quenching induced initial residual stresses are analyzed separately. The contacting analysis technique is used to simulate the machining process of aluminum alloy and predict the residual stresses distribution which is created during machining and after machining. A direct coupled field analysis is adopted to simulate the initial residual stress field in the workpiece. The distortions affected by two kinds of residual stresses in different thickness are also analyzed. If the thickness of thin workpiece is less than 5-6 mm, machining induced residual stresses is the main cause generating distortion. Whereas, if the thickness of the workpiece is greater than 10 mm, quenching induced residual stresses are mostly responsible for the distortion.

Arc shaped workpieces have been adopted to establish initial residual stress fields and simulate the distortion in different cutting quantity and cutting sequence. Based on the simulation results, arranging appropriate cutting quantity and cutting sequence in inner ring and outer ring can decrease the distortion and can achieve uniform stress distribution.

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