DEVELOPMENT OF SLOTTED ARRAY ANTENNA FOR AIRBORNE RADAR APPLICATION

A DISSERTATION SUBMITTED TO THE
FACULTY OF TECHNOLOGY
OF
UNIVERSITY OF DELHI

TOWARDS THE PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE AWARD OF DEGREE OF MASTER OF ENGINEERING
IN
MECHANICAL ENGINEERING
(PRODUCTION ENGINEERING BRANCH)

SUBMITTED
BY
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UNDER THE VALUABLE GUIDANCE
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CERTIFICATE

This is to certify that the dissertation entitled **"DEVELOPMENT OF SLOTTED ARRAY ANTENNA FOR AIRBORNE RADAR APPLICATION"** being submitted by **S. MANI,** in partial fulfillment for the award of the degree of **Master of Engineering** in **Mechanical Engineering** (**Production Engineering Branch**) of **DELHI UNIVERSITY**, is a record of bonafide research work carried out by him at Electronics and Radar Development Establishment, Defence Research & Development Organization, Ministry of Defence, Government of India, Bangalore-560 093 during the year 2004-05.

He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the required standard. Further, it is also certified that this work has not been submitted for any other degree or diploma in any college to the best of our knowledge and belief.

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This is to certify that S.MANI, Scientist 'C', LRDE, Bangalore and who is at present M.E. student of DELHI COLLEGE OF ENGINEERING, DELHI-110042 has carried out his major project work entitled "DEVELOPMENT OF SLOTTED ARRAY ANTENNA FOR AIRBORNE RADAR APPLICATION" at this Establishment in Mechanical Engineering Division under the guidance of MR. S. SIVAKUMAR Scientist 'E', LRDE, Bangalore as his co-guide.

During his project work the student has shown keen interest in learning new areas and a high degree of perseverance and skill in applying Finite Element Method and CNC machining techniques for the development of Slotted Array Antenna for Airborne Radar application.

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LIST OF SYMBOLS

A	Amperes
GPa	Giga Pascal
HB	Brinell Hardness
IXX, IYY, IZZ	Area moment of inertia
J	Joules
K	Kelvin
Kg	Kilo gram
Km	Kilo meter
KW	Kilowatts
MPa	Mega Pascal
N	Revolutions Per Minute (RPM)
R	Range to target
S	Second
V	Cutting speed
W	Weber
c	Speed of light
g	Gravitational load
m	Meter
min	Minute
mm	Millimeter
$\mathbf{R_a}$	Roughness average value
°C	Degree centigrade
θ	Orientation of the element
μ	Micron or Micrometer
Ø	Diameter
%	Percent

ACKNOWLEDGEMENT

I express my sincere thanks to **Professor Maji**, HOD, Department of Mechanical Engineering, Delhi College of Engineering and **Professor C. K. DUTTA**, former HOD, Department of Mechanical Engineering, who provided me a great opportunity to do my project in Electronics and Radar Development Establishment (LRDE) Bangalore-93.

I convey my profound gratitude to **Shri. M. A. SUNDER SINGH**, Scientist 'F', Additional Director and Divisional Officer, Mechanical Engineering Division, Electronics and Radar Development Establishment (LRDE) Bangalore-93, for his acceptance, invaluable guidance, support, and untiring enthusiasm in motivating me in the right direction during entire course of this project work.

I convey my deepest gratitude to my revered guide **Shri. A. K. MADAN**, Lecturer, Department of Mechanical Engineering, Delhi College of Engineering for his expert guidance, inspiration, suggestion and constant encouragement during entire course of this project work, which enabled me to bring out this report in an eloquent manner.

I express my sincere thanks to **Shri. D. GANESHAN** Scientist 'F', Deputy Divisional Officer, Mechanical Engineering Division, Electronics and Radar Development Establishment, Bangalore, for his cooperation, constant support and help which led to the successful completion of this project work.

I am deeply indebted to my co-guide **Shri. S. SIVAKUMAR** Scientist 'E', Electronics and Radar Development Establishment, Bangalore, for his patience, constant support, expert guidance and mainly his faith in my abilities which led to the successful completion of this project work.

I convey my gratitude to **Professor S. K. GARG**, Department of Mechanical Engineering, Delhi College of Engineering for his valuable suggestions and constant encouragement.

I would like to thank **Shri. SANDIP KUMAR**, Scientist 'B', MED, LRDE, Bangalore for his timely help and co-operation in different stages of this project work.

I thank Technical Officers **Shri. Jagadeesha**, **Shri. R.Rajashekar Shri. S.R. Mahendra** and all other staff of MED, LRDE, Bangalore for their support and co-operation at all stages of this project work.

S. MANI

ABSTRACT

In the current work, an attempt has been made to develop manufacturing techniques for Planar Slotted Array Antenna of modern Fighter Aircraft Radar. The Antenna is a lightweight thin walled Aluminium Alloy structure made of four layers of precision wave-guide cavities with inclined coupler and longitudinal radiating slots. In addition modeling of the Antenna assembly is carried out to run the FEM static analysis using the ANSYS 8.0 FEM software to study the deflection and stress conditions at high levels of gravitational loads (g).

All the required CNC part programs for machining has been prepared using the "CAPPSMILL 7.0", Computer Aided Manufacture software. Since the machining involves large volume of material removal, from a solid plate stock, leaving a thin wall all around (1.2mm), due care was taken to maintain the close tolerance by adopting the recent High Speed milling techniques and also control of the distortions by adopting intermediate vibration stress relieving techniques. Further enough attention has been given in the areas viz., selection of cutting tools, optimum cutting parameters, operation sequence, clamping method etc.

In addition due care has been taken for the in-process inspection to maintain the close dimensional and positional tolerances as per the International wave-guide specifications.

All the critical components of the Antenna viz., Aperture plate, Radiating plate, set of Power Dividers, set of Microwave layer-transition cover plates etc., were machined to the required accuracy and surface finish.

The machined components have been finally inspected with 3D-CMM successfully and assembled to join by DIP BRAZING method.

CHAPTER 1

1 OBJECTIVE

The modern battlefield, with highly mobile combat forces having long-range ground based and airborne weapon systems, makes it absolute necessary that sensors like RADARS, which can detect far distance targets are developed in various forms to provide accurate and timely information about the battle field to commanders in the tactical zone.

Among the various Radar systems, the one required for the Airborne application is most complex in nature. To design and develop the components of such Radar system is always been a challenging task. To import such systems from technologically advanced countries it is very expensive and also due to imposed sanctions, it is impossible to import the item from most of these countries.

Hence there is an absolute requirement to indigenously design and manufacture these complex Radar system components not only at low cost but also to make the country technologically advanced and self-reliant.

One of the most important components of this vital Radar system is the ANTENNA, which is a precision mechanical hardware and acts as a link between the free space and the other components of the Radar system**.** The figure-1 shows the Planar Slotted Array Antenna with scanner in the nose of the aircraft.

The objective of this project is to develop the manufacturing techniques of the planar slotted array antenna for air borne Radar application. In addition, modeling of the Antenna assembly is carried out to run the FEM static analysis using the ANSYS 8.0 Finite Element Method software to study the deflection and stress conditions at high levels of gravitational loads (g).

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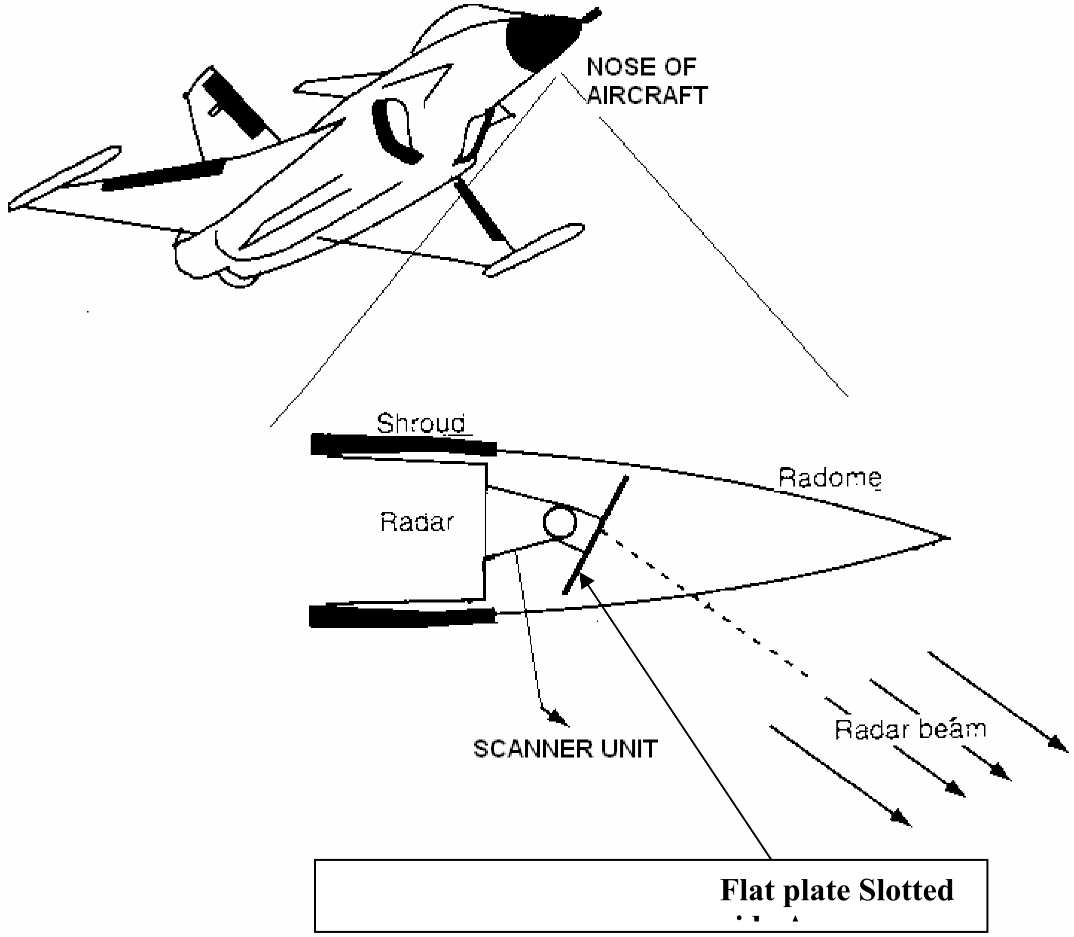


FIG.-1 ANTENNA WITH SCANNER IN THE NOSE OF THE AIRCRAFT

CHAPTER 2

2 RADAR FUNDAMENTALS

2.1 AN OVERVIEW OF RADAR

Radar is an electromagnetic system used for the detection and location of reflecting objects (viz., vehicles, aircraft, ships, spacecraft, people and the natural environment). The term RADAR is a contraction of the words ***RA*DIO *D*ETECTION *A*ND *R*ANGING**. It operates by radiating energy into space and detecting the echo signal reflected from an object, or target. The reflected energy that is returned to the radar not only indicates the presence of a target, but by comparing the received echo signal with the signal that was transmitted, its location can be determined along with other target-related information such as target velocity, acceleration and direction.

Radar can perform its function at long or short distances and under conditions of darkness, haze, fog, rain and snow. Its ability to measure distance with high accuracy and in all weather condition is one of its most important attributes. There is no competitive technique available to radar, which can accurately measure long ranges in both clear and adverse weather condition. Figure 2.1 shows the typical Airborne Radar Environment.

2.2 RADAR SYSTEM COMPONENTS

The basic principle of radar is illustrated in the figure2.2. A transmitter generates an electromagnetic signal (such as a short pulse of sine wave) that is radiated into space by an antenna. A portion of the transmitted energy is intercepted by the target and reradiated in many directions. The reradiation directed back towards the radar is collected by the radar antenna, which delivers it to a receiver. There it is processed to detect the presence of the target and determine its location. A single antenna is usually used on a time-shared basis for both transmitting and receiving when the radar waveform is a repetitive series of pulses. The Range or distance to a target is found by measuring the time it takes for the radar signal to travel to the target and return back to the radar. (Radar engineers use the term Range to mean distance). The target's location in angle can be found from the direction the narrow-beam width radar antenna points when the received echo signal is of maximum amplitude. If the target is in motion, there is a shift in the frequency of the echo signal due to the Doppler effect. This frequency shift is proportional to the velocity of the target relative to the radar.

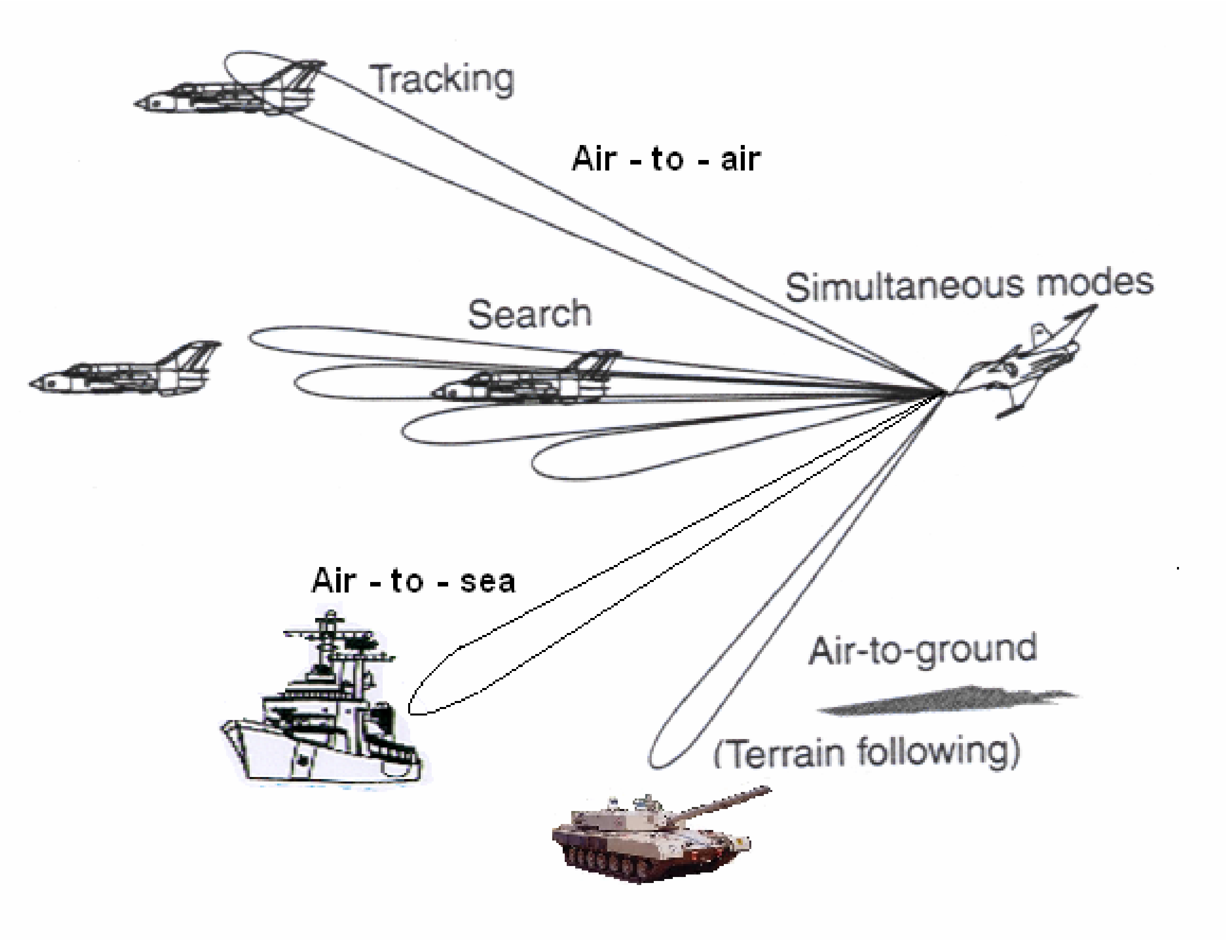


FIG.- 2.1 AIRBORNE RADAR ENVIRONMENT

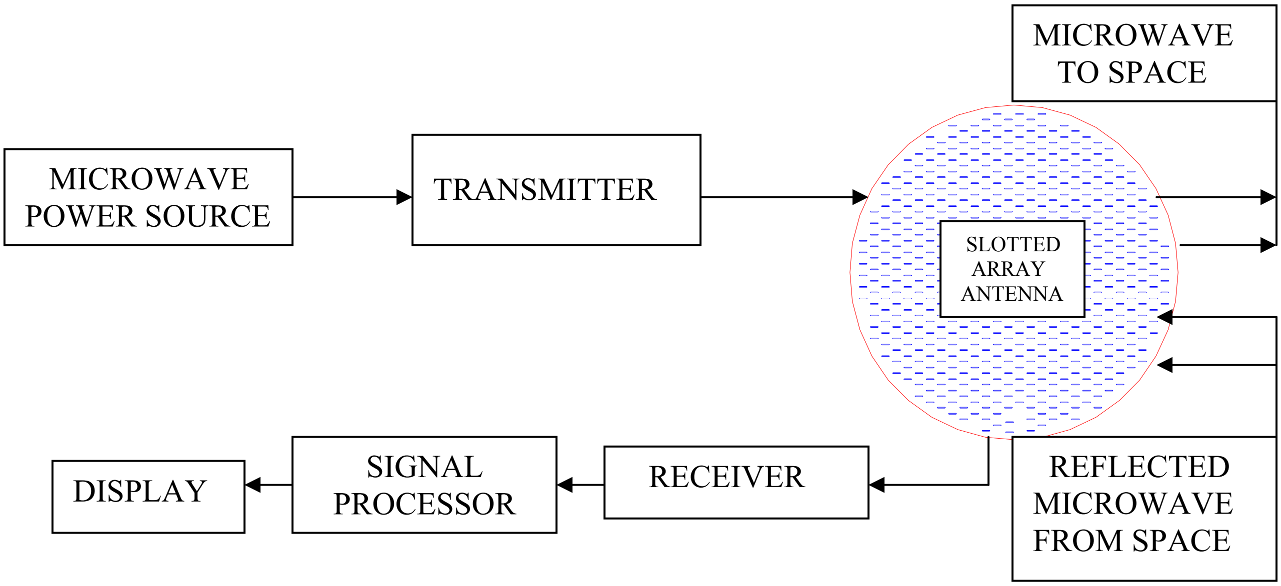


FIG.-2.2 RADAR SYSTEM COMPONENTS

2.2.1 Range to a Target

The most common radar signal or waveform is a series of short duration rectangular pulses. (i.e. pulse train).The range to a target is determined by the time T it takes the radar signal to travel to the target and back. Electromagnetic energy in free space travels with the speed of light, which is $c = 3*10^8$ m/s. Thus the time for the signal to travel to a target located at a range R and return back to the radar is 2R/c.

The range to the target is then $R= cT/2$

i.e., for each microsecond of round-trip travel time corresponds to a distance of 150 meters (1,50,000 km per sec.)

2.3 AN OVER VIEW OF ANTENNA

An Antenna is a device, which serves for

1. Transmitting Electromagnetic Waves into free Space

or

2. Receiving Electromagnetic Waves from free Space

or

3. Both

It may be a transmitting antenna, as in a **television station antenna**, or a receiving antenna, as in a conventional **domestic receiver**, or it may serve both functions, as in a **radar system**.

In all cases, its prime purpose is to provide as efficient a link as possible between the transmitter (or receiver) and free space so as to allow the maximum transfer of power from the transmitter circuit into free space (or to the receiver input terminals from free space).

2.4 SLOTTED ARRAY ANTENNA FOR AIRBORNE RADAR APPLICATION

Slotted wave-guide arrays are required for several airborne applications and for various missile seeker heads. High gain and efficient antennas are required for these radar applications. Since wave-guides provide exceptionally low path loss and accurately repeatable array elements, wave-guide slotted arrays have been attractive candidates for high efficiency planar antennas. The rugged and compact structure, high radiation efficiency and high power handling capacity of the mechanically scanned slotted wave guide antenna array makes it the workhorse of the most tactical aircraft radars and missile systems deployed in the field today, apart from a number of nonmilitary radar applications.

2.5 INTRODUCTION TO THE DEVELOPED FLAT PLATE ANTENNA

A high performance multi-function, flat plate, slotted array antenna has been developed. This type of state-of-the-art antenna with stringent electrical, mechanical and environmental specifications has been developed for the first time in the country.

Salient Features

- Broadband
- Low side lobe levels
- Integrated IFF and Guard channels
- Lightweight and compact

The Planar wave-guide Slotted Array Antenna has been developed in Four Layers and each layer divided into four quadrants, and each quadrant is further divided into a number of sub-arrays to get the required bandwidth performance. This array uses longitudinal offset slots as radiating elements and center-inclined slots as feeding elements. The performance of very low side lobe array depends on the positional and dimensional accuracy with which individual radiating and coupling slots are machined.

Novel methods were developed to machine planar slotted wave-guide array consisting of radiating slots and various levels of coupling slots to get the required antenna radiation pattern requirements like side lobe levels, beam widths and gain etc.

The complicated three-dimensional structure of the slotted arrays have been of great concern mechanically as it requires perfect electrical contact at joining and high accuracy of alignment in assembling the various parts of the antenna. All the four layers of the antenna were joined by dip brazing process.

2.6 WAVE GUIDE ACCURACY AND SURFACE FINISH

At higher frequency bands such as X, Ku, Ka etc., to get the required antenna radiation pattern requirements like low side lobe levels, power, beam-width, gain etc., the positional and dimensional accuracy of the rectangular wave guide and each & every radiating (longitudinal) and coupling (inclined) slot are to be maintained to a close tolerance level in the order of ±30 microns and the wave guide propagating surface to a roughness value of 1.5microns Ra value. (Reference- " International wave guide specifications"-APPENDIX-I)

Since the Planar Slotted Array Antenna consists of an array of 200 numbers (approx.) of high frequency wave guide pockets adjacent to each other in all the four layers, sharing the in-between 1.2mm thick common wall, the machining accuracy requirement for the Antenna parts (especially the positional accuracy) are to a close tolerance level in the order of ±30 microns even for the larger dimensions.

CHAPTER 3

3 ANTENNA STATIC ANALYSIS

3.1 INTRODUCTION TO FINITE ELEMENT METHOD

The finite element method is a numerical procedure that can be used to obtain solutions to a large class of engineering problems involving steady, transient, linear, nonlinear problems in stress analysis, heat transfer and fluid flow.

In general engineering problems include mathematical models of physical situations. Mathematical models are differential equations with a set of corresponding boundary and initial conditions. The differential equations are derived by applying the fundamental laws and principles of nature to a system or a control volume. These governing equations represent balance of mass, force, or energy.

When possible, the exact solution of these equations renders detailed behavior of a system under given set of conditions.

There are many practical engineering problems for which we cannot obtain exact solutions. This inability to obtain an exact solution may be attributed to either the complex nature of governing differential equations or the difficulties that arise from dealing with the boundary and initial conditions. To deal with such problems, it is required to resort to numerical approximations.

In contrast to analytical solutions, which show the exact behavior of a system at any point within the system, numerical solutions approximate exact solutions only at discrete points, called nodes. The first step of any numerical procedure is discretization.

This process divides the medium of interest into a number of small sub-regions and nodes.

There are two common classes of numerical methods:

1. Finite Difference Method and
2. Finite Element Method

With Finite Difference Method, the differential equation is written for each node, and the derivatives are replaced by difference equations. This approach results in a set of simultaneous linear equations. Although finite difference method is easy to understand

and employ in simple problems, it becomes difficult to apply to problems with complex geometries or complex boundary conditions.

In contrast, Finite Element Method uses integral formulations rather than difference equations to create a system of algebraic equations. Moreover, an approximate continuous function is assumed to represent the solution for each element. Connecting or assembling the individual solutions, allowing for continuity at the inter-elemental boundaries, then generates the complete solution.

3.2 INTRODUCTION TO ANSYS FEM PACKAGE

ANSYS is a general-purpose finite element computer program. ANSYS is capable of performing static, dynamic, heat transfer and fluid-flow analyses. ANSYS has been a leading FEA PACKAGE for well over 30 years. The current version of ANSYS i.e., ANSYS 8.0 has a completely new look, with multiple windows incorporating pull down menus, dialog boxes and toolbars. Today ANSYS is finding its use in many engineering fields, including aerospace, automotive, electronics and nuclear involving problems of complex nature.

3.2.1 Basic Steps in the Finite Element Method

The basic steps involved in any finite element analysis consist of the following

I Preprocessing Phase

1. Create and discretise the solution domain into finite elements; i.e., the problem is subdivided into nodes and elements.
2. Assume a shape functions to represent the physical behaviour of an element i.e., an approximate continuous function is assumed to represent the solution of an element.
3. Develop equations for an element.
4. Assemble the elements to present the entire problem. Construct the global stiffness matrix.
5. Apply boundary conditions, initial conditions, and loading.

II Solution Phase

6. Solve a set of linear or nonlinear algebraic equations simultaneously to obtain nodal results, such as displacement values at different nodes or temperature values at different nodes in a heat transfer problem.

III Post-processing Phase

7. Obtain the information of interest such as displacement, principal stresses, and heat fluxes etc., in graphical and/or numerical format.

If the values are within the acceptable limits then it is the indication that the physical dimensions of the system is all right.

If the values are not within the acceptable limits then it is the indication that the physical dimensions of the system is not alright and changes in the physical dimensions are necessary and again the above three steps are to be repeated for verification.

It is also as a customary practice, to carry out a few iterations of the analysis till the results converge.

3.3 ANTENNA STATIC ANALYSIS

3.3.1 Modeling

In ANSYS, the term *model generation* usually takes the meaning of generating the nodes and elements that represent the spatial volume and connectivity of the actual system. Thus, *model generation* in this discussion will mean the process of *defining the geometric configuration of the model's nodes and elements.* The ANSYS program offers the following approaches to model generation:

- Creating a solid model within ANSYS.
- Using direct generation.
- Importing a model created in a computer-aided design (CAD) system.

There are two different methods available to generate the model with in ANSYS: *solid modeling* and *direct generation*. With *solid modeling*, the geometric boundaries of model are described first and control is established over the size and desired shape of elements. Then the ANSYS program is finally instructed to generate all the nodes and elements automatically.

By contrast, the *direct generation* method, determines the location of every node and the size, shape, and connectivity of every element prior to defining these entities in the ANSYS model.

In spite of the many advantages of solid modeling, there are circumstances where direct generation will be more useful especially when

Solid modeling

- Requires large amount of CPU time.
- Sometimes be more cumbersome, requiring more data entries than direct generation.
- Sometimes "fail" (the program will not be able to generate the finite element mesh) under certain circumstances

The advantages of direct generation method are

- It is convenient for small or simple models.
- Provides complete control over the geometry and numbering of every node and every element.

3.3.2 Importing Solid Models Created in CAD systems

As an alternative to creating solid models within ANSYS, they can be created using the available popular CAD system and then import them into ANSYS for analysis, by saving them in the IGES file format or in a file format supported by an ANSYS connection product. Creating a model using a CAD package has the following advantages:

- Avoids a duplication of effort by using existing CAD models to generate solid models for analysis.
- Use of more familiar tools to create models.

However, models imported from CAD systems may require extensive repair if they are not of suitable quality for meshing.

3.3.3 Choosing the Model Type (2-D, 3-D, etc.)

Finite element model may be categorized as being 2-D or 3-D, and as being composed of point elements, line elements, area elements, or solid elements. Of course, it can intermix different kinds of elements as required. For example, the model can be a stiffened shell structure using 3-D shell elements to represent the skin and 3-D beam elements to represent the ribs. The choice of model dimensionality and element type will often determine which method of model generation will be most practical for the given problem.

LINE models can represent 2-D or 3-D beam or pipe structures, as well as 2-D models of 3-D axis-symmetric shell structures. Solid modeling usually does not offer much benefit for generating line models; they are more often created by direct generation methods.

2-D SOLID analysis models are used for thin planar structures (plane stress), "infinitely long" structures having a constant cross section (plane strain), or axis-symmetric solid structures. Although many 2-D analysis models are relatively easy to create by direct generation methods, they are usually easier to create with solid modeling.

3-D SHELL models are used for thin structures in 3-D space. Although some 3-D shell analysis models are relatively easy to create by direct generation methods, they are usually easier to create with solid modeling.

3-D SOLID analysis models are used for thick structures in 3-D space that have neither a constant cross-section nor an axis of symmetry. Creating a 3-D solid analysis model by direct generation methods usually requires considerable effort. Solid modeling will nearly always make the job easier.

3.3.4 Advantage of Symmetry

Many objects have some kind of symmetry, be it repetitive symmetry (such as evenly spaced cooling fins on a long pipe), reflective symmetry (such as a molded plastic container), or axis-symmetry (such as a electric bulb). When an object is symmetric in all respects (geometry, loads, constraints, and material properties), it can often take advantage of that fact to reduce the size and scope of the model.

3.3.5 Details of the Generated Slotted Array Antenna model for Analysis

Thus, considering all the above mentioned facts, in the present work only one quadrant of the Slotted Array Antenna has been modeled for the static analysis, since the Antenna Assembly and loading is symmetric about X & Y-axis and also to overcome the problem of limitation in the maximum number of elements that can be used to run the analysis.

Further, the Direct Generation method has been adopted for modeling the antenna assembly in the present work using the macro feature available in the ANSYS program. Since the created solid model of the antenna assembly using **SOLIDWORKS 2001 Plus** CAD package, could not be imported effectively into **ANSYS 8.**0 as mid surfaces are required for shell element and beam elements are required for joining the two plates. Automatic or mapped meshing of circular plate will not help in getting desired mesh to join beam elements.

For modeling the antenna assembly using the macro feature available in the ANSYS program, the MATLAB and AUTOCAD packages were used to calculate the co-ordinates of the required nodes. The model was constructed layer-by-layer using 3-D elastic shell elements to represent the 1.2mm thick horizontal broad wall of wave-guide cavities and 3-D elastic beam elements to represent the ribs i.e., 1.2mm thick short vertical wall of the wave-guide cavities. For the mounting pad of the antenna assembly 3-D solid brick element was used.

The Ø650mm Radiating plate was modeled using the MACROS for the generation of the Nodes and Elements with the help of MATLAB program. The node spacing along the X and Y directions were decided by considering the pitch distance of the wave-guide pockets on either side of the Aperture plate. The reason for this is to construct the ribs (i.e. vertical wall of the wave guide pockets) using the beam elements at these spacing. Thus the node spacing along the X-axis was arrived to be 5.529mm and the same along the Y-axis was arrived to be 5.5975mm.

The Ø650mm Radiating plate nodes were copied at a layer distance of 6.28mm along the Z-axis, to form the Ø650mm common broad wall of the Aperture plate. On the radiating side of the Aperture plate, the beam models were constructed again through the MACRO, which is the output of MATLAB program at the pitch distance of the vertical ribs. On the coupler side of the Aperture plate similar ribs with beam models were constructed in a direction perpendicular to the ribs on the radiating side. These coupler side beam models join the Ø650mm common broad wall of the aperture plate to the microwave transition cover plate. The microwave transition cover plate is again a common broad wall of the wave-guide between second and third layer and its area is generated using the Key points on nodes from the Ø650mm common broad wall of the aperture plate at a layer distance of 6.28mm along the Z-axis. This completes the first and second layers of the Antenna.

The third and fourth Power divider layers were modeled through the MACRO using the nodes generated with the help of AUTOCAD. Since the Power divider has complex geometry, it's profile was approximated to match the spacing of the model along X and Y direction. An area was generated at a layer distance of 6.28mm along the Z-axis using the profile of the power divider and again by using the beam elements it was connected to microwave transition cover plate along the profile of the power divider to complete the third layer of the Antenna.

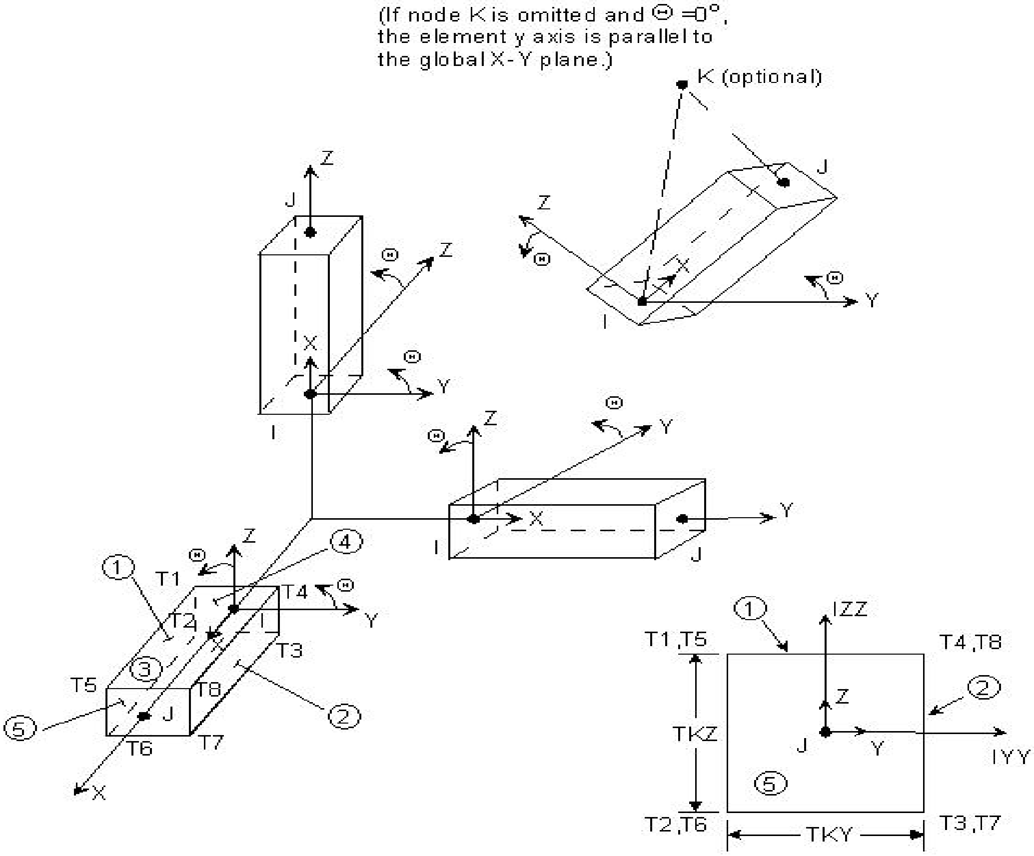
Finally for the fourth layer of the Antenna, again an area was generated at a layer distance of 6.28mm along the Z-axis using the profile of the power divider to form the divider cover model and again by using the beam elements it was connected to power divider along the profile of the power divider.

Thus the modeling of the antenna assembly was completed using **15,607 nodes** and **13,533 elements**.

The details of the used ANSYS 8.0 elements are elaborated as follows:

I. 3-D Elastic Beam Element Description

BEAM4 is a uniaxial element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Stress stiffening and large deflection capabilities are included.



(If node K is omitted and Θ =0°, the element y axis is parallel to the global X-Y plane.)

FIG. 3.1 BEAM4 ELEMENT

BEAM4 Input Data

The geometry, node locations, and coordinate systems for this element are shown in figure-3.1. The element is defined by two or three nodes, the cross-sectional area, two area moments of inertia (IZZ and IYY), two thicknesses (TKY and TKZ), an angle of orientation (θ) about the element x-axis, the torsional moment of inertia (IXX), and the material properties.

II. SHELL63 Element Description

SHELL63 has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Stress stiffening and large deflection capabilities are included.

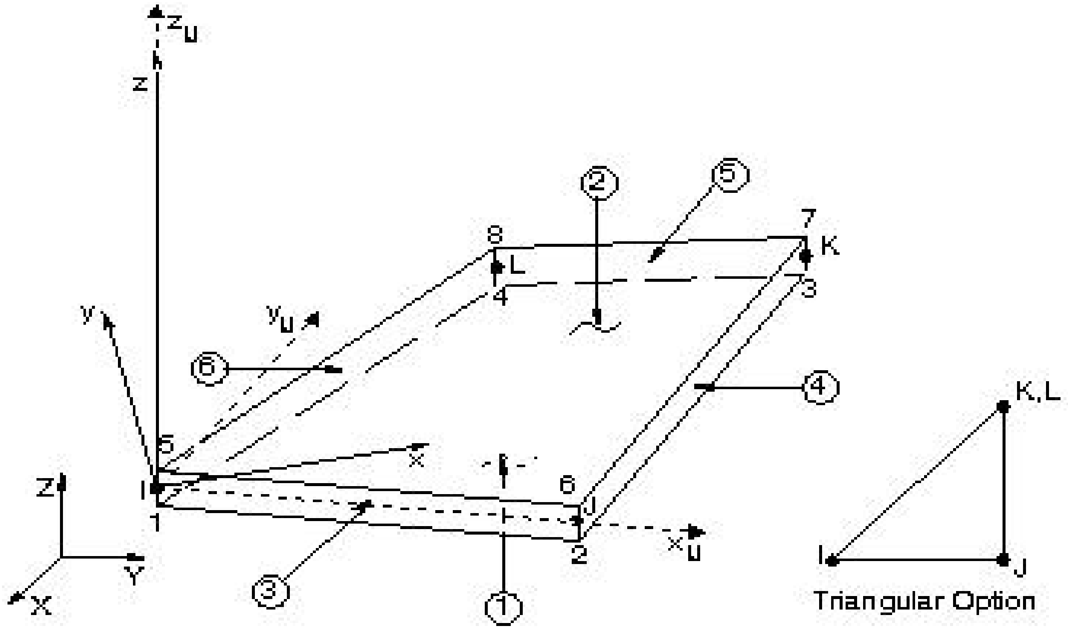


FIG. 3.2 SHELL63 ELEMENT

SHELL63 Input Data

The geometry, node locations, and the coordinate system for this element are shown in figure-3.2. The element is defined by four nodes, four thicknesses, and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element x-axis may be rotated by an angle THETA (in degrees). The thickness is assumed to vary smoothly over the area of the element, with the thickness input at the four nodes. If the element has a constant thickness, only TK (I) need be input. If the thickness is not constant, all four thicknesses must be input.

III. SOLID45 Element Description

SOLID45 is used for the 3-D modeling of solid structures. Eight nodes having three degrees of freedom at each node define the element: translations in the nodal x, y and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

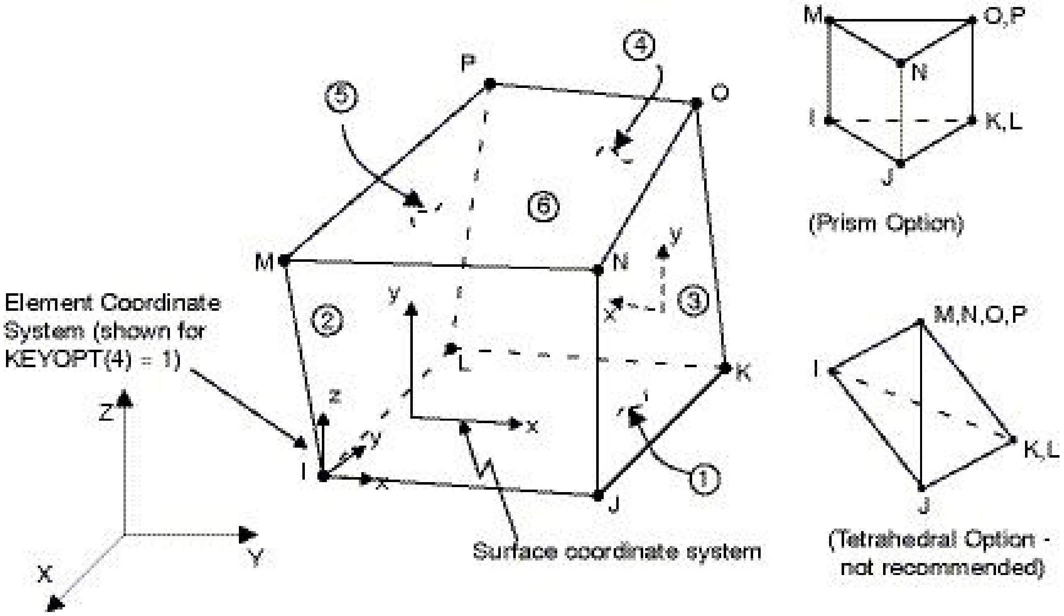


FIG. 3.3 SOLID45 ELEMENT

SOLID45 Input Data

The geometry, node locations, and the coordinate system for this element are shown in figure 3.3. Eight nodes and the orthotropic material properties define the element. Orthotropic material directions correspond to the element coordinate directions. Pressures may be input as surface loads on the element faces as shown by the circled numbers on figure 3.3. Positive pressures act into the element.

CHAPTER 4

4 MACHINING OF ANTENNA PARTS

4.1 DESCRIPTION OF THE ANTENNA PARTS:

All the Slotted Array Antenna Parts, especially the critical components viz.,

1. The Radiating Plate,
2. The Aperture plate,
3. A set of four power dividers &
4. A set of microwave transition cover plates,

were machined on the high precision CNC machines such as heavy duty RAMBAUDI High Speed Milling Machine with vacuum clamping table, SIP-640 CNC Double column milling machine and CNC Turret Punch Press.

All the above-mentioned parts were machined out of Aluminium alloy 6061-T6, which was selected on the basis of mechanical, electrical and environmental properties.

4.1.1 Description of the Radiating Plate:

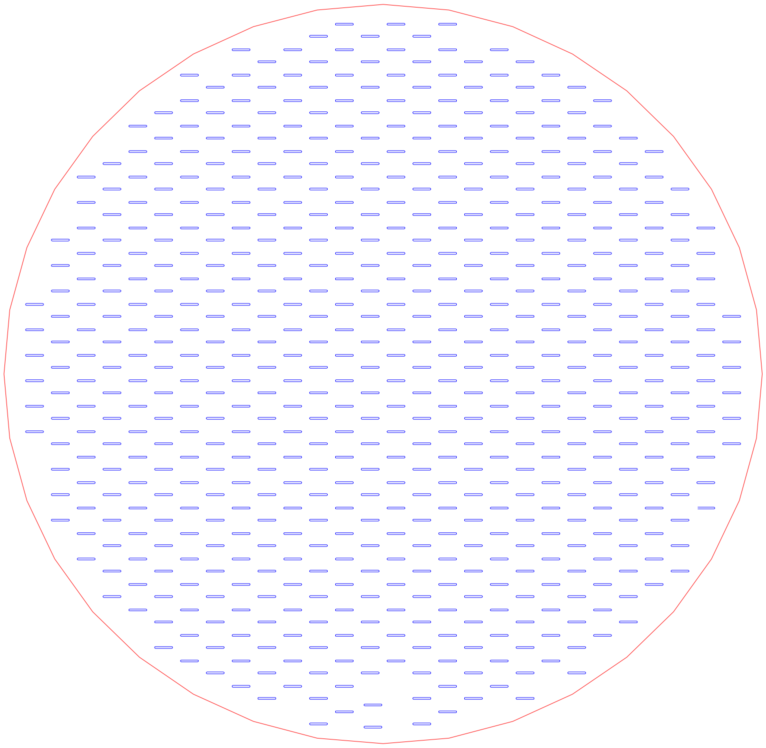


FIG.-4.1 RADIATING PLATE

The Ø650mm Radiating Plate shown in the above figure 4.1is a thin sheet metal (1.05mm thick) high precision component of the Antenna made out of aluminium alloy cladded with filler material for brazing.

It consists of 606 nos. of precisely located longitudinal radiating slots to transmit and receive the microwaves. All the slots are of 2.5mm width and of varying length to achieve the required electrical performance. The positional and dimensional accuracy is ±30microns and the surface finish is 1.5micron R_a value.

4.1.2 Description of the Aperture Plate:

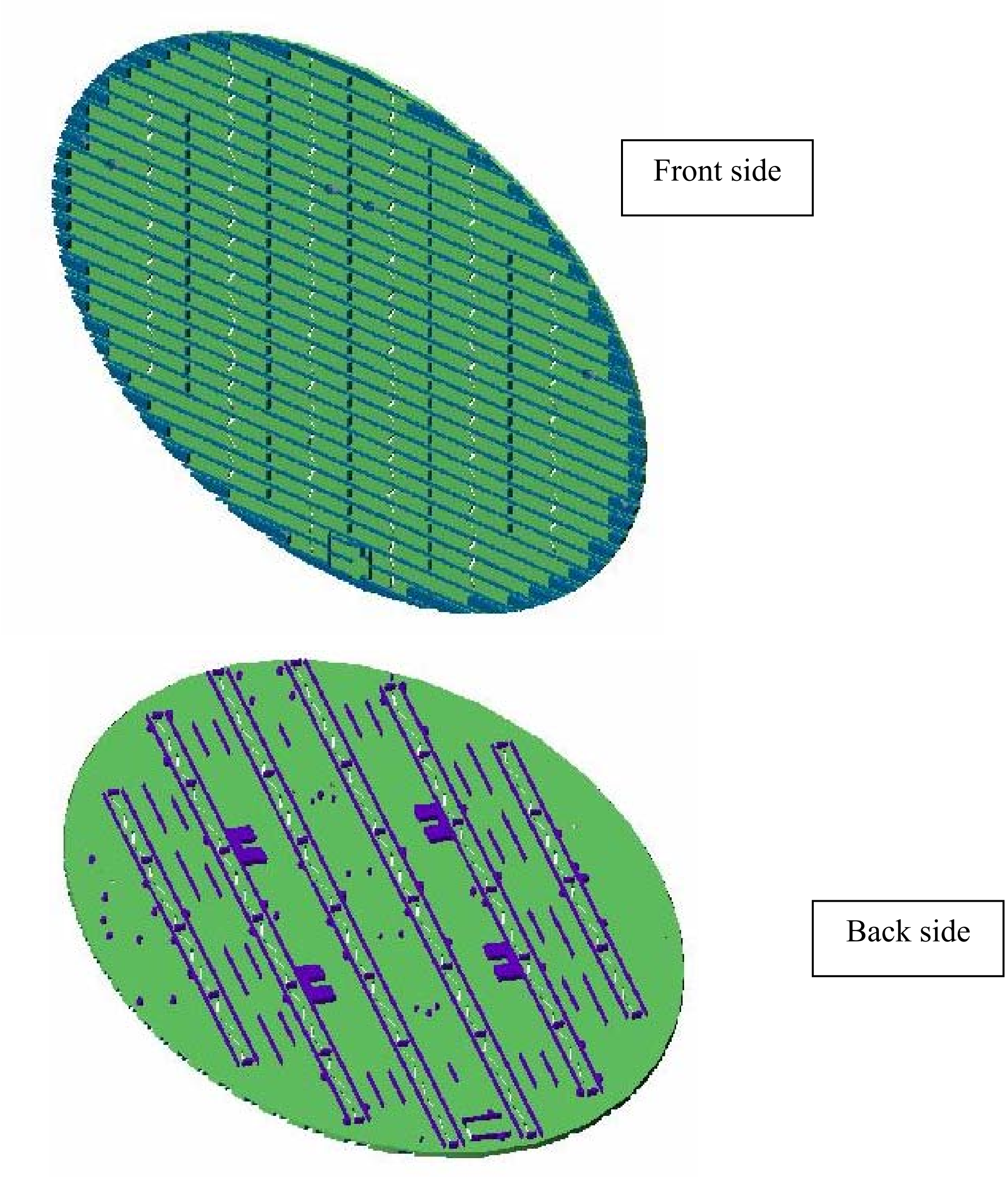


FIG.-4.2 APERTURE PLATE

The Ø650mm Aperture Plate shown in the above figure 4.2 forms the first and second layer of the wave-guide pocket array on its both front and backside and it is also the main component, which supports and precisely locates all the other antenna parts. It is a thin walled (1.2mm wall thickness all around) high precision component made out of aluminium alloy plate of thickness 15mm.

It consists of an array of 134nos. of wave guide pockets on the front side, each pocket with a precisely located inclined coupler slots for microwave transition from first to the second layer of the antenna. All the slots are of 2.5mm width and of varying length and angular orientation to achieve the required electrical performance. The second layer in the backside of the Aperture plate consists of a similar array of 32 nos. of wave-guide pockets. The two layers share the 1.2mm thick common wall in-between. The positional and dimensional accuracy is ±30microns and the surface finish is 1.5micron R_a value.

4.1.3 Description of the Power Divider:

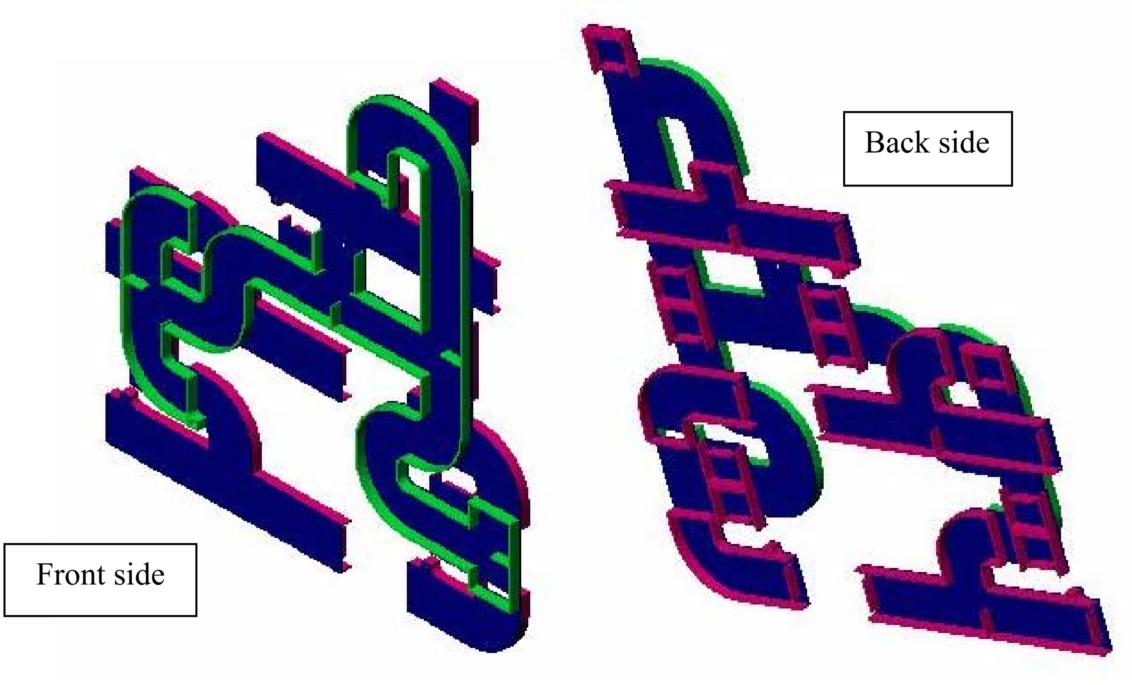


FIG.-4.3 POWER DIVIDER

A set of four Power Dividers forms the third and fourth layer of the Antenna. It is a thin walled (1.2mm wall thickness all around) high precision component made out of aluminium alloy plate of thickness 15mm.

It is a complex geometry component and it consists of wave-guide pockets on both sides, and rectangular cut through openings for microwave transition from third to fourth layer of the Antenna as shown in the figure 4.3. The two layers share the 1.2mm thick common wall in-between. The positional and dimensional accuracy is ±30microns and the surface finish is 1.5micron R_a value.

4.1.4 Description of the Transition cover Plate:

The two numbers of Microwave Transition Cover plates are the thin sheet metal (1.05mm thick) high precision components of the Antenna made out of aluminium alloy, cladded with filler material for brazing.

Each cover consists of 16 nos. of precisely located inclined coupler slots for microwave transition from second to the third layer of the Antenna as shown in the figure 4.4. All the slots are of 2.5mm width and of varying length and angular orientation to achieve the required electrical performance. The positional and dimensional accuracy is ±30microns and surface finish is 1.5micron R_a value.

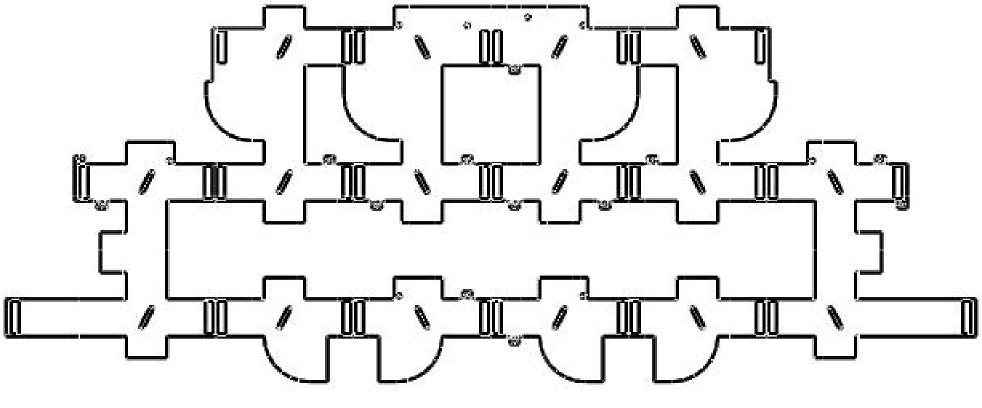


FIG.-4.4 MICROWAVE TRANSITION COVER PLATE

4.2 ALUMINIUM AND ITS ALLOYS

4.2.1 Properties of Aluminium and its Alloys

One of the most important properties of Aluminium is lightweight, which makes it an attractive material for airborne applications. The specific gravity is 2.7 times that of water and roughly 1/3rd of Steel or Copper. The other properties of Aluminium are

1. **Formability**

   Aluminium can be formed by every process in use today and in more ways than any other metals. It has relatively low melting point, 660 degrees Celsius, which restricts its high temperature applications to about 260 to 300 degrees Celsius and at the same time makes it easy to cast.

2. **Mechanical Properties**

   Aluminium has good mechanical properties like good ductility; tensile strength and it can be cast and machined easily. Through alloying, naturally soft Aluminium can attain strength twice as that of mild steel.

3. **Strength-Weight Ratio**

   Some Aluminium alloys are among the highest strength-weight ratio materials in use today.

4. **Cryogenic Properties**

   Unlike most steels, which tend to become brittle at cryogenic temperatures, Aluminium alloys actually get tougher at lower temperatures and enjoy most cryogenic applications.

5. Corrosion Resistance

   Aluminium possesses excellent resistance to corrosion by natural atmospheres and by many foods and chemicals.

6. High Electrical and Thermal Conductivity

   On a volume basis the electrical conductivity of pure Aluminium is roughly 60% of copper. It is good conductor of heat and electricity than many other metals.

TABLE 4.1 MECHANICAL PROPERTIES OF ALUMINIUM

PROPERTIES	VALUES
Density (1000 kg/cubic m)	2.7
Poisson's ratio	0.33
Elastic Modulus (GPa)	70-80
Tensile Strength (MPa)	115
Yield Strength (MPa)	48
Elongation (%)	25
Hardness (HB)	30
Shear Strength (MPa)	83
Fatigue Strength (MPa)	62

TABLE 4.2 ELECTRICAL AND THERMAL PROPERTIES OF ALUMINIUM

PROPERTIES	VALUES
Thermal Expansion (µm/m/ K)	24
Thermal Conductivity (W/m per K)	230
Specific Heat (J/Kg K)	0.22
Electrical Resistivity (ohm-m10^{-8})	2.7
Electrical Conductivity (%)	63

4.2.2 Classification of Aluminium alloys

a. Wrought Aluminium Alloy
b. Cast Aluminium Alloy.

1. Cast Alloys- These Alloys contains silicon, copper, magnesium/zinc as the primary alloying elements. Thus these are well suited for intricate shape castings.
2. Wrought Alloys- These Alloys have excellent machining and welding characteristics. Thus these are well suited for multi operational machining.
3. Strain-hardenable alloys - These Alloys have no alloying elements that would render hardness by solution heat treatment and precipitation, but they can be strengthened to some extent by cold working.
4. Heat treatable alloys - Most of the alloys in this group have fairly high percentage of alloying elements such as copper, silicon, magnesium and zinc. These are easier to machine when heat-treated.

4.2.3 Designation of Wrought Aluminium Alloys

The advantage of the designation is to clearly distinguish the various types of Wrought Aluminum Alloys by their chemical composition and characteristics.

TABLE 4.3 DESIGNATION SYSTEM OF WROUGHT ALUMINIUM ALLOYS

Aluminium Alloy Group	Designation Number of the Group
Aluminum-99% purity	1xxx
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium & Silicon	6xxx
Zinc	7xxx
Other elements	8xxx

- The first digit designates the alloy type
- The second digit designates the alloy modifications
- The last two digits designates the purity of Aluminium

4.3 THE ALUMINIUM ALLOY FOR THE ANTENNA

From the above classification, the Aluminium alloy 6061 has been selected for the development of flat plate slotted array antenna since, it is an aircraft structural grade material with Good Strength combined with outstanding Brazeability and corrosion resistance.

TABLE 4.4 COMPOSITION OF AA-6061-T6 (BIS-65032 WP)

Element	Weight Percentage
Aluminum - Al	97.9
Magnesium - Mg	1.00
Silicon - Si	0.6
Copper - Cu	0.3
Chromium - Cr	0.2

4.3.1 Heat treatment Condition

Since the above aluminium alloy 6061 is a heat treatable alloy, it is used in the T6 temper condition i.e., Solution treated and Precipitation hardened condition for the fabrication of the Antenna. Because in this temper condition only the AA6061 possess the maximum tensile strength and thereby the maximum hardness which facilitates easy machining of the aluminium alloy.

TABLE 4.5 MECHANICAL PROPERTIES OF AA-6061-T6 (BIS-5032 WP)

PROPERTIES	VALUES
Elastic Modulus (GPa)	70
Tensile Strength (MPa)	310
Yield Strength (MPa)	275
Elongation (%)	17
Hardness (Brinell)	95
Shear Strength (MPa)	207
Fatigue Strength (MPa)	190

TABLE 4.6 ELECTRICAL AND THERMAL PROPERTIES OF AA-6061-T6

PROPERTIES	VALUES
Thermal Expansion (µm/m/ K)	24
Thermal Conductivity (W/m per K)	156
Specific Heat (J/Kg K)	896
Liquidus temperature (°C)	652
Solidus temperature (°C)	582
Electrical Resistivity (ohm-m10^{-8})	4
Electrical Conductivity (%)	43

4.4 AN OVERVIEW OF CNC MACHINING TECHNOLOGY

Numerical control (NC) of machine tools is the operation of machine tools i.e., controlling all the motions of machine tools by means of codes comprising Alphabets, Numbers and special symbols.

All instructions are written in a logical order and in predetermined form. The collection of all the instructions necessary to machine a part is called NC programming or Part programming.

4.4.1 Computer Numerical Control

Computer Numerical Control (CNC) is the process where a machine tool can be controlled and guided through a series of coded instructions comprising letters, numbers and symbols to carryout a machining operation quickly and accurately with help of a mini or micro computer. CNC uses a mini or microcomputer built into the machine control Unit. CNC machine tool have revolutionized the metal processing by greatly increasing manufacturing productivity and making it possible to produce more accurate and complex work pieces than was previously possible. These CNC machines have been able to reduce manufacturing costs and produce parts of consistent quality. The continual development of CNC machines and their computer control systems has led to a wide acceptance of this technology in industry. Almost 90% of machine tools manufactured in the world today have some form of computer control systems.

Features of CNC

Programs can be stored on floppy disks, tapes or cassettes, which can be loaded into the machine control unit memory (MCU). The same program can be recalled as many times as required from the memory.

- The MCU has Random Access Memory (RAM) which allows program to be edited, and also allows for on-board programming (Manual Data Input -MDI)
- An external device (Personal Computer) can be used to make the program, which is then up-loaded directly to the MCU through telecommunication network.
- CNC controls can compensate for size and tool wear, inspect parts and communicate with other computers and Robots. The tool path can be displayed on the screen (CRT) and errors in the program can be corrected before machining begins.

Computers in CNC

The use of computers in CNC provides following purpose

- Generating CNC part program.
- Uploading and down loading part programs to various CNC machines.
- Managing inventory, scheduling, and record keeping.

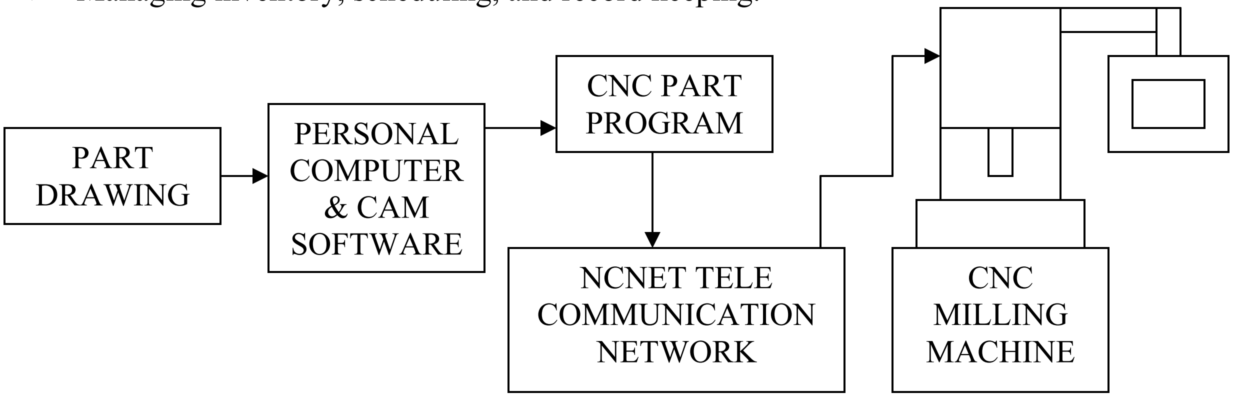


FIG.-4.5 BLOCK DIAGRAM OF CNC

CNC Performance:

Accuracy

The accuracy of a CNC machine is the closeness with which the machine tool can maintain the given size to the absolute standard size. CNC machine tools were accepted by industry for superior accuracy because they are calibrated and set to such accuracy using laser calibration techniques. Modern CNC machines are capable of producing parts, within a tolerance limit of 0.005mm. The machine tools have been built better, and the machine control units ensure that the parts are machined with in the tolerance allowed by the engineering drawing. The accuracy, which formerly depended on the machinist's experience and skill, is now being exceeded by reliable CNC control systems and better machine tool construction.

Repeatability

The repeatability of a machine tool is the ability to produce similar parts every time by maintaining size, shape and accuracy. The repeatability of a CNC machine is generally one half of the machine accuracy. The machine tools capable of greater accuracy and repeatability will naturally cost more, but this increase in cost will be quickly offset by reduced scrap and increased productivity.

Productivity

Industry is always striving to produce better products at competitive or lower prices to gain a bigger share of the market. To meet competition throughout the world, manufacturers use the CNC machines to lower manufacturing costs and produce better quality products.

Advantages of CNC:

CNC as grown at an ever increasing rate and its use will continue to grow because of the many advantages it has in offers to industries. ***The capability of the CNC machine to reproduce the predefined part to any number of times makes it advantageous*** as mentioned below:

1. **Less scrap -** Because of the accuracy of the CNC machines and the elimination of human errors, scrap has been greatly reduced or eliminated.
2. **Reduced production lead-time -** The time for program preparation and the tool and work setup time for CNC machines are usually short. Many jigs and fixtures,

which were required earlier for precision, are not necessary now. The Part program can be stored in machine memory and can be used again and again as required.

3. **Less human error** -The CNC eliminates the need for an operator to make table-positioning movements. The operator does not have to change cutting tools except during setup and when tools become dull.
4. **High part accuracy** -CNC ensures that all parts produced will be accurate and precise in quality. The improved accuracy of the parts produced by CNC assures the interchangeability of parts.
5. **Complex Machining operations -** Machining of complex geometrical shapes can be done quickly and accurately with CNC.
6. **Lower tooling cost -** CNC generally does not require complex holding fixtures, therefore the cost of fixtures may be reduced by as much as 70%
7. **Increased productivity -** Because CNC controls all the machine functions, parts are produced faster, which improves productivity.
8. **Reduced inventory –** Huge inventory of spare parts is no longer necessary, since duplicate parts can be made to same accuracy with the stored program, any time.
9. **Less machine tool damage -** the damage to machine tools as a result of operator error or carelessness is almost eliminated because there is less need for operator intervention.
10. **Greater machine uptime**- Because there is less time required for setup and operator adjustments, production rates could increase as much as 80%

General procedure in machining a Part using CNC is as follows:

1 Obtain and study the Part drawing to be machined.
2 Select the most suitable machining technique.
3 Select the appropriate machine, cutting tools and measuring instruments.
4 Decide the job clamping arrangement and Device methods for in process inspection.
5 Decide the sequence of operation.
6 Establish speeds and feeds.
7 Generate the required CNC Part Programs.
8 Actual Machining of the part.

4.5 HIGH SPEED MACHINING

The significance for high speed machining and especially high speed milling in production has increased since the development of new machines, drives and cutting tool materials with high resistance due to temperature and wear resistance and enables machining at high removal rates.

High speed machining enables the possibility to reduce process time on the one hand and to improve work piece accuracy and work piece surface on the other hand.

High speed machining is mostly related to the application of high cutting speeds up to two or three times higher as in conventional cutting. An impairment of the component quality and the surface integrity with increasing cutting speed could not be proven.

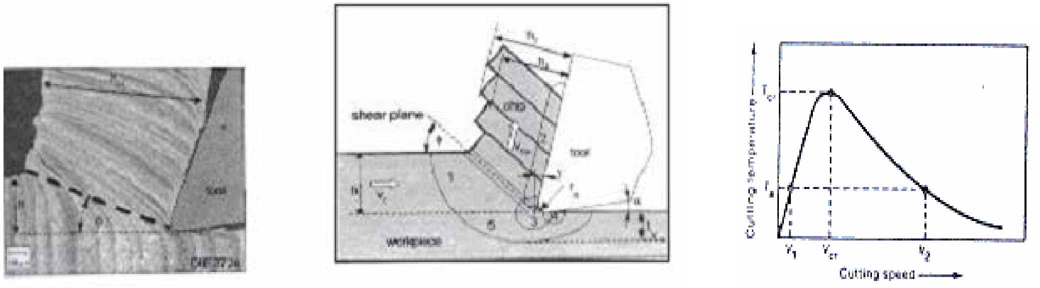


FIG.-4.6 CUTTING SPEED Vs TEMPERATURE

Within the range of generally used cutting speeds, the cutting force decreases with increasing cutting speed. The investigations show that an increase of cutting speed leads to more segmented chips. The residual stress depth profile was only slightly affected by the cutting speed increase.

4.5.1 Influence of cutting speed increase on cutting force and Temperature

The investigations have shown that increasing cutting speed leads to reduced cutting forces and temperature as shown in the figures 4.6 and 4.7. The effect of the cutting speed increase on the cutting forces during the turning process is shown in the figure 4.7. It clearly shows that the reduction of forces due to the increase of cutting speed from 50m/min to 2200m/min.

The tests proved that for every investigated steel the cutting force decreases down to approximately 450N.

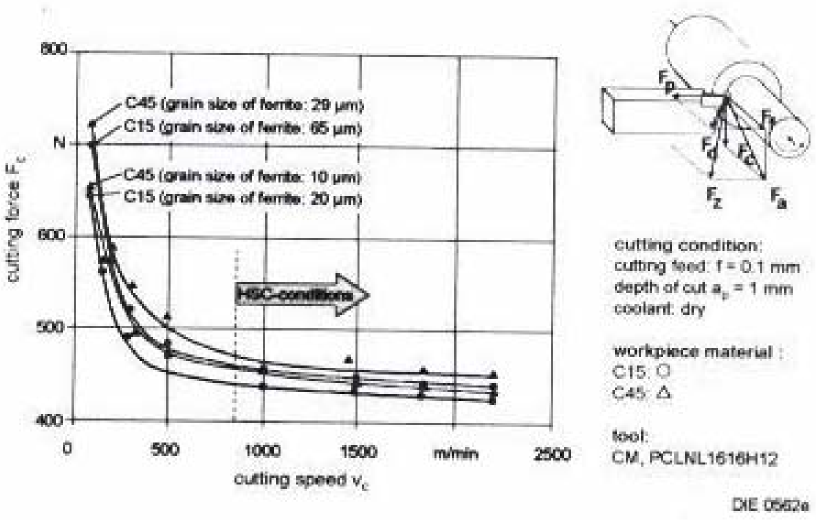


FIG.-4.7 CUTTING SPEED Vs CUTTING FORCE

At cutting speeds above 800m/min (approx.) no further reduction of cutting forces was detected. Therefore it can be assumed that above this cutting speed HSC conditions are present for these steels.

4.5.2 Influence of cutting speed increase on Surface Quality

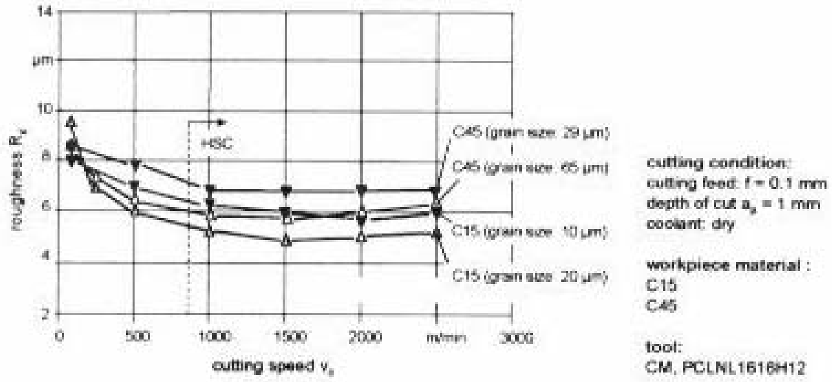


FIG.-4.8 CUTTING SPEED Vs SURFACE ROUGHNESS

The figure 4.8 shows the influence of the cutting speed on the finish of the machined surface. An improvement of the surface quality is achieved by the increase of the cutting speed for both materials and grain sizes.

Starting from the cutting speed of 800-900m/min no more further improvement of the surface quality occur.

4.5.3 Influence of cutting speed increase on Residual stress

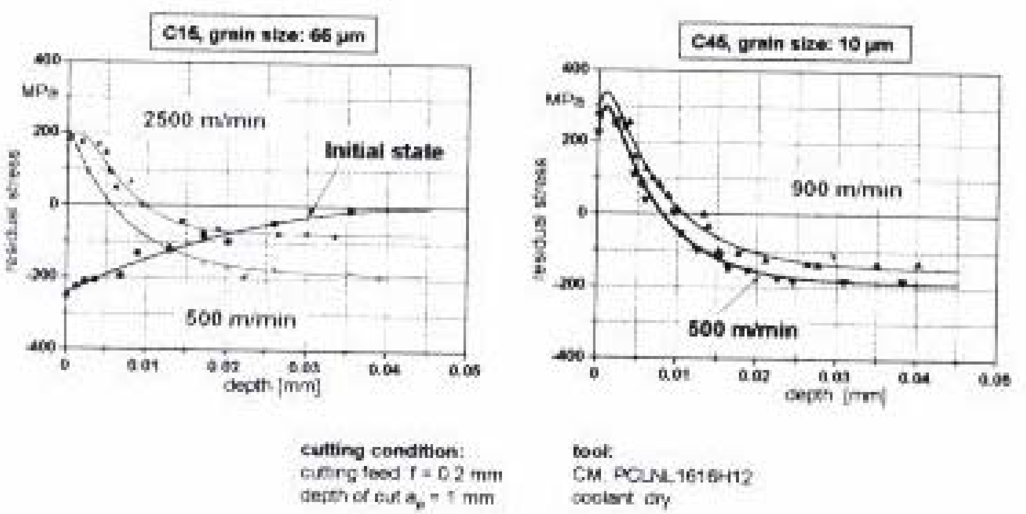


FIG.-4.9 CUTTING SPEED Vs RESIDUAL STRESS

In addition to the influence of the grain size on chip formation and cutting forces the experiments aimed at determining the influence of cutting speed and of the grain size on the affected zone near the work piece surface. This zone can be characterized by the depth of transition of tensile and compressive residual stresses. The depth of zero stress is deduced from the measurement of the depth profile of residual stresses by X-ray diffraction method. Figure 4-9 shows the depth profiles of residual stresses on C15 and C45 machined with different cutting speed. It clearly indicates that the residual stress depth profile was only slightly affected by the cutting speed increase.

4.5.4 High Speed Machining for the Aerospace Application

For shops in the aerospace industry, High Speed Machining offers a practical way to mill large, intricate and/or delicate aircraft components out of solid aluminum as shown in the figure 4.10. The speed permits high metal removal rates, as well as light cuts that help minimize work piece deflection. Aerospace shops use this capability to machine parts in one piece that once were built through assembly. However, the same practice applies to any job in aluminum where a large volume of material must be removed or where deflection is a concern in thin walled components.

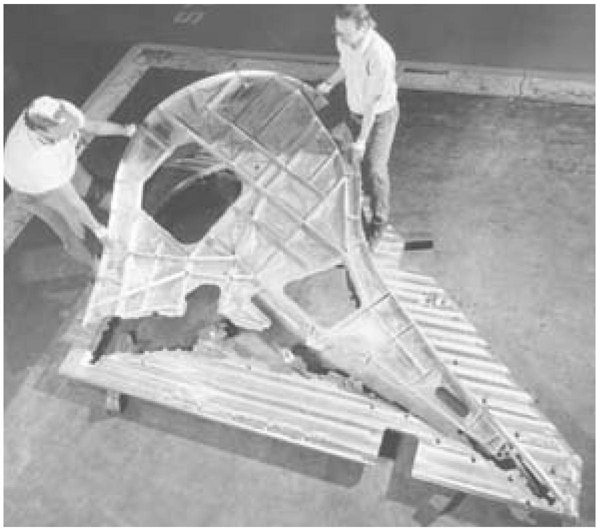


FIG.-4.10 AIRCRAFT COMPONENT MACHINED BY HIGH SPEED MILLING

4.5.5 High Speed Spindle

A high-speed spindle is the most fundamental component of a high speed machining process. A detailed sectional view of the High Speed Spindle is shown in the figure 4.11. The CNC, cutting tool, machining center and other process components are all optimized around the goal of using the higher spindle speed productively. In more basic cases, just retrofitting a faster spindle to a conventional machining center can allow a shop to begin realizing some of HSM's benefits.

A high-speed spindle presents a tradeoff between cutting force and cutting speed. First, the size of the motor is limited. High-speed spindles generally have direct-drive motors, meaning the motor must fit inside the spindle housing. Another limiting factor is the bearing. High-speed spindle bearings trade stiffness for speed. This is one more reason why high speed machining generally employs light depths of cut.

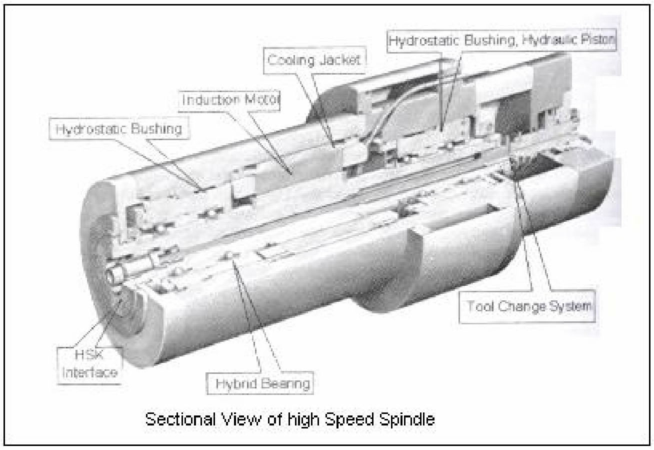


FIG.-4.11 HIGH SPEED SPINDLE

4.6 VACUUM CLAMPING

While machining flat plate thin walled Aluminium alloy wave guide components of considerably larger dimensions without any place for clamping access in the central portions, it is very difficult to maintain uniform wave guide pocket depth to a closer tolerance by conventional job clamping methods using T-bolts and nuts. For such components Vacuum clamping is the right answer, where the clamping pressure is uniformly distributed throughout the job area there by permitting to maintain uniform wave-guide pocket depth to a closer tolerance anywhere in the job area.

In vacuum clamping the vacuum pressure (negative pressure) is maintained between –600millibar to –800millibar using a motor driven vacuum pump with automatic control for pressure regulation. Airtight rubber gaskets are used to clamp the jobs to the vacuum-clamping table.

4.7 CNC MACHINE USED FOR THE SLOTTED ARRAY ANTENNA

NAME OF MACHINE	**RAMMATIC 801/NC**
MANUFACTURER	**RAMBAUDI INDUSTRIAL, ITALY**
NUMERICAL CONTROL	**FANUC 15 MB**

Machine features:

- The machine is a heavy-duty multi-purpose milling machine with the FANUC15 MB Numerical Control.
- It has been designed for mass production, copying a model set on the side of the table.
- The worktable slides in both longitudinal and transverse directions, where as upright is fixed and integral to the machine base.
- The head holder slides vertically on the upright.
- The milling head spindle is ISO50 standard with hydraulic tool locking.
- The spindle is driven by 15 KW AC servomotor.
- The three axes (X, Y, Z) machine movements are through re-circulating ball screw each driven by AC brush-less servomotor.

TABLE4.7 TECHNICAL FEATURES OF RAMBAUDI CNC MILLING MACHINE

Working strokes:

Longitudinal Displacement (X-axis)	1500 mm
Transverse Displacement (Y-axis)	800 mm
Vertical Displacement (Z -axis)	800 mm
Forward Revolution (A-axis)	-28 deg to 30deg
Transverse Revolution (B-axis)	-30 deg to 30 deg

***Work-table*:**

Length	3950 mm
Width	815 mm
Number of T-Slots	5 (28 x 46)
Maximum Permissible load	5000 Kg

Spindle Motor:

Type of Motor	FANUC ALPHA 50/6000
RPM	6000
Current Consumption	43 A (18.5 KW)

***Linear axes feeding speed*:**

Machining Speed	3000 mm/min
Quick Feed	5000 mm/min
Maximum Permissible Acceleration	200 mm/sq.sec

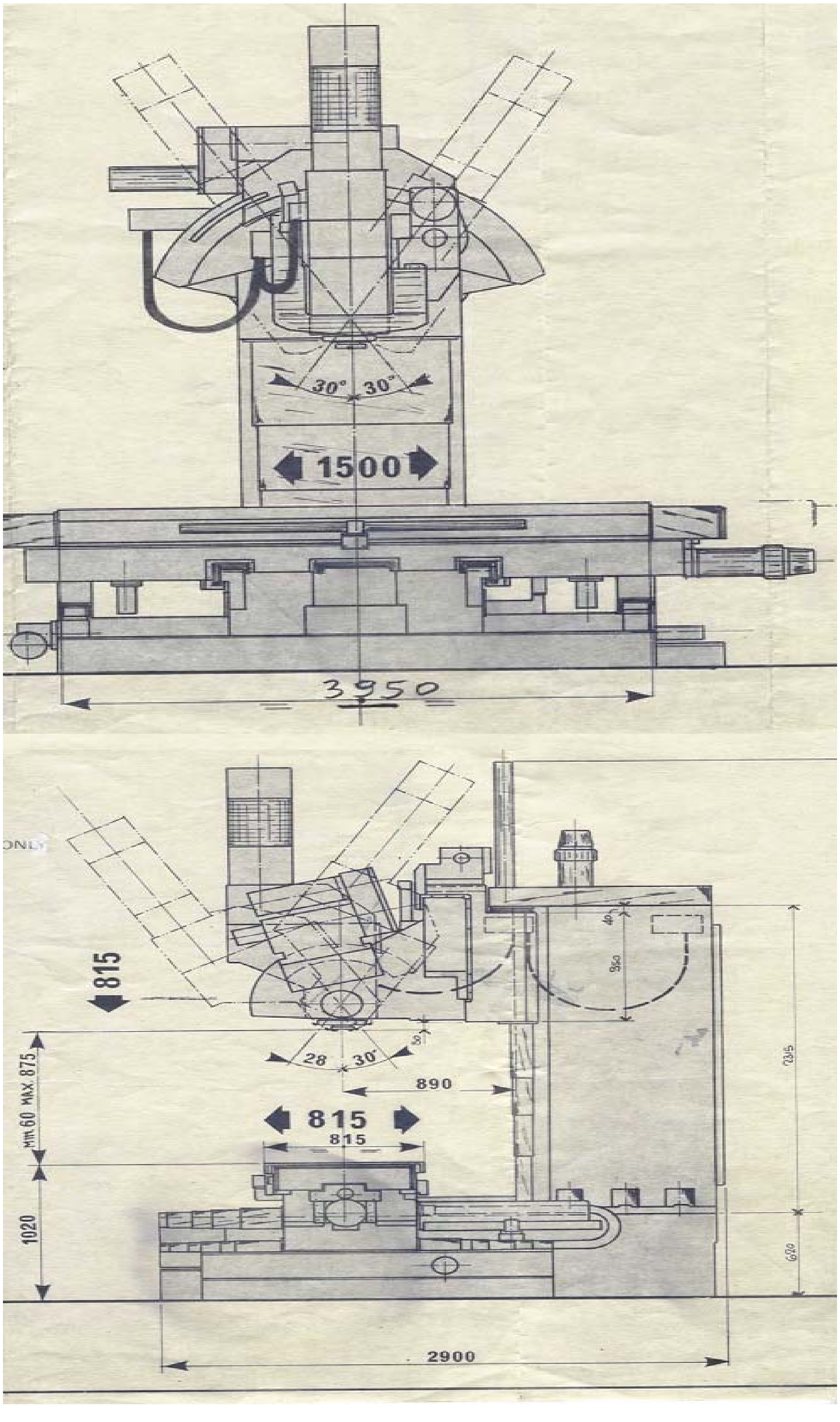


FIG 4.12 RAMBAUDI CNC HIGH SPEED MILLING MACHINE

***Positional Accuracy*:** The Positional Accuracy of the machine is ± 15 Microns.

Repeatability: The repeatability of the machine is ± 10 Microns

***Power*:** The cutting power of the machine is 20 KW.

Vacuum clamping Table:

The machine is electrically and mechanically prepared to operate with an optional vacuum table (1400mm X 800mm), that can be mounted over the standard worktable. It is capable of holding the work piece having a thickness range of 4 to 30mm. The pressure is maintained between 600-800milli-bars below atmosphere, so as to hold the job. When the pressure increases to 600 milli-bar, the vacuum pump starts automatically.

The vacuum table consists of twenty-three circular channels for holding the work piece. When the channel is open, it will hold the work piece airtight and when it is closed, it releases the work piece. Various sizes of rubber gaskets are used for holding the work piece airtight.

High Speed Electro Spindle

The machine is equipped with a catridge type high-speed electro spindle (6,000 -40,000 rpm) and relevant control system. This equipment can be plugged into the control panel whenever it is needed. The high frequency spindle accessory is fastened to the lower part of the milling head and the main spindle is automatically disconnected. The spindle can run at a maximum speed of 40,000-rpm. But it can hold only up to Ø10mm end mill cutters.

Control Panel

The control panel in this machine consists of a monitor in which all the codes necessary for machining the part can be input. It has an emergency stop switch to stop the machine suddenly. It has facilities to view the tool path according to the program and it can be checked with the original diagram. Provisions are given for automatic coolant ON and OFF and over riding of the speed and feed.

4.8 CUTTING TOOLS AND THE METAL CUTTING PARAMETERS

HSS Drills & Reamer and Carbide milling cutters& Reamer have been used for the machining of Slotted Array Antenna. The Solid Carbide End mills are of stub (short) length type as shown the figure 4.13 to avoid deflection of the cutter while milling at high speeds (40,000 rpm) and feeds (1100mm/min).

Cutting Speed

Cutting speed refers to the rotating speed of the cutter (Primary motion) at which the material is sheared and removed and it depends on the following factors:

1. Cutting tool material
2. Work piece material

The speed used for specific application is normally a compromise between a high speed that will yield a high rate of metal removal or a speed that will result in desirable tool life.

Cutting speed V = (3.14 x D x N) / 1000

Therefore Cutter rotation (N) = (V x 1000) / (3.14 x D)

Where D is the cutter diameter in mm

If Cutting speed V is taken to be 200 m/min and the cutter diameter to be 3.0mm

Then N = (200 x 1000) / (3.14 x 3) = 21,200 RPM

Feed

Feed is expressed as the rate at which the work moves past the cutter in millimeter per tooth. Feed per tooth is the linear distance of tooth advancement for each revolution of the cutter. Therefore feed per revolution of the cutter is the product of feed per tooth and the number of teeth on the cutter.

Factors influencing the feed are

1 Type of cutter.
2 No. of teeth.
3 Cutter material.
4 Work metal composition and hardness.
5 Depth of cut.
6 Width of cut.
7 Speed.

TABLE 4.8 SPEED AND FEED FOR SOLID CARBIDE END MILL CUTTERS

Material to be machined	**Speed (m / min)**	**Feed (mm / tooth)**		
		Cutter dia. up to 6 mm	**Cutter dia. up to 12 mm**	**Cutter dia. up to 25 mm**
Aluminium alloys	183 - 365	0.005 -0.05	0.05-0.1015	0.1015-0.2030

Depth of Cut

Depth of cut is the perpendicular distance, the tool digs into material from the top surface of the job in end milling operation. Depth of cut in rough milling is usually 3.2 mm or more. In finish milling, depth of cut may vary from several hundredths of a millimeter to 1.6 mm for optimum surface finish. Roughing cuts with maximum DOC value is used for the optimum power utilization of the machine without affecting the quality of the machined part. It is then followed by a finishing cut considering the surface finish required for the part. When using carbide-tipped cutters, it is often possible to attain the required surface finish in a single cut.

Recommendations for Depth of Cut:

For Lighter Radial Depths of Cut:

Higher range of recommended surface speeds should be used.

For Greater Radial Depths of Cut:

Lower range of recommended surface speeds should be used.

Axial Depth of Cut:

Recommendations are not to exceed one and a half times the cutter diameter.

4.9 MACHINING OF RADIATING PLATE

Before starting the machining, Thickness and Surface Quality of the clad sheet were checked and ensured such that it is with in the given tolerance limits i.e., $1.05^{0.00/+0.03}$ and also the sheet is free from any sort of scratch. The clad sheet was first loaded on the CNC Turret Punch press table with clad side at bottom to cut the blank to the size 700mm x 700mm, after punching the clamp holes of Ø10.5mm at four places.

After deburring the blank was loaded on the CNC High Speed milling machine table with vacuum clamping table and Aluminium Alloy fixture plate in position. The pocket size lever type dial indicator (one-micron accuracy) was used to dial the Ø20mm reamed hole in the fixture plate to arrive the center of the radiating plate (job origin). While loading the clad sheet, the clad side was kept bottom against fixture plate surface and the sheet was firmly clamped using M10 Allen screws and the four punched holes.

Four numbers of Ø3mm dowel holes were drill & reamed and four numbers of Ø5mm dipole holes were drilled keeping flat mild steel (MS) dead weight at suitable location over the blank. The drilled & reamed holes were checked using the GO/NOGO Gauge.

A trial slot was milled in the unwanted area of the blank and inspected to correct the radius compensation of the cutter if necessary, to ensure the slot dimensions are with in tolerance limits. For this in-process inspection slip gauges and digital inside micrometer were used.

The 604 numbers of 2.5mm width & varying lengths longitudinal radiating slots were milled using Ø1.5mm solid carbide cutter, quadrant by quadrant, placing the one-quadrant cut open NOVOPAN sheet above the blank and flat mild steel (MS) dead weight over the NOVOPAN sheet.

The in-process inspection of the milled radiating slots has been carried out at regular time intervals to ensure whether the slot dimensions were with in tolerance limits.

The two numbers of 2mm width guard slots were also milled while milling the 4th quadrant radiating slots.

Finally the outside profile Ø650mm was milled using the same Ø1.5mm solid carbide cutter after covering all the four quadrants of the job with NOVOPAN sheet under flat mild steel (MS) dead weight.

The finished Radiating plate was degreased for internal shop inspection using STIEFELMAYER 3D Co-ordinate Measuring Machine (CMM).

4.10 MACHINING OF APERTURE PLATE

The Aluminium Alloy blank 810mm x 810mm x 15mm was first cut using band saw machine and then loaded on SIP-640 Double Column Milling machine. The Raw material blank with bend was then leveled by proper packing on the machine table to give face-milling cut to get a flat surface such that it can be loaded on the vacuum clamping table of the CNC-High Speed milling machine.

After thorough deburring the blank was shifted to CNC-High Speed milling machine for further operations. The vacuum table was thoroughly cleaned and prepared by placing the Gasket Rings at the appropriate locations such that the blank gets uniformly and firmly clamped over the vacuum table surface. Then the blank was placed with the face-milled surface butting against the vacuum table surface.

Thickness machining to 12.7mm was carried out, with minimum 3 reversals using Ø160.0mm Carbide tipped face-milling cutter with 0.25mm depth of cut. Before every reversal thorough deburring and perfect cleaning of the vacuum clamping table & Gasket Rings was done.

The thickness-machined blank was then subjected to vibration stress relieving to remove the stress induced due to machining.

Again the thickness machining was continued to achieve 11.76mm with minimum 2 reversals using the same face-milling cutter with 0.2mm depth of cut.

Two- Ø20mm reference holes were drill & reamed on the blank at a pitch distance of 400mm. The first hole was located approximately 20mm X 200mm from left lower corner of the blank. For this operation the blank was clamped on the vacuum table with 40mm projecting out of the vacuum table towards the -X direction. For this operation the following tools such as Ø2.0mm HSS center drill bit, Ø6.0mm, Ø12.0mm Ø19.5mm HSS drills and Ø20.0mm HSS Reamer were used

The blank was again loaded on the vacuum-clamping table of High Speed milling machine for further operation.

Front side-machining operations:

By dialing the two-Ø20mm reamed reference holes, using pocket size lever type dial indicator of 1- micron accuracy, the job origin is fixed at a definite distance in X and Y directions towards the center of the blank.

Four numbers of Ø3mm dowel holes were drill & reamed using Ø2.0mm center drill, Ø2.7mm HSS drill & Ø3.0mm Solid Carbide Reamer. Similarly four numbers of Ø5mm Dipole antenna holes were drilled using Ø2.0mm center drill, Ø2.7mm HSS drill & Ø5.0mm HSS drill. The Ø3.0mm holes were inspected using GO-NOGO Gauge.

Wave-Guide cavities end short opening and width finishing was done using Ø5.0mm Solid Carbide cutter to a depth of 5.28mm with 1mm depth of cut. Then the rough milling of Wave-Guide Cavities has been carried out, using Ø8.0mm Solid Carbide cutter with 5.0mm depth of cut. Finally the length & depth finish milling of Wave-Guide Cavities, has been carried out using the same Ø8.0mm Solid Carbide cutter with 0.28mm depth of cut to maintain the pocket depth to 5.28mm.

At intermediate stages the milled pocket dimensions were inspected using Digital inside Micrometer, Digital Vernier Caliper and Digital Depth Gauge.

Finally out side contour Ø650mm milling was done using Ø8.0mm, two-lip Solid Carbide cutter with 3.5mm depth of cut to a depth of 6.5mm.

Again after completion of the front side Wave-Guide Cavities the machined blank was subjected to vibration stress relieving to remove the stress induced due to pocket-milling operation.

The blank was then subjected to chemical cleaning/degreasing at plating section.

Low Temperature Melting CERROBEND Alloy

Before taking up the job for the backside machining the front side machined Wave-Guide Cavities were filled with Low Temperature Melting CERROBEND alloy at foundry shop to get the rigidity and a flat solid surface for vacuum clamping.

The Cerro bend alloy filled blank was then loaded on the vacuum table of High Speed milling machine with the Cerro bend alloy filled side facing up to face-mill the filled surface using the Ø160.0mm carbide tipped face-milling cutter. Face milling was done to a depth of 0.2mm such that the wave-guide pocket depth is maintained to 5.08mm.

After the Cerro bend alloy surface milling, the blank was reversed for backside operations. By dialing the same two- Ø20mm reamed reference holes, using pocket size lever type dial indicator of 1-micron accuracy the same front side job origin is refixed.

Again by using the same Ø160mm carbide tipped face-milling cutter the thickness of the blank has been maintained to final thickness dimension i.e., 11.36mm.

Back side machining operations:

All the Ø3mm dowel holes were drill & reamed using Ø2.0mm center drill, Ø2.7mm HSS drill & Ø3.0mm Solid Carbide Reamer. Similarly all the other M2.5 & M3 holes were drilled using Ø2.0mm center drill, Ø2.1mm HSS drill & Ø2.5mm HSS drill. The Ø3.0mm holes were inspected using GO-NOGO Gauge.

Wave-guide pocket out side contour milling was done using Ø6.0mm solid carbide cutter with 2.0mm depth of cut to finish the depth to 5.08 mm.

Then Wave Guide cavities end short opening and width finishing, was done using Ø5.0mm Solid Carbide cutter with 1mm depth of cut to finish the depth to 5.08mm. Then the rough milling of Wave-Guide Cavities has been carried out, using Ø8.0mm Solid Carbide cutter with 5.0mm depth of cut. Finally the length & depth finish milling of Wave-Guide Cavities, has been carried out using the same Ø8.0mm Solid Carbide cutter with 0.28mm depth of cut to maintain the pocket depth to 5.08mm.

At intermediate stages the milled pocket dimensions were inspected using Digital inside Micrometer, Digital Vernier Caliper and Digital Depth Gauge.

The inclined coupling slots of 2.5mm width and varying length and angular orientation were then milled using Ø1.5mm solid carbide cutter with 2.0mm depth of cut. At intermediate stages the coupling slots were checked using Digital Inside Micrometer and slip gauges.

The Bosses at fifteen places were milled using Ø6.0mm & Ø3.0mm HSS ball end mill cutters with 2.0mm depth of cut to finish the depth to 5.08mm.

Finally the Extra material removal leaving the 1.5mm support ribs was carried out using Ø10.0mm solid carbide cutter with 1.0mm depth of cut to finish the depth to 5.08mm.

The blank was removed from the machine table after checking for the completion of all the backside operations. The Cerro bend alloy was then removed by immersing the machined blank in the hot water at foundry shop.

The separated job i.e. the APERTURE PLATE was then subjected to chemical cleaning/degreasing at plating section. The machined APERTURE PLATE has been inspected for its flatness. Since the flatness was not with in the given limit i.e., 0.2mm it was thermally stress relieved at foundry shop, to remove the bend and twist.

After achieving the flatness with in 0.2mm the job was thoroughly deburred. The finished APERTUREPLATE was cleaned and degreased for internal shop inspection using STIEFELMAYER 3D-CMM.

4.11 MACHINING OF MICROWAVE POWER DIVIDER

The Aluminium Alloy blank 810mm x 730mm x 15mm was first cut using band saw machine and then loaded on SIP-640 Double Column Milling machine. The Raw material blank with bend was then leveled by proper packing to give face-milling cut to get a flat surface such that it can be loaded on the vacuum clamping table.

After thorough deburring the blank was shifted to CNC-High Speed milling machine for further operations. The vacuum table was thoroughly cleaned and prepared by placing the Gasket Rings at the appropriate locations such that the blank gets uniformly and firmly clamped over the vacuum table surface. Then the blank was placed with the face-milled surface butting against the vacuum table surface.

Thickness machining to 12.7mm was carried out, with minimum 3 reversals using Ø160.0mm carbide tipped face-milling cutter with 0.25mm depth of cut. Before every reversal thorough deburring and perfect cleaning of the vacuum clamping table & Gasket Rings was done.

The thickness-machined blank was then subjected to vibration stress relieving to remove the stress induced due to machining.

Again the thickness machining was continued to achieve 11.36mm with minimum 2 reversals using the same face-milling cutter with 0.2mm depth of cut.

The blank was then cut to smaller blank size 320 x 270 x 11.36 mm in band saw cutting machine. The blanks are then cleaned and deburred to drill the Ø6.2mm clamping holes and drill & ream the Ø5mm locating dowel holes on KIWA-CNC drilling center.

After deburring and stage inspection, a set four blanks were clamped using the suitable clamps and dowel pins over the 810 x 810 x 25mm Aluminium alloy fixture plate which in turn clamped on the CNC- High Speed milling machine’s vacuum clamping table using the gasket rings at suitable locations.

By dialing the two- Ø20mm reamed reference holes, using pocket size lever type dial indicator of 1- micron accuracy, the job origin is fixed at a definite distance in X and Y directions towards the center of the fixture plate.

All the Ø3mm dowel holes were drill & reamed using Ø2.0mm center drill, Ø2.7mm HSS drill & Ø3.0mm Solid Carbide Reamer. The Ø3.0mm holes were inspected using GO-NOGO Gauge.

Then the finish milling of Wave-Guide Cavities to a depth of 5.08 mm has been carried out, using Ø8.0mm Solid Carbide cutter with 2.0mm depth of cut, leaving 0.2mm allowance on the width of the Wave-Guide Cavities. Finally the finish milling of Wave-Guide Cavities width has been carried out using the Ø3.0mm Solid Carbide cutter to maintain the minimum corner radius. At intermediate stages the milled pocket's length, width & depth dimensions were inspected using Digital inside Micrometer, Digital Vernier Caliper and Digital Depth Gauge.

After thorough Cleaning and Deburring, all the four divider blanks were reversed for 2nd side machining.

All the Ø3mm dowel holes were drill & reamed using Ø2mm center drill, Ø2.7mm HSS drill & Ø3.0mm Solid Carbide Reamer. The Ø3.0mm holes were inspected using GO & NO GO Gauges.

Then the finish milling of Wave-Guide Cavities to a depth of 5.08 mm has been carried out, using Ø8.0mm Solid Carbide cutter with 2.0mm depth of cut, leaving 0.2mm allowance on the width of the Wave-Guide Cavities. The outside contour of the wave-guide cavities were machined using Ø6.0mm Solid Carbide cutter with 2.5mm depth of cut to a finish depth of 5.08mm.Finally the finish milling of Wave-Guide Cavities width has been carried out using the Ø3.0mm Solid Carbide cutter to maintain the minimum corner radius. The layer feeding rectangular openings were also milled using the same Ø3.0mm Solid Carbide cutter. At intermediate stages the milled pocket's width & depth dimensions were inspected using Digital inside Micrometer, Digital Vernier Caliper and Digital Depth Gauge. Finally down milling of the extra-area was carried out using the Ø8mm solid carbide cutter with 2.5mm depth of cut to a finish depth of 5.08mm.

After thorough Cleaning and Deburring, all the four divider blanks were again reversed for the 1st side to continue the left out machining operations.

The outside contours of the narrow gap wave-guide cavities were machined using the Ø4mm solid carbide cutter in two depths to a depth of 5.08mm.

The outside contours of the remaining wave-guide cavities were machined using the Ø6mm solid carbide cutter in two depths to a depth of 5.08mm. Finally down milling of the extra-area was carried out using the Ø8mm solid carbide cutter with 2.5mm depth of cut to a finish depth of 5.08mm.

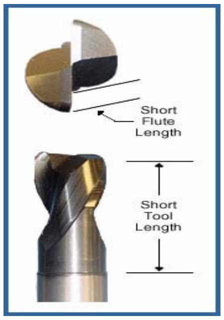
The in-between narrow gap contours of the wave-guide cavities were also machined using the Ø4mm solid carbide cutter in single depth.

Finally the outside contour of the complete divider profile was milled using Ø6mm solid carbide cutter in two depths to a depth of 6.28mm to remove the job out of blank. The finished jobs i.e. a set of four Power Dividers were thoroughly cleaned and deburred for internal shop inspection using STIEFELMAYER 3D CMM.

4.12 CNC PART-PROGRAMS

The required CNC Part-programs for the given AutoCAD Part-drawings were generated using the '*CAPS MILL*' CAM software package. The AUTOCAD drawings were saved in the DXF file format in the 1:1 scale and then exported to the *CAPS MILL* software package and the required sequential operations were done to generate the CNC Part programs. The Part-programs generated were then transferred to the CNC control (i.e. Machine memory) through telecommunication network using DNC software called NC-NET. Before transferring the Part-programs to the CNC machine memory, they were verified by the simulation of Tool-path on the PC MONITOR itself as shown in the below figures 4.14 & 4.15. Some of the generated and used CNC Part Programs has been enclosed in APPENDIX-II and the table of G codes & M codes for the used CNC Machine has been enclosed in APPENDIX-III.

FIG 4.13 SOLID CARBIDE END MILL CUTTER



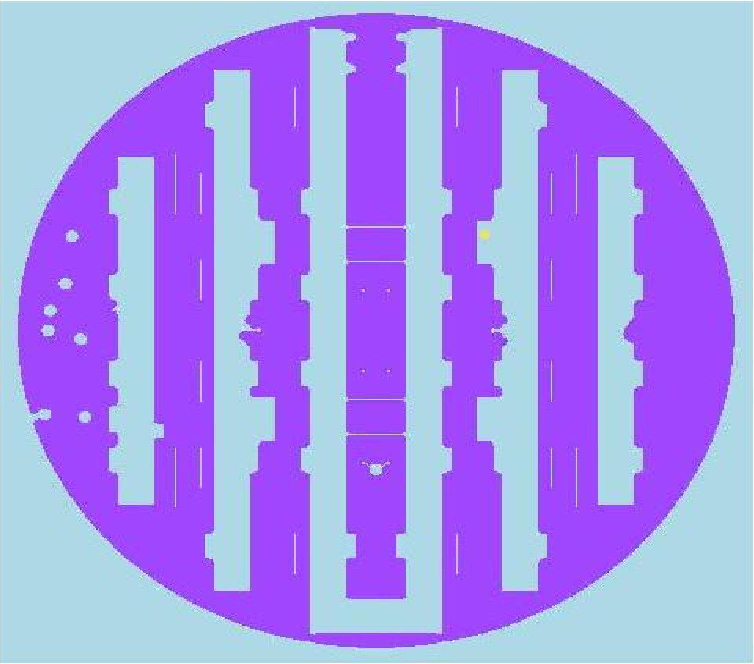


FIG. 4.14 Tool path simulation of extra area down milling of Aperture plate back side

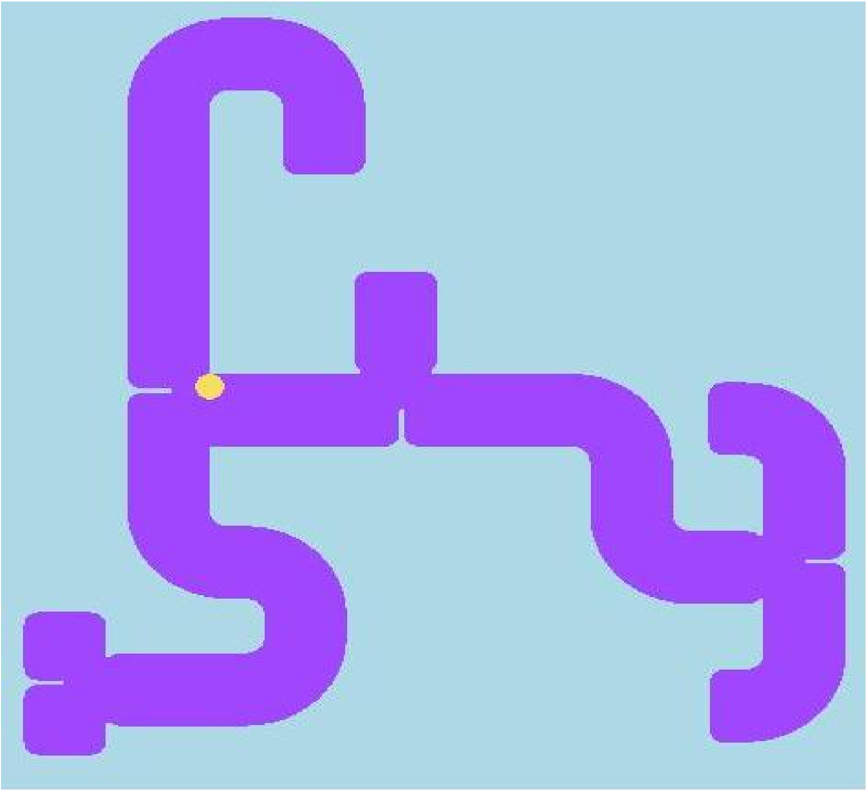


FIG. 4. 15 Tool path simulation of wave-guide pocket milling of Power divider front side

CHAPTER 5

5 INSPECTION

5.1 INTRODUCTION TO CO-ORDINATE MEASURING MACHINE (CMM)

A CMM is an advanced, multi purpose quality control system used to quickly inspect components and keep pace with the productivity of CNC machines. It replaces long, complex, inefficient conventional inspection methods with simple procedures that are up to twenty times faster, and much more accurate. A CMM can reduce or eliminate CNC machine down time, reduce scrap or rework and is easy to operate. It uses probe to obtain measurements on a manufactured part's surface, usually one point at a time. Probe movements may be programmed or determined manually. CMMs have gained tremendous popularity over conventional measuring instruments for dimensional measurements due to their flexibility, accuracy and adaptation for automation.

Scales and Encoders

The scales of a CMM show where the probe is located on the X, Y and Z-axis within work area of the machine. The scales used are machine-readable and thus cannot be read by naked eye due to the high degree of resolution of the CMM. The CMM encoder reads the scales and inputs this measurement data into the computer for computation and display.

Sensor and Probes

Sensors and probes are devices through which the CMM collects the measurement input. A broad variety of probes are currently available with its own application permitting users to obtain very accurate measurement of virtually any type of part features, contour surfaces and so on.

CMM Measuring Techniques

A CMM takes measurements of an object with in its work area by moving a sensing device called 'Probe' along the various axis of travel until the probe contacts the object. The precise position of contact is recorded and made available as an output. The CMM is used to make numerous contacts with the probe, using all axis of travel, until an adequate database of the surface of the object has been obtained. For example, a plane surface or a circular hole can be recorded with a minimum of three contacts. Once repeated contacts or readings have been made and stored, they can be applied in a variety of ways through the computer and geometric measurement software of the CMM to get the required final output dimensions of the part.

5.2 INSPECTION OF ANTENNA PARTS ON CMM

All the precision machined Slotted Array Antenna Parts, viz.,

1. The Radiating Plate,
2. The Aperture plate,
3. A set of four power dividers &
4. A set of microwave transition cover plates,

were subjected to STIEFELMAYER 3D CMM inspection for faster and accurate measurement of locations and dimensions using fixtures wherever required.

CHAPTER 6

6 ASSEMBLY AND DIPBRAZING – A BRIEF OVERVIEW

All the above precision machined and inspected Slotted Array Antenna Parts along with other small components such as End boxes, Mounting pads etc., were precisely located and assembled with Ø3mm dowel pins in a dust free atmosphere after thorough chemical cleaning and degreasing. A process called Dip-brazing, which is explained, below in brief, then joins the assembly.

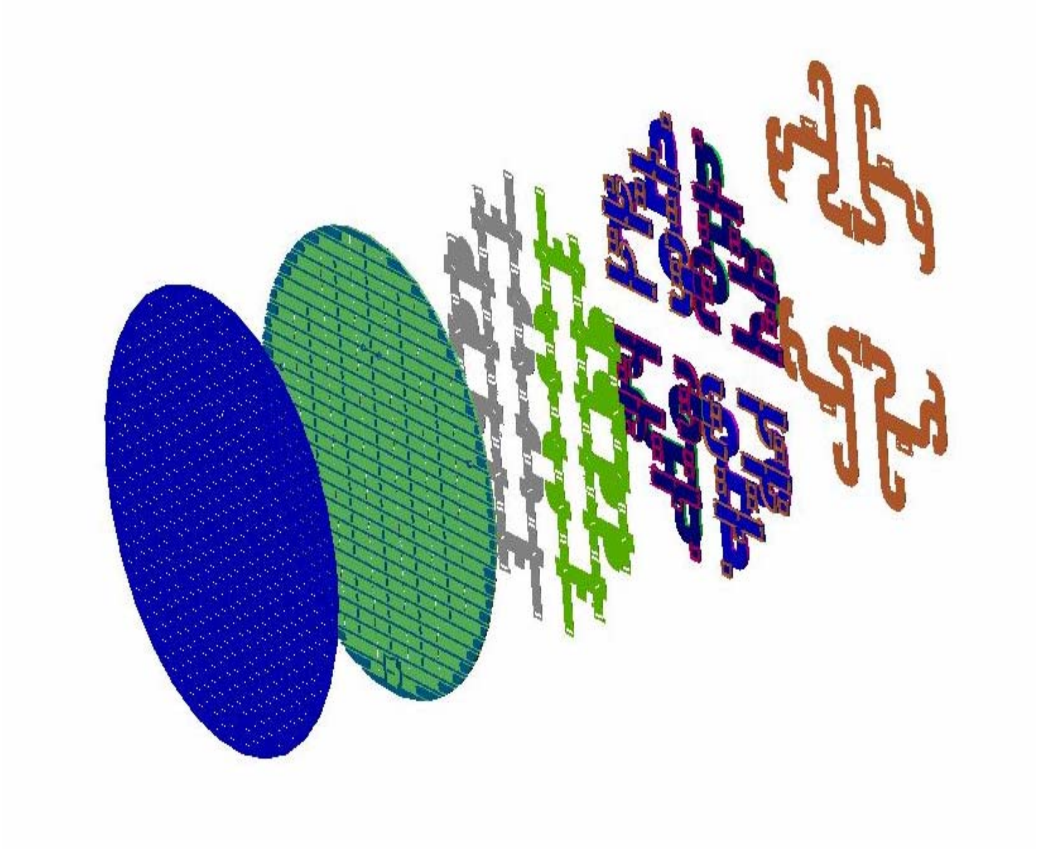


FIG -6.1 EXPLODED VIEW OF THE SLOTTED ARRAY ANTENNA ASSEMBLY

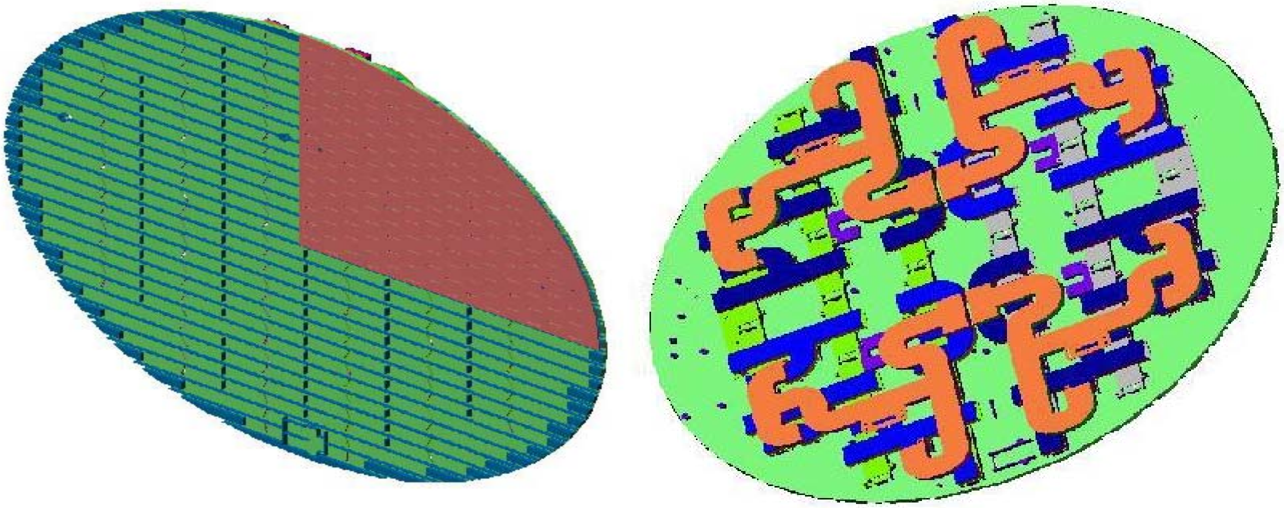


FIG -6.2 ASSEMBLY OF SLOTTED ARRAY ANTENNA

6.1 BRAZING

The word “BRAZING” suggests “brass” and its root meaning comes from the art of joining iron and copper using various brass or bronze alloys.

The American welding society defines brazing as “A group of welding processes wherein coalescence is produced by heating to suitable temperatures above 425^0C and by using a non-ferrous filler metal having a melting point below that of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary action.

Where as aluminium brazing is a way of joining aluminium parts with an alloy whose melting point is slightly below the melting range of the parent alloy. In welding, both parent alloy and filler alloy melt and joining takes place. Where as in brazing, only the filler alloy melts and flows into the crevices by capillary action.

6.2 DIP-BRAZING

Dip brazing is the process of joining aluminium parts by the immersion of the assembly into a molten flux bath.

The molten flux typically is at a temperature of 600^0C which is below the melting point of base aluminium alloy. At all joints to be brazed, there is a filler metal that is another alloy of aluminium containing about 7.5 % to 12% silicon and it melts at 580^0C to 590^0C. The molten filler alloy is drawn by capillary action and gravity to form fillets at intersecting surfaces.

Immersing entire assembly into molten flux has many advantages. The main advantage is that, the heat is applied to all parts simultaneously and uniformly, which minimizes the distortions caused by local heating of the joints to be brazed. It applies a flux without a separate operation. It protects the parts against corrosive effects by enveloping the parts being dib brazed.

Dip Brazing Process

The sequential steps involved in the Dip brazing process are as follows:

1. Deburring
2. Degreasing and thorough chemical Precleaning
3. Assembly of part in the dust free atmosphere
4. Application of filler metal
5. Masking to prevent brazing alloy flow
6. Pre-heating
7. Immersion into molten flux bath
8. Air cooling
9. Post chemical cleaning

Advantages

Dip brazing method of making joints offers some unique design and fabricating freedoms that can lead to important cost savings. Designers should avail themselves of the advantages it can bring by considering it early, in their planning.

Some important advantages are mentioned below:

1. Complicated assemblies with many inaccessible joints, fabricated both of thick and thin materials can be joined in a single operation.
2. Many joints can be brazed simultaneously.

3. No skilled personnel are required.
4. The size of fillets can be controlled. This is a most desirable feature in respect of electrical characteristics of microwave equipments. Ex: wave-guides.
5. The 'as-brazed shape' gives good stress distribution and fatigue resistance.
6. As the molten filler metal is drawn into joint space by capillary action, the as brazed shape will be smooth. Hence again this is a most desirable feature in respect of electrical characteristics of microwave equipments. Ex: wave-guides.

Limitations

The dip brazing operation has got some limitations also. These are

1. High initial equipment cost.
2. All aluminium alloys cannot be dip brazed.
3. Large assemblies having one or two small joint areas may not be economical to dip braze, particularly in small quantities.

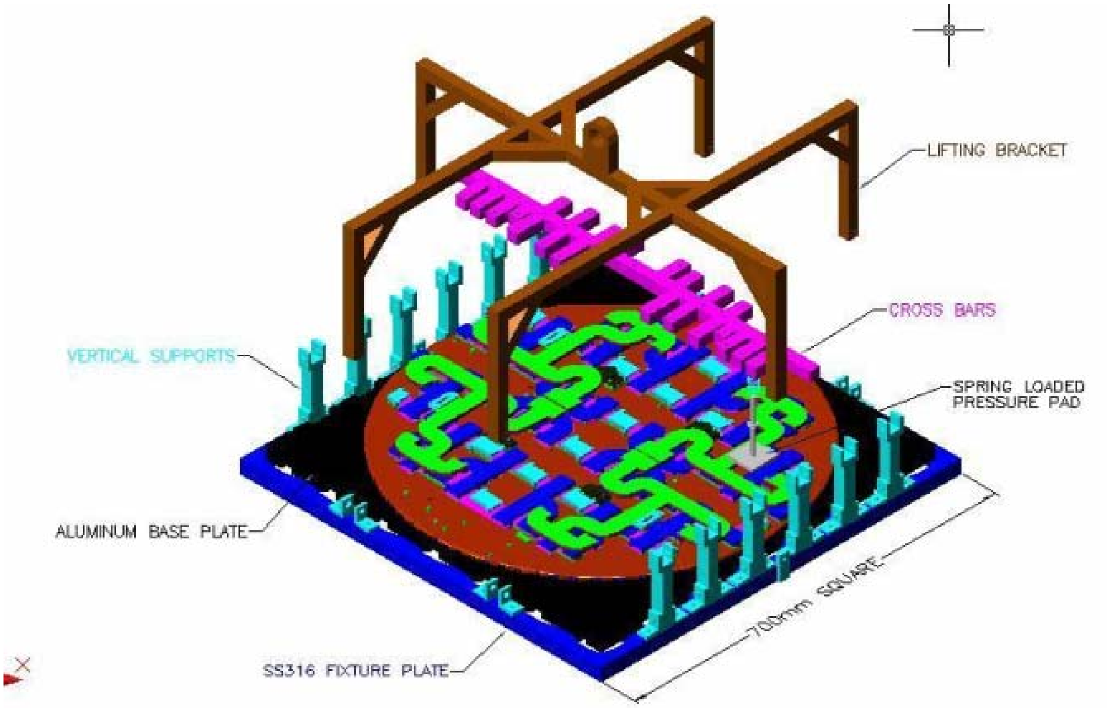


FIG.-6. 3 ANTENNA ASSEMBLY IN THE DIP BRAZING FIXTURE

CHAPTER 7

7 RESULTS AND DISCUSSIONS

7.1 RESULTS OF THE FINITE ELEMENT STATIC ANALYSIS

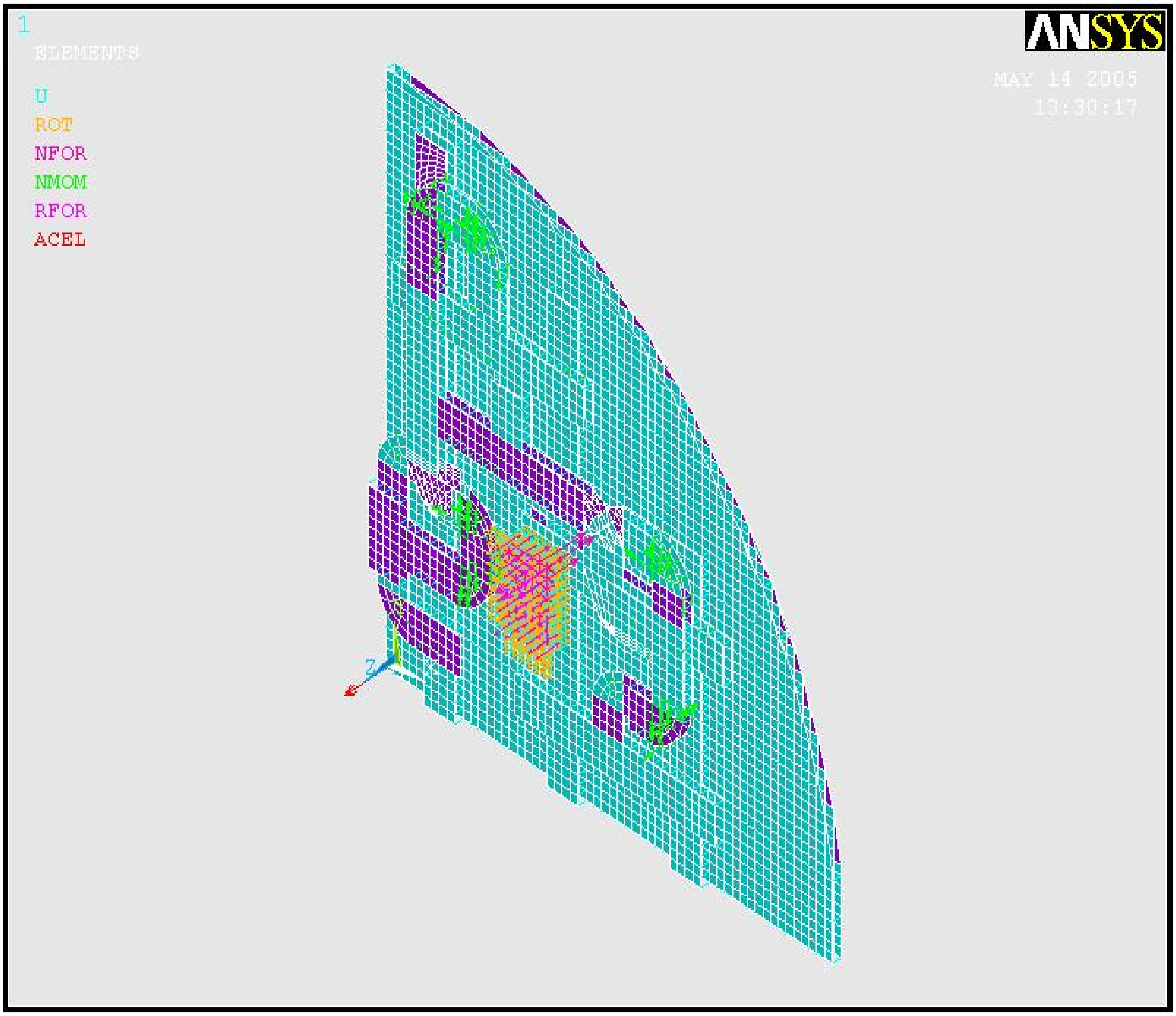


FIG. 7.1 FINITE ELEMENT MESH OF ONE QUADRANT

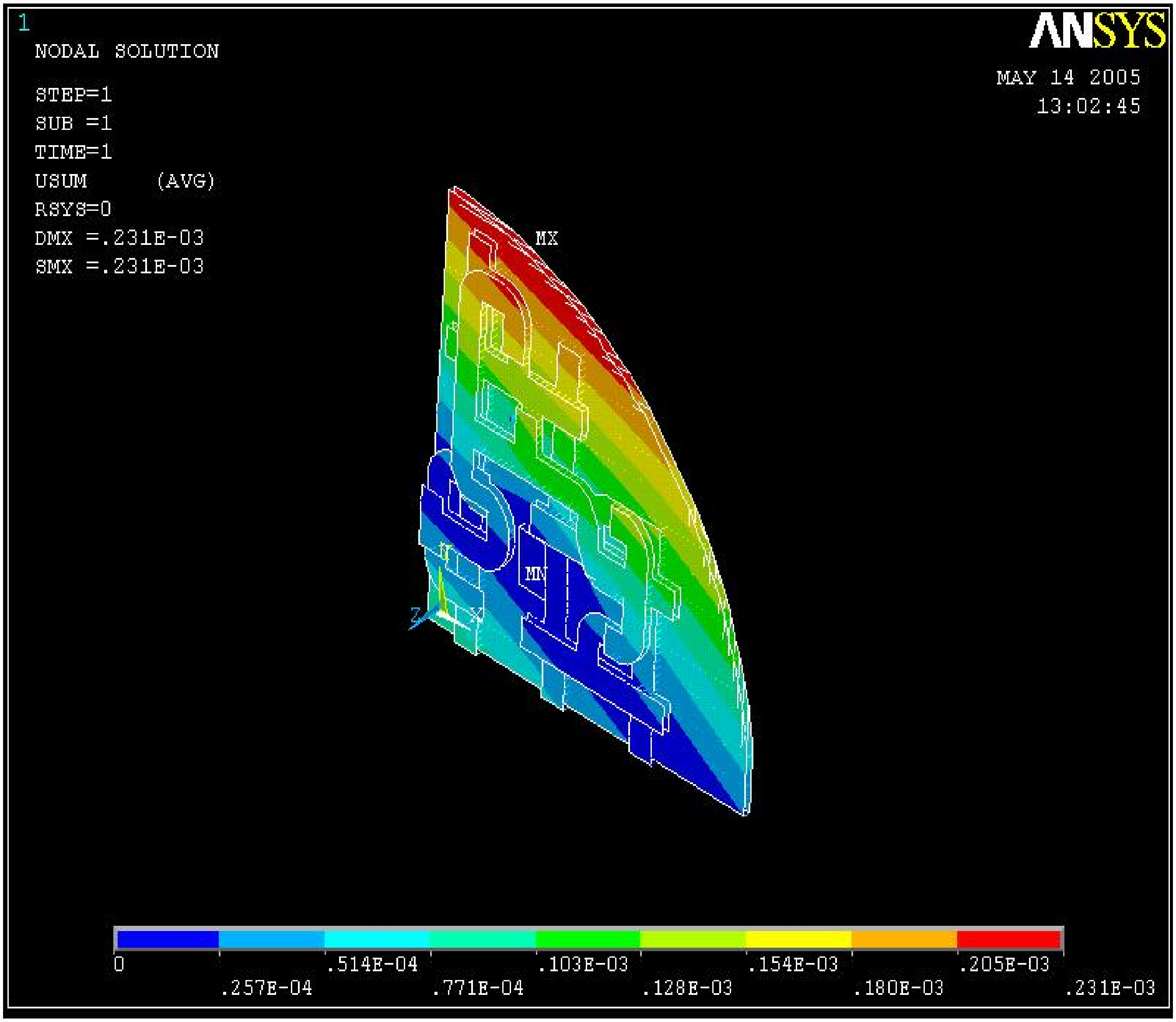


FIG. 7.2 DISPLACEMENT PLOT

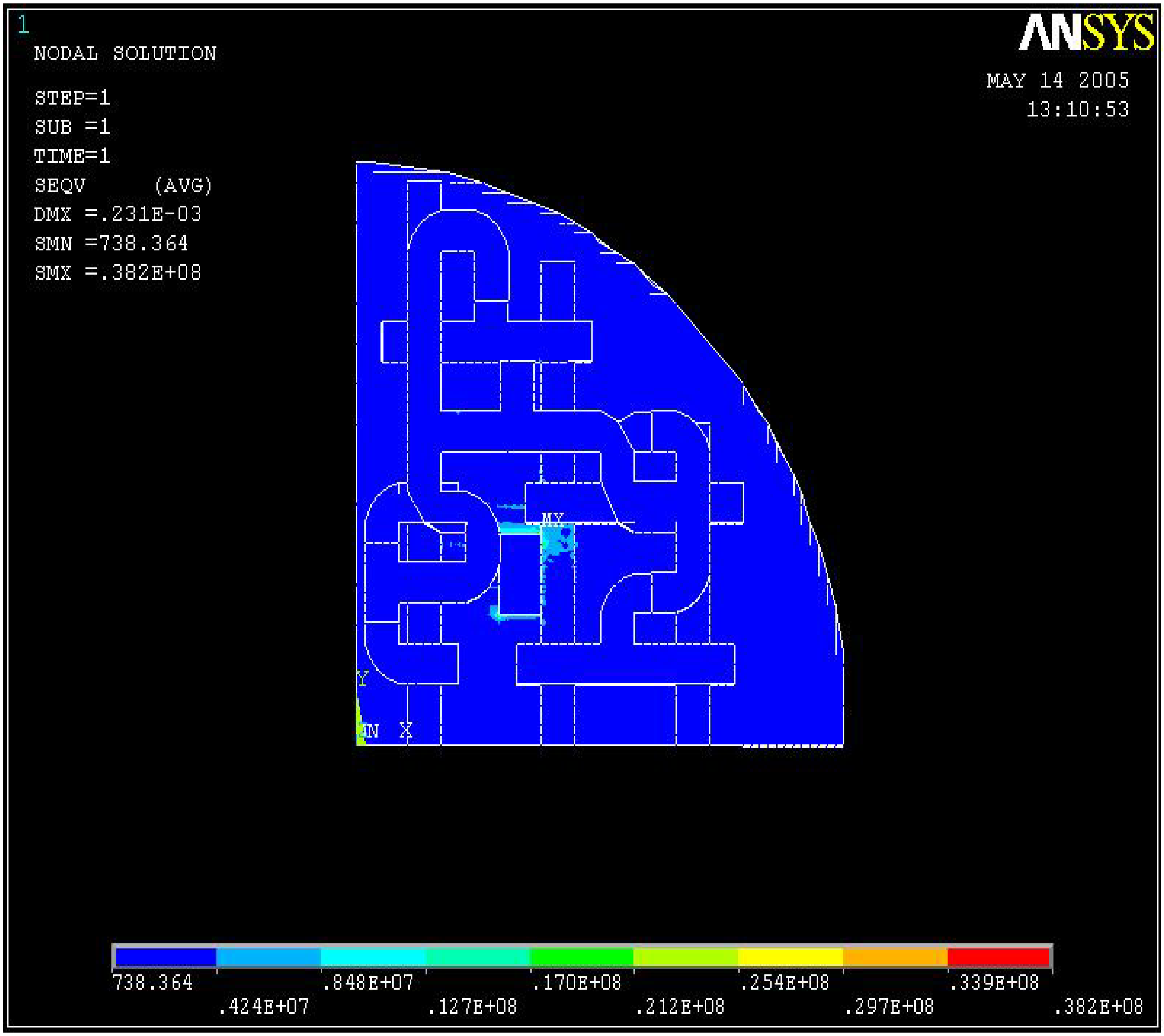


FIG. 7.3 VON MISES STRESS PLOT

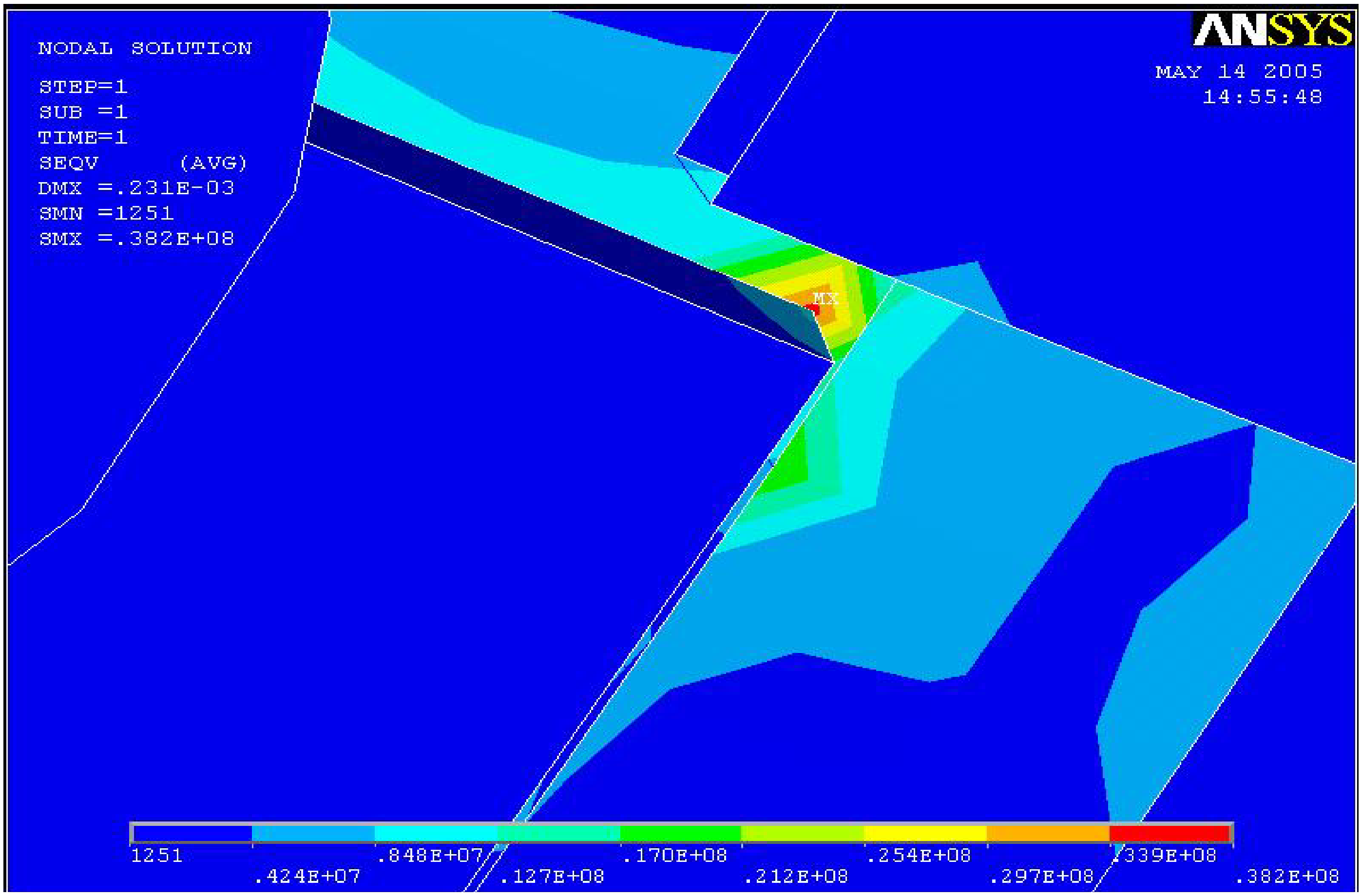


FIG. 7.4 MAXIMUM VONMISES STRESS PLOT AT MOUNTING PAD ROOT

TABLE 7.1 MINIMUM STRESS VALUES

	SX (MPa)	SY (MPa)	SZ (MPa)	SXY (MPa)	SYZ (MPa)	SXZ (MPa)
NODE	3982	3982	3522	4091	3522	3982
VALUE	-23.85	-43.95	-5.56	-1.82	-0.97	-2.40

TABLE 7.2 MAXIMUM STRESS VALUES

	SX (MPa)	SY (MPa)	SZ (MPa)	SXY (MPa)	SYZ (MPa)	SXZ (MPa)
NODE	3982	3982	3522	4091	3522	3982
VALUE	27.09	40.83	11.20	2.79	0.33	0.63

VON MISES STRESS = 38.2 MPa (MAX.)

The Antenna after Dip Brazing attains T4 temper condition i.e., solution treated and natural aged condition and its mechanical properties in that condition is as follows:

Max. Tensile strength = 241 MPa

Yield strength = 145 MPa

Max. Shear strength = 165 MPa.

The obtained maximum vonmises stress value from Finite Element Static Analysis was 38.2 Mpa (Figure7.3 & 7.4) which is approximately ¼ th of the Yield strength (145 Mpa) in T4 Temper condition. Hence it is very clear and evident from the Finite Element Static Analysis that the maximum stress in the Antenna is well within the allowable limits of the material.

In addition, the obtained maximum displacement value from Finite Element Static Analysis was 0.231mm (Figure 7.2), which is acceptable. Hence it is also very clear and evident from the Finite Element Static Analysis that the maximum displacement in the Antenna for the inertial load of magnitude 5g is well within the allowable limits of the design.

Further, the Finite Element Static Analysis of the Antenna using the ANSYS 8.0 FEM package has provided the enough scope for learning the complex FEM analysis of the difficult airborne structure.

7.2 RESULTS OF THE CNC MACHINING OF ANTENNA COMPONENTS

The machined components were assembled and dip brazed after ensuring the functional wave-guide and slot dimensions by hundred percent inspection using the 3D CMM. Finally the fabricated Slotted Array Antenna was subjected to electrical performance evaluation and the results were found to be highly satisfactory, meeting all the functional requirements of the Radar.

Thus, the successful CNC machining of all the critical components of the Slotted Array Antenna **in-house** has not only led to the gain of experience, it has also provided the confidence and command over such difficult machining tasks in future.

Especially with light aluminium alloys to maintain a very close tolerance of ±30 microns in large dimensions involving large volume of material removal, that too leaving a thin wall of 1.2mm thick all-round, was really a challenging task.

The latest HIGH-SPEED machining and vacuum clamping techniques of Aluminium alloys were economically and advantageously utilized for both improving the quality of the machined parts and also for drastically reducing the machining time.

It has provided the enough scope for learning new techniques and gaining expertise in the areas of CNC Part Program generation of complex geometries using CAM software viz., CAPSMILL and NCNET for transferring the generated CNC Part Program from PC to CNC Machine and vice versa.

CHAPTER 8

8 FUTURE SCOPE OF THE WORK

Weight reduction is the prime requirement for Airborne Radar applications and hence an attempt for further reduction in all around wall thickness to 1mm, without affecting the structural requirement can be made.

With the experience and expertise gained in successful machining of 1.2mm wall thickness Aluminium alloy Antenna parts, by applying the latest high speed milling & vacuum clamping techniques and recently introduced solid carbide end milling cutters with unique cutting tool geometry for machining aluminium alloy, the antenna parts can be machined with further reduction in wall thickness to 1mm.

Since slotted wave-guide antennas are the one, which is more widely used for Airborne Radar application because of its ruggedness, reliability, compactness and high power handling capacity, the developed manufacturing techniques can be used for the realization of similar Antennae but for various other types of military and civil Airborne Radar applications to make the country self-reliant.

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APPENDIX-I

INTERNATIONAL WAVEGUIDE SPECIFICATIONS : MECHANICAL 13

I.E.C. R( )	U.K. WG.( )	US. JAN. RG.( )/U Al.	Brass	E.I.A. WR.( )	INSIDE DIMENSIONS			OUTSIDE DIMENSIONS			MAX. RAD. INT. CORNER	RAD. OF OUTSIDE CORNER		a/b
					a	b	Tol.	A	B	Tol.		Min	Max	
3				2300	584.20	292.10					1.50			2.0
4				2100	533.40	266.70					1.50			2.0
5	1	201		1800	457.20	228.60					1.50			2.0
6	2	202		1500	381.00	190.50					1.50			2.0
8	3	203		1150	292.10	146.05					1.50			2.0
9	4	204		975	247.65	123.82					1.20			2.0
12	5	205		770	195.58	97.79					1.20			2.0
14	6	103	69	650	165.10	82.55	0.330	169.16	86.61	0.200	1.20	1.00	1.50	2.0
18	7			510	129.54	64.77	0.260	133.60	68.83	0.200	1.20	1.00	1.50	2.0
22	8	105	104	430	109.22	54.61	0.220	113.28	58.67	0.200	1.20	1.00	1.50	2. 0
	9				88.90	44.45	0.200	92.96	48.51	0.200	1.20	1.00	1.50	2.0
26	9A	113	112	340	86.36	43.18	0.170	90.42	47.24	0.170	1.20	1.00	1.50	2.0
32	10	75	48	284	72.14	34.04	0.140	76.20	38.10	0.140	1.20	1.00	1.50	2.119
	10A				76.20	25.40	0.140			0.140	1.20	1.00	1.50	3.000
35					66.37	29.50	0.140	70.37	33.50	0.150	1.20	1.00	1.50	2.250
	11				60.25	28.499	0.120	63.50	31.75	0.120	1.20	0.80	1.30	2.095
40	11A			229	58.17	29.083	0.120	61.42	32.33	0.120	1.20	0.80	1.30	2.0
41					57.00	25.330	0.120	61.00	29.33	0.150	1.20	0.80	1.30	2.25
F45	12A				50.80	16.940								3.0
48	12	95	49	187	47.55	22.149	0.095	50.80	25.40	0.095	0.80	0.80	1.30	2.151
58	13			159	40.39	20.193	0.081	43.64	23.44	0.081	0.80	0.80	1.30	2.0
70	14	106	50	137	34.85	15.799	0.070	38.10	19.05	0.070	0.80	0.80	1.30	2.0
84	15	68	51	112	28.499	12.624	0.057	31.75	15.88	0.057	0.80	0.80	1.30	2.257
100	16	67	52	90	22.860	10.160	0.046	25.40	12.70	0.050	0.80	0.65	1.15	2.250
120	17			75	19.050	9.525	0.038	21.59	12.06	0.050	0.80	0.65	1.15	2.0
140	18		91	62	15.799	7.899	0.031	17.83	9.93	0.050	0.40	0.50	1.0	2.0
180	19			51	12.954	6.477	0.026	14.99	8.51	0.050	0.40	0.50	1.0	2.0
220	20	121	53	42	10.668	4.318	0.021	12.70	6.35	0.050	0.40	0.50	1.0	2.470
260	21			34	8.636	4.318	0.020	10.67	6.35	0.050	0.40	0.50	1.0	2.0
			Ag.											
320	22		96	28	7.112	3.556	0.020	9.14	5.59	0.050	0.40	0.50	1.0	2.0
400	23		97	22	5.690	2.845	0.020	7.72	4.88	0.050	0.30	0.50	1.0	2.0
500	24			19	4.775	2.388	0.020	6.81	4.42	0.050	0.30	0.50	1.0	2.0
620	25		98	15	3.759	1.880	0.020	5.79	3.91	0.050	0.20	0.50	1.0	2.0
740	26		99	12	3.099	1.549	0.020	5.13	3.58	0.050	0.15	0.50	1.0	2.0
900	27			10	2.540	1.270	0.020	4.57	3.30	0.050	0.15	0.50	1.0	2.0
1200	28		138	8	2.032	1.016	0.020	4.06	3.05	0.050	0.15	0.50	1.0	2.0
1400	29		136	7	1.651	0.826								2.0
1800	30		135	5	1.295	0.648								2.0
2200	31		137	4	1.092	0.546								2.0
2600	32		139	3	0.864	0.432								2.0

ALL DIMENSIONS IN MILLIMETRES

14 INTERNATIONAL WAVEGUIDE SPECIFICATIONS : ELECTRICAL

I.E.C. R( )	U.K. WG.( )	US. JAN. RG.( )/U Al.	Brass	E.I.A. WR.( )	MIN. FREQ. GHz.	MAX. FREQ. GHz.	FREQ. GHz.	THEORETICAL dB/m.	MAX. dB/m.	$(\lambda_g/\lambda)P_{max}$
3				2300	0.32	0.49	0.386	0.00078	0.0011	256 MW.
4				2100	0.35	0.53	0.422	0.00090	0.0012	213
5	1	201		1800	0.41	0.62	0.490	0.00113	0.0015	157
6	2	202		1500	0.49	0.75	0.59	0.00149	0.002	109
8	3	203		1150	0.64	0.98	0.77	0.00222	0.003	64.0
9	4	204		975	0.76	1.15	0.91	0.00284	0.004	46.0
12	5	205		770	0.96	1.46	1.15	0.00405	0.005	28.7
14	6	103	69	650	1.14	1.73	1.36	0.00522	0.007	20.4
18	7			510	1.45	2.20	1.74	0.00749	0.010	12.6
22	8	105	104	430	1.72	2.61	2.06	0.0097	0.013	8.95
	9				2.17	3.30	2.53	0.0132		5.93
26	9A	113	112	340	2.17	3.30	2.61	0.0138	0.018	5.59
32	10	75	48	284	2.60	3.95	3.12	0.0189	0.025	3.68
	10A				2.46	3.74	2.95	0.0224		2.90
35					2.82	4.29	3.39	0.0223	0.029	2.94
	11							0.0246		2.58
40	11A			229	3.22	4.90	3.87	0.0249	0.032	2.54
41					3.29	5.00	3.95	0.0280	0.035	2.17
F45	12A				3.68	5.60	4.43	0.0411		1.29
48	12	95	49	187	3.94	5.99	4.73	0.0355	0.046	1.58
58	13			159	4.64	7.05	5.57	0.0431	0.056	1.22
70	14	106	50	137	5.38	8.17	6.46	0.0576	0.075	825 KW.
84	15	68	51	112	6.57	9.99	7.89	0.0794	0.103	540
100	16	67	52	90	8.20	12.5	9.84	0.110		348
120	17			75	9.84	15.0	11.8	0.133		272
140	18		91	62	11.9	18.0	14.2	0.176		187
180	19			51	14.5	22.0	17.4	0.238		126
220	20	121	53	42	17.6	26.7	21.1	0.370		68.9
260	21			34	21.7	33.0	26.1	0.435		55.9
			Ag.							
320	22		96	28	26.4	40.0	31.6	0.583		37.9
400	23		97	22	32.9	50.1	39.5	0.815		24.3
500	24			19	39.2	59.6	47.1	1.06		17.1
620	25		98	15	49.8	75.8	59.9	1.52		10.1
740	26		99	12	60.5	91.9	72.6	2.03		7.20
900	27			10	73.8	112	88.6	2.74		4.84
1200	28		138	8	92.2	140	110.0	3.82		3.10
1400	29		136	7	114	173	136.2	5.21		2.05
1800	30		135	5	145	220	173.6	7.50		1.26
2200	31		137	4	172	261	205.9	9.70		0.71
2600	32		139	3	217	330	260.2	13.8		0.56

APPENDIX-II

RADIATING PLATE

SAMPLE PART PROGRAM

```
%
O0010 (RAD.PL.Q1Q3)
(24-10-2004)
(ENSURE THE
FOLLOWING BEFORE
START)
(USE HIGH SPEED
SPINDLE)
#13=1(1=WITHOUT
MIRROR IMAGE-1 st QTR)
(=2 WITH MIRROR IMAGE-
3 RD QTR)
#1=2(TOOL DEPTH)
#4=1200(FEED)
#28=11(TOOL NO.)
IF[#13EQ1]THEN
#28=10
#27=1(0=C-DRILL;1=MILL)
#10=0(SLOT LENGTH)
#20=2.5(SLOT WIDTH)
G54G00X0Y0A0B0
F#4
G68R#500
/GO270(CLAMPING BORE)
(DIA-2CUTTER)
/GO220(HOLES-
DIA 3.0 MM)
/GO230(HOLE-
DIA 5.0)
/GO240(TRIAL SLOT)
/GO210(O/S-COUNTR USE
2MM CUTTR.)
GO260(DIALING BORE)
M03S35000
G43H#28Z20
IF[#13EQ1]GO1002
G51.1X0Y0
N1002#32=22.13(PITCH
DISTANCE)
#33=11.065
#15=#33(START X POSIT)
/GO154 (BRANCH TO
SLOT)
N1X#15Y13.432
#10=15.294
M98P42
N2X#15Y9.009
#10=15.269
M98P42
N3X#15Y13.283
#10=15.224
M98P42
N4X#15Y9.243
#10=15.166
M98P42
N5X#15Y13.735
#10=15.454
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N6X#15Y8.949
#10=15.298
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N7X#15Y13.144
#10=15.165
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#10=15.051
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#10=14.925
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#10=15.299
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N24X#15Y31.443
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N26X#15Y32.337
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N28X#15Y32.807
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N32X#15Y54.023
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N33X#15Y58.520
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N35X#15Y57.921
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#10=15.157
M98P42
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N77X#15Y125.953
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#10=15.157
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N143X#15Y255.692
#10=15.102
M98P42
IF[#13EQ2]GO145(3-QTR)
N144#15=#33
X#15Y281.762
#10=15.139
M98P42
N145#15=[#33*3]
X#15Y278.028
#10=15.123
M98P42
N146X#15Y281.649
#10=15.095
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N147X#15Y278.195
#10=15.060
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N148X#15Y281.451
#10=15.024
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N149X#15Y278.392
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IF[#13EQ2]GO151(3-QTR)
N150#15=#33
X#15Y304.774
#10=15.437
M98P42
N151#15=[#33*3]
X#15Y299.786
#10=15.420
M98P42
N152X#15Y304.684
#10=15.387
M98P42
```

```
IF[#13EQ1]GO9999(1-QTR)
N153X8.640Y290.920
(GUARD SLOT)
#10=17.154
#20=2.0(SLOT WIDTH)
M98P42
N154X8.640Y310.420
#10=17.154
#20=2.0
M98P42
GO9999
N210G00G54X-5Y-
350S5000
M03
G43H12Z2
G01Z-1.4F300
G01G42D12Y-325
X0
G03X0Y-325I0J325
G01X5
G40Y-330
Z2
GO9999
N220(3MM HOLE)
S1000M03
X-139.398Y279.875
X76.599Y-302.265
X-297.09Y-78.365
X297.090Y78.365
GO220
N230(8MM HOLE)
S1000M03
X-262.495Y67.170
X262.495
X22Y156.73
X-22
GO230
N240(TRIAL SLOT)
M03
X200Y-305
G43H#28Z2
#10=10
M98P42
GO9999
N250(CLAMP HOLES)
S1000M03
X-250Y-250
```

```
X250
Y250
X-250
GO9999
N260M03
#4=200(FEED)
#10=20(BORE)
#11=1.5(CUTTER DIA)
#1=[#10-#11](MINUS CUTTER DIA)
#2=[[#1]/[2]]
#3=[[#1]/[4]]
#5=200
N262G90G00X-#5Y-270
G43H11Z2
G01Z-1.5F[#4/4]
G01G91X-#3F[#4/2]
G02X[#2+#3]Y0R#1
G02X0Y0I-#2J0
G02X0Y0I-#2J0F#4
G02X-[#2+#3]Y0R#1
G01X#3
G00G90Z50
#5=[[#5]*[-1]]
IF[#5EQ-200]GO262
GO9999
N270S5000
M03
#4=200(FEED)
#10=10.2(BORE)
#11=2(CUTTER DIA)
#1=[#10-#11](MINUS CUTTER DIA)
#2=[[#1]/[2]]
#3=[[#1]/[4]]
#21=-250(X-POSIT)
#22=-250(Y-POSIT)
#23=1(COUN)
N272IF[#23EQ2]THEN#21=250
IF[#23EQ3]THEN#22=250
IF[#23EQ4]THEN#21=-250
G90G00X#21Y#22
G43H12Z2
G01Z-1.2F[#4/4]
G01G91X-#3F[#4/2]
G02X[#2+#3]Y0R#1
G02X0Y0I-#2J0
/G02X0Y0I-#2J0F#4
G02X-[#2+#3]Y0R#1
G01X#3
G00G90Z30
#23=[#23+1]
IF[#23LE4]GO272
GO9999
N9999G00G90Z200
M30
%
```

SUB-PROGRAM

```
%
O0042 (SUBPGM-RP)
(FOR SLOT MACHINING)
IF[#27EQ0]GO9997
IF[#27EQ1]GO9998
N9997(CENTER-DRILLING)
Z2
G81Z-#1R2F#4
G00G80
GO9999
N9998(SLOT MILLING)
Z0.2
#24=[#10-#20]
/G01Z-#1F25
G01G91Z-0.2F[#4/4]
X-[#24/2]Z-#1
/X[#24/2]F[#4/2]
/X[#24/2]F[#4/4]
X#24
X-[#24/2]F#4
/GO9999
#21=1
G91G42D#28X[[#10-#20]/2]Y[#20/2]F[#4/2]
N142G02X0Y-#20R[#20/2]
G01X-[#10-#20]
G02X0Y#20R[#20/2]
G01X[#10-#20]
#21=[#21+1]
F#4
IF[#21LE2]GOTO142
G02X0Y-#20R[#20/2]
G01G40X-[[#10-#20]/2]Y[#20/2]
N9999G90Z2(RETURN TO MAIN PROGRAM)
#15=[[#15]+[#32]]
G00G90
M99
%
```

APERTURE PLATE SAMPLE PART PROGRAMS

```
%
O0020(LCA-AP-EXTRA-AA1)
#1=5.08(DEPTH)
#2=20(TOOL NUMBER)
#3=1400(FEED)
(10.4 MM END MILL-ROUGH-3 FLUTE)
G00G90G54X0Y0A0B0
G68R#500
(IRREGULAR POCKET MILLING)
G00G43H#2Z10
/GO45
X19.83Y-11.27
Z3
Z0
G01X22.374Y57.69Z-#1F600
X-22.374F#3
Y49.37
X22.374
Y41.05
X18.461
G00
Z3
X-22.374Y24.41
Z0
G01Y32.73Z-#1F600
X22.374F#3
Y24.41
X-22.374
Y16.09
X22.374
Y7.77
X-22.374
Y-0.55
X22.374
Y-8.87
X-22.374
Y-17.19
X22.374
Y-25.51
X-22.374
Y-33.83
X22.374
Y-42.15
X18.461
G00
Z3
X-22.374Y-58.79
Z0
G01Y-50.47Z-#1F600
X22.374F#3
Y-58.79
X-22.374
G00
Z3
X5.061Y41.05
Z0
G01Z-#1F600
X-5.061F#3
G00
Z3
X-18.461
Z0
G01Z-#1F600
X-22.374F#3
G00
Z3
X5.061Y-42.15
Z0
G01Z-#1F600
X-5.061F#3
G00
Z3
X-22.374
Z0
G01X-18.461Z-#1F600
X-22.374F#3
G00
Z3
X13.261Y35.442
Z0
G01X10.261Z-#1F600
X13.261F#3
G03X18.461Y40.642I0J5.2
G01Y43.642
G03X13.261Y48.842I-5.2J0
G01X10.261
G03X5.061Y43.642I0J-5.2
G01Y40.642
G03X10.261Y35.442I5.2J0
G01X-5.061Y40.642
Y43.642
G03X-10.261Y48.842I-5.2J0
G01X-13.261
G03X-18.461Y43.642I0J-5.2
G01Y40.642
G03X-13.261Y35.442I5.2J0
G01X-10.261
G03X-5.061Y40.642I0J5.2
G01Z3
G00X13.261Y-35.442
Z0
G01Z-#1F600
X10.261F#3
G03X5.061Y-40.642I0J-5.2
G01Y-43.642
G03X10.261Y-48.842I5.2J0
G01X13.261
G03X18.461Y-43.642I0J5.2
G01Y-40.642
G03X13.261Y-35.442I-5.2J0
G00
Z3
X-13.261
Z0
G01X-10.261Z-#1F600
X-13.261F#3
G03X-18.461Y-40.642I0J-5.2
```

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G01Y-43.642
G03X-13.261Y-48.842I5.2J0
G01X-10.261
G03X-5.061Y-43.642I0J5.2
G01Y-40.642
G03X-10.261Y-35.442I-5.2J0
G00
Z3
X-22.374Y66.01
Z0
G01Z-#1F600
X22.374F#3
Y-66.01
X-22.374
Y66.01
G00
Z10

(IRREGULAR POCKET MILLING)
N45G00X-19.665Y-86.124
Z3
X22.988Y-94.25
Z0
G01Y-85.93Z-#1F600
X-22.989F#3
Y-94.25
X22.989
G00
N50Z3
X-22.988Y-77.61
Z0
G01Y-101.51Z-#1F600
X-22.988F#3
/Y-77.61
Y-79
X22.988
Y-101.51
X-22.988
G00
Z10
(IRREGULAR POCKET MILLING)
G00X-13.437Y92.764
Z3
Z0
G01X22.988Y93.19Z-#1F600
X-22.989F#3
Y84.87
X22.989
G00
Z3
Y101.51
Z0
G01Y77.61Z-#1F600
X-22.988F#3
Y100
X22.988
Y77.61
G00
Z10
(IRREGULAR POCKET MILLING)
G90G00G54X-3.201Y317.319
Z3
Z0
G01X27.601Y316.48Z-#1F600
X-27.601F#3
G02X-27.409Y315.56I-4.973J-1.52
G01X-23
G02X-13.577Y308.16I0J-9.7
G01X13.577
G03X15.394Y299.84I9.423J-2.3
G01X-15.394
G02X-22.989Y296.16I-7.606J6.02
G01Y291.52
X22.989
Y283.2
X-22.989
Y282.56
G02X-13.513Y274.88I-0.011J-9.7
G01X13.513
G03X15.624Y266.56I9.487J-2.02
G01X-15.624
G02X-22.989Y263.16I-7.376J6.3
G01Y258.24
X22.989
Y249.92
X-22.989
Y241.6
X-21.81
G03X-22.989Y241.176I1.157J-5.08
G01Y263.16
G03Y282.56I-0.011J9.7
G01Y296.16
G03X-23Y315.56I-0.011J9.7
G01X-27.409
G03X-32.574Y320.16I-5.165J-0.6
G01X-54.705
G02X54.705I54.705J-320.16
G01X32.574
G03X27.409Y315.56I0J-5.2
G01X23
G03X22.989Y296.16I0J-9.7
G01Y282.56
G03Y263.16I0.011J-9.7
G01Y241.176
G03X20.653Y241.73I-2.336J-4.646
G01X19.453
G03X14.253Y236.53I0J-5.2
G01Y233.28
X-14.253
Y224.96
X14.253
Y216.64
X-14.253
Y211.27
G02X-15.171Y208.32I-5.2J0
G01X15.171
G03X19.453Y206.07I4.282J2.95
G01X20.653
```

```
G03X22.989Y206.624I0J5.2
G01Y200
X-22.989
Y191.68
X22.989
Y183.36
X-22.989
Y175.04
X22.989
Y166.72
X-22.989
Y158.4
X22.989
Y150.08
X9.805
G02X11.2Y144.667I-9.805J-5.413
X11.198Y144.478I-11.2J0
G01X13.261
G02X17.83Y141.76I0J-5.2
G01X22.989
Y133.44
X17.619
Y125.12
X-22.989
X22.989
Y116.8
X-22.989
G00
Z3
X18.296Y241.6
Z0
G01X22.989Z-#1F600
X-18.296F#3
G00
Z3
X-22.989Y150.08
Z0
G01X-9.805Z-#1F600
X-22.989F#3
Y141.76
X-17.83
G00
N60Z3
X0Y130
Z0
G01X5.904Z-#1F600
X0F#3
X-5.904
X-17.619
G00
N70Z3
X11.198Y144.478
Z0
G01X13.261Z-#1F600
X11.198F#3
G03X11.2Y144.667I-11.198J0.189
X0Y155.867I-11.2J0
X-11.2Y144.667I0J-11.2
X-11.198Y144.478I11.2J0
G01X-13.261
G03X-18.461Y139.278I0J-5.2
G01Y136.278
G03X-13.261Y131.078I5.2J0
G01X-10.261
G03X-5.279Y134.789I0J5.2
X0Y133.467I5.279J9.878
X5.279Y134.789I0J11.2
X10.261Y131.078I4.982J1.489
G01X13.261
G03X18.461Y136.278I0J5.2
G01Y139.278
G03X13.261Y144.478I-5.2J0
G00
Z3
X-54.705Y320.16
Z0
G01Z-#1F600
G02X54.705I54.705J-320.16F#3
G01X32.574
G03X27.409Y315.56I0J-5.2
G01X23
G03X22.989Y296.16I0J-9.7
G01Y282.56
G03Y263.16I0.011J-9.7
G01Y241.176
G03X20.653Y241.73I-2.336J-4.646
G01X19.453
G03X14.253Y236.53I0J-5.2
G01Y211.27
G03X19.453Y206.07I5.2J0
G01X20.653
G03X22.989Y206.624I0J5.2
G01Y113.11
X-22.989
Y206.624
G03X-20.653Y206.07I2.336J4.646
G01X-19.453
G03X-14.253Y211.27I0J5.2
G01Y236.53
G03X-19.453Y241.73I-5.2J0
G01X-20.653
G03X-22.989Y241.176I0J-5.2
G01Y263.16
G03Y282.56I-0.011J9.7
G01Y296.16
G03X-23Y315.56I-0.011J9.7
G01X-27.409
G03X-32.574Y320.16I-5.165J-0.6
G01X-54.705
G00
Z10
(IRREGULAR POCKET MILLING)
G00X18.295Y-189.384
Z3
Z0
G01X22.989Y-121.43Z-#1F600
```

```
X-22.989F#3
Y-129.75
X22.989
Y-138.07
X18.461
Y-139.278
G02X13.261Y-144.478I-5.2J0
G01X11.198
G02X11.2Y-144.667I-11.198J-0.189
X11.067Y-146.39I-11.2J0
G01X22.989
Y-154.71
X4.957
Y-163.03
X-22.989
X22.989
Y-171.35
X-22.989
Y-179.67
X22.989
Y-187.99
X-22.989
Y-196.31
X22.989
Y-204.63
X-22.989
Y-206.624
G02X-20.653Y-206.07I2.336J-4.646
G01X-19.453
G02X-14.253Y-211.27I0J-5.2
G01Y-212.95
X14.253
Y-221.27
X-14.253
Y-229.59
X14.253
Y-236.53
G03X14.44Y-237.91I5.2J0
G01X-14.44
G02X-19.453Y-241.73I-5.014J1.38
G01X-20.653
G02X-22.989Y-241.176I0J5.2
G01Y-246.23
X22.989
Y-254.55
X-22.989
Y-262.87
X22.989
Y-271.19
X-22.989
G00
Z3
X-22.989Y-138.07
Z0
G01X-18.461Z-#1F600
X-22.989F#3
Y-146.39
X-11.067
G03X-4.957Y-154.71I11.067J1.723
G01X-22.989
G00
Z3
X-13.261Y-131.078
Z0
G01X-10.261Z-#1F600
X-13.261F#3
G03X-18.461Y-136.278I0J-5.2
G01Y-139.278
G03X-13.261Y-144.478I5.2J0
G01X-11.198
G03X-11.2Y-144.667I11.198J-0.189
X0Y-155.867I11.2J0
X11.2Y-144.667I0J11.2
X11.198Y-144.478I-11.2J0
G01X13.261
G03X18.461Y-139.278I0J5.2
G01Y-136.278
G03X13.261Y-131.078I-5.2J0
G01X10.261
G03X5.279Y-134.789I0J-5.2
X0Y-133.467I-5.279J-9.878
X-5.279Y-134.789I0J-11.2
X-10.261Y-131.078I-4.982J-1.489
G00
Z3
X-22.989Y-125
Z0
G01Y-113.11Z-#1F600
X22.989F#3
Y-206.624
G03X20.653Y-206.07I-2.336J-4.646
G01X19.453
G03X14.253Y-211.27I0J-5.2
G01Y-236.53
G03X19.453Y-241.73I5.2J0
G01X20.653
G03X22.989Y-241.176I0J5.2
G01Y-273.84
X-22.989
Y-241.176
G03X-20.653Y-241.73I2.336J4.646
G01X-19.453
G03X-14.253Y-236.53I0J5.2
G01Y-211.27
G03X-19.453Y-206.07I-5.2J0
G01X-20.653
G03X-22.989Y-206.624I0J-5.2
G01Y-113.11
G00
Z10
(IRREGULAR POCKET MILLING)
G00X-4.1Y-320.388
Z3
Z0
G01X-54.705Y-320.16Z-#1F600
X54.705F#3
```

```
G02X-54.705I-54.705J320.16
G00
Z10
G69
G00G90Z100
M30
%
------------
%
O0021(LCA-EXTRA-BB1)
#1=5.08(DEPTH)
#2=20(TOOL NUMBER)
#3=1400(FEED)
#10=1
(10.0MM END MILL-FINISH-3 FLUTE)
N5G00G90G54X0Y0A0B0
G68R#500
(IRREGULAR POCKET MILLING)
N10G90G00G54X-69.077Y263.846
G43H#2Z10
Z3
/GO20
Z0
G01X-66.146Y309.673Z-#1F600
X-97.967F#3
G03X-121.166Y301.353I97.967J-309.673
G01X-66.146
Y293.033
X-140.095
G03X-156.312Y284.713I140.095J-293.033
G01X-66.146
Y276.393
X-170.592
G03X-172.223Y275.38I170.592J-276.393
G01X-116.094
G02X-110.894Y270.18I0J-5.2
G01Y268.073
X-66.146
Y259.753
X-110.894
Y251.433
X-104.8
Y243.113
X-110.894
Y234.793
X-104.8
Y226.473
X-110.894
Y218.153
X-104.8
Y211.27
G03X-104.598Y209.833I5.2J0
G01X-110.894
Y201.513
X-66.146
Y193.193
X-110.894
Y184.873
X-66.146
Y176.553
X-110.894
Y168.233
X-66.146
Y159.913
X-110.894
Y152.17
X-109.173
X-107.973
G02X-105.593Y151.593I0J-5.2
G01X-71.448
G03X-74.267Y146.97I2.381J-4.623
G01Y143.273
X-102.773
Y134.953
X-74.267
Y126.633
X-102.773
Y119.04
X-93.09
G02X-90.438Y118.313I0J-5.2
G01X-73.004
G03X-69.067Y116.51I3.937J3.397
G01X-67.867
X-66.146
Y109.993
X-87.89
Y101.673
X-66.146
Y93.353
X-87.89
Y86
Y85.033
X-66.146
Y76.713
X-87.89
Y70.16
G02X-88.199Y68.393I-5.2J0
G01X-66.146
Y62.61
X-67.867
X-69.067
G03X-73.534Y60.073I0J-5.2
G01X-102.773
Y51.753
X-74.267
Y43.433
X-102.773
Y35.113
X-74.267
Y32.15
G03X-69.067Y26.95I5.2J0
G01X-67.867
X-66.146
Y26.793
X-110.894
Y18.473
X-66.146
Y10.153
X-107.366
```

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G02X-101.045Y1.833I-4.728J-10.153
G01X-66.146
Y-6.487
X-102.964
G02X-110.894Y-11.136I-9.13J6.487
G01Y-14.807
X-66.146
Y-23.127
X-110.894
Y-26.95
X-107.973
G02X-102.821Y-31.447I0J-5.2
G01X-74.219
G03X-74.267Y-32.15I5.152J-0.704
G01Y-39.767
X-102.773
Y-48.087
X-74.267
Y-56.407
X-102.773
Y-57.41
G02X-107.973Y-62.61I-5.2J0
G01X-110.894
Y-64.727
X-66.146
Y-73.047
X-87.89
Y-81.367
X-66.146
Y-89.687
X-87.89
Y-98.007
X-66.146
Y-106.327
X-87.89
Y-113.84
G02X-87.953Y-114.647I-5.2J0
G01X-66.146
Y-116.51
X-69.067
G03X-74.267Y-121.71I0J-5.2
G01Y-122.967
X-102.773
Y-131.287
X-74.267
Y-139.607
X-102.773
Y-146.97
G02X-102.862Y-147.927I-5.2J0
G01X-74.179
G03X-69.067Y-152.17I5.111J0.956
G01X-66.146
Y-156.247
X-110.894
Y-164.567
X-66.146
Y-172.887
X-110.894
Y-181.207
X-66.146
Y-189.527
X-110.894
Y-197.847
X-66.146
Y-206.167
X-73.344
G02X-69.14Y-211.27I-0.996J-5.104
G01Y-214.487
X-66.146
Y-222.807
X-69.14
Y-231.127
X-66.146
Y-239.447
X-69.14
Y-247.767
X-66.146
Y-256.087
X-69.827
Y-264.407
X-110.894
X-66.146
Y-272.727
X-111.56
G02X-116.094Y-275.38I-4.534J2.547
G01X-172.223
G03X-162.812Y-281.047I172.223J275.38
G01X-66.146
Y-289.367
X-147.519
G03X-129.914Y-297.687I147.519J289.367
G01X-66.146
Y-306.007
X-108.88
G03X-81.815Y-314.327I108.88J306.007
G01X-66.146
G00
Z3
X-69.14Y251.433
Z0
G01X-66.146Z-#1F600
X-69.14
Y243.113
X-66.146
Y234.793
X-69.14
Y226.473
X-66.146
Y218.153
X-69.14
Y211.27
G02X-69.343Y209.833I-5.2J0
G01X-66.146
G00
Z3
X-93.2Y251.433
Z0
G01X-80.74Z-#1F600
X-93.2F#3
Y243.113
X-80.74
Y234.793
X-93.2
Y226.473
X-80.74
Y218.153
X-93.2
Y211.27
```

```
G02X-93.403Y209.833I-5.2J0
G01X-80.538
G00
Z3
X-97.404Y-206.167
Z0
G01X-76.537Z-#1F600
X-97.404F#3
G02X-93.2Y-211.27I-0.996J-5.104
G01Y-214.487
X-80.74
Y-222.807
X-93.2
Y-231.127
X-80.74
Y-239.447
X-93.2
Y-247.767
X-80.74
Y-253.504
G03X-80.054Y-256.087I5.2J0
G01X-93.887
G00
Z3
X-110.894Y-206.167
Z0
G01X-100.597Z-#1F600
X-110.894F#3
Y-214.487
X-104.8
Y-222.807
X-110.894
Y-231.127
X-104.8
Y-239.447
X-110.894
Y-247.767
X-104.8
Y-253.504
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X-75.54F#3
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G01Y253.504
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Y-211.27F#3
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G01X-98.4
G03X-93.2Y-253.504I0J5.2
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Z3
X-69.14Y-211.27
Z0
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G01X-74.34
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Y152.17F#3
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X-69.067
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G01X-67.867
X-66.146
Y62.61
X-67.867
X-69.067
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G03X-69.067Y26.95I5.2J0
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G01Y-57.41
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G91X5
X-5
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G01Y-119.04
X-93.09
G03X-87.89Y-113.84I0J5.2
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Y-70.16
G03X-93.09Y-64.96I-5.2J0
G01X-110.894
Y-62.61
X-107.973
G03X-102.773Y-57.41I0J5.2
G01Y-32.15
G03X-107.973Y-26.95I-5.2J0
G01X-110.894
Y-11.136
G03Y11.136I-1.2J11.136
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X-102.773Y32.15I0J5.2
G01Y64.96
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X-110.894(C)

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G01X-102.773
Y146.97
G03X-107.973Y152.17I-5.2J0
G01X-109.173
X-110.894
Y270.18
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X-5
G90G00
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X0Y0
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IF[#10EQ3]GO100
G51.1X0
GO10
N100G69
N1000G00G90Z100
G50.1X0
M30
%
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%
O0023(LCA-AP-EXTRA-CC1)
#1=5.08(DEPTH)
#2=20(TOOL NUMBER)
#3=1400(FEED)
(10.0MM END MILL-FINISH-3 FLUTE)
G00G90G54X0Y0A0
B0
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G68R#500

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X-169.13F#3
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Y260.651
X-193.794
G03X-204.51Y252.331I193.794J-260.651
G01X-154.666
Y244.011
X-214.368
G03X-223.484Y235.691I214.368J-244.011
G01X-162.787
Y227.371
X-231.943
G03X-239.816Y219.051I231.943J-227.371
G01X-162.787
Y211.27
G03
X-162.759Y210.731I5.2
J0
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G03X-254.018Y202.411I247.159J-210.731
G01X-154.666
Y194.091
X-260.43
G03X-266.394Y185.82I260.43J-194.091
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G01X-204.614

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Y169.131
X-190.917
Y160.811
X-199.414
Y152.491
X-190.917
Y144.171
X-199.414
Y135.851
X-190.917
Y127.531
X-199.414
Y119.211
X-190.277
Y110.891
X-154.666
X-199.414
Y102.571
X-154.666
Y94.251
X-179.535
Y85.931
X-154.666
Y77.611
X-156.527
G02X-155.475Y74.475I-4.148J-3.136
G01Y69.291
X-154.666
Y60.971
X-155.475
Y52.651
X-154.666
Y44.331
X-155.475
Y36.011
X-154.666
Y27.691
X-158
Y19.371
X-199.414
X-154.666
Y11.051
X-199.414
Y2.731
X-154.666
Y-5.589
X-199.414
Y-13.909
X-154.666
Y-22.229
X-199.414
Y-30.549
X-190.882
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G01Y-38.869
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Y-47.189
X-191.135
Y-55.509
X-199.414
Y-63.829
X-191.135
Y-72.149
X-199.414
Y-80.469
X-191.135
Y-88.789
X-199.414
Y-91.705
X-195.5
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G02X-179.535Y-32.15I0J-5.2
G01Y-95.021
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X-200.931
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G01X-154.666
Y-271.829
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G01Y177.451
X-154.666
Y169.131
X-159.422
G02X-155.257Y164.035I-1.035J-5.096
G01Y160.811
X-154.666
Y152.491
X-155.257
Y144.171
X-154.666
Y135.851
X-155.257
Y127.531
X-154.666
Y119.211
X-155.898
G00
Z3
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Z0
G01X-162.693Z-#1F600
X-179.317F#3
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X-166.857
Y152.491
X-179.317
Y144.171
X-166.857
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X-179.317
Y127.531
X-166.857
Y121.71
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G00
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X-199.414F#3
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Y77.611
X-199.414
Y69.291
X-191.135
Y60.971
X-199.414
Y52.651
X-191.135
Y44.331
X-199.414
Y36.011
X-191.135
Y32.15
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G01X-199.414
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Z0
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X-179.535F#3
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X-167.075
Y60.971
X-179.535
Y52.651
X-167.075
Y44.331
X-179.535
Y36.011
X-167.075
Y32.15
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G00
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G01X-154.666Z-#1F600
X-155.727F#3
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Y-47.189
X-155.475
Y-55.509
X-154.666
Y-63.829
X-155.475
Y-72.149
X-154.666
Y-80.469
X-179.535
Y-88.789
X-154.666
G00
Z3
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Z0
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X-179.787F#3
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G01Y-38.869
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X-179.535
Y-55.509
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Y-63.829
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Y-72.149
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X-179.317
Y-130.389
X-166.857
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X-166.857
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X-166.857
G00
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G00
Z3
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Z0
G01X-190.917Z-#1F600
X-199.414F#3
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X-199.414
Y-147.029
X-190.917
Y-155.349
X-199.414
Y-163.669
X-190.917
G00
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Z0
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G03X-160.457Y169.235I-5.2J0
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G01Y160.811
X154.666
Y152.491
X155.257
Y144.171
X154.666
Y135.851
X155.257
Y127.531
X154.666
Y119.211
X155.898
Y110.891
X199.414
X154.666
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Y94.251
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Y144.171
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X190.917
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Z0
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Y69.291
X155.475
Y60.971
X154.666
Y52.651
X155.475
Y44.331
X154.666
Y36.011
X155.475
Y32.15
G03X158Y27.691I5.2J0
G01X154.666
G00
Z3
X190.882Y-30.549
Z0
G01X199.414Z-#1F600
X190.882F#3
G02X191.135Y-32.15I-4.947J-1.601
G01Y-38.869
X199.414
Y-47.189
X191.135
Y-55.509
X199.414
Y-63.829
X191.135
Y-72.149
X199.414
Y-80.469
X191.135
Y-88.789
X199.414
Y-97.109
X190.697
G00
Z3
X166.822Y-30.549
Z0
G01X179.787Z-#1F600
X166.822F#3
G02X167.075Y-32.15I-4.947J-1.601
G01Y-38.869
X179.535
Y-47.189
X167.075
Y-55.509
X179.535
Y-63.829
X167.075
Y-72.149
X179.535
G00
Z3
X166.857Y-122.069
Z0
G01X179.317Z-#1F600
X166.857F#3
Y-130.389
X179.317
Y-138.709
X166.857
Y-147.029
X179.317
Y-155.349
X166.857
Y-163.669
X179.317
Y-171.989
X154.666
G00
Z3
X154.666Y-122.069
Z0
G01X155.257Z-#1F600
X154.666F#3
Y-130.389
X155.257
Y-138.709
X154.666
Y-147.029
X155.257
Y-155.349
X154.666
Y-163.669
X155.257
G00
Z3
X220Y-188.629
Z0
G01X264.413Z-#1F600
X188.981F#3
G00
Z3
X161.657Y116.51
Z0
G01X160.457Z-#1F600
X161.657F#3
G03X166.857Y121.71I0J5.2
G01Y164.035
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G03X161.657Y169.235I-5.2J0
G01X160.457
G03X155.257Y164.035I0J-5.2
G01Y121.71
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G01X184.517
X185.717
G03X190.917Y121.71I0J5.2
G01Y184.581
G03X185.717Y189.781I-5.2J0
G01X184.517
G03X179.317Y184.581I0J-5.2
G01Y121.71
G03X184.517Y116.51I5.2J0
G01X161.875Y79.675
X160.675
G03X155.475Y74.475I0J-5.2
G01Y32.15
G03X160.675Y26.95I5.2J0
G01X161.875
G03X167.075Y32.15I0J5.2
G01Y74.475
G03X161.875Y79.675I-5.2J0
G00
N80Z3
X191.135Y95
Z0
G01X191.135Z-#1F600
Y95.021F#3
G03X185.935Y100.221I-5.2J0
G01X184.735
G03X179.535Y95.021I0J-5.2
G01Y32.15
G03X184.735Y26.95I5.2J0
G01X185.935
G03X191.135Y32.15I0J5.2
G01Z2
G00X167.075Y-74.475
Z0
G01Z-#1F20
Y-32.15F#3
G03X161.875Y-26.95I-5.2J0
G01X160.675
G03X155.475Y-32.15I0J-5.2
G01Y-74.475
G03X160.675Y-79.675I5.2J0
G01X161.875
G03X167.075Y-74.475I0J5.2
G00
N90Z3
X191.135Y-32.15
Z0
G01Y-95.021Z-#1F600
Y-32.15F#3
G03X185.935Y-26.95I-5.2J0
G01X184.735
G03X179.535Y-32.15I0J-5.2
G01Y-95.021
G03X184.735Y-100.221I5.2J0
G01X185.935
G03X191.135Y-95.021I0J5.2
G00
Z3
X166.857Y-140
Z0
G01Y-164.035Z-#1F600
Y-121.71F#3
G03X161.657Y-116.51I-5.2J0
G01X160.457
G03X155.257Y-121.71I0J-5.2
G01Y-164.035
G03X160.457Y-169.235I5.2J0
G01X161.657
G03X166.857Y-164.035I0J5.2
G00
Z3
X179.317Y-150
Z0
G01Y-121.71Z-#1F600
Y-184.581F#3
G03X184.517Y-189.781I5.2J0
G01X185.717
G03X190.917Y-184.581I0J5.2
G01Y-121.71
G03X185.717Y-116.51I-5.2J0
G01X184.517
G03X179.317Y-121.71I0J-5.2
G00
N100Z3
X154.666Y285.611
Z0
G01Z-#1F20
G02X266.394Y185.82I-154.666J-285.611F#3
G01X204.614
G03X199.414Y180.62I0J-5.2
G01Y-180.62
G03X204.614Y-185.82I5.2J0
G01X266.394
G02X154.666Y-285.611I-266.394J185.82
G01Y-241.73
X157.587
G03X162.787Y-236.53I0J5.2
G01Y-211.27
G03X157.587Y-206.07I-5.2J0
G01X154.666
Y-180
G91X20
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X-20
G90Y206.07
X157.587
G03X162.787Y211.27I0J5.2
G01Y236.53
G03X157.587Y241.73I-5.2J0
G01X154.666
Y285.611
G00
Z10
G69
G00G90Z100
M30
%
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%
O0022(LCA-AP-EXTRA-DD1)
#1=5.08(DEPTH)
#2=20(TOOL NUMBER)
#3=1400(FEED)
(10.0OMM END MILL-FINISH-3 FLUTE)
G00G90G54X0Y0A0B0
G68R#500
(IRREGULAR POCKET MILLING)
G90G00G54X-260.132Y161.408
G43H#2Z10
Z3
Z0
G01X-243.186Y206.984Z-#1F600
X-250.306F#3
G03X-256.959Y198.664I250.306J-206.984
G01X-243.186
Y190.344
X-263.181
G03X-269.003Y182.024I263.181J-190.344
G01X-243.186
Y173.704
X-274.449
G03X-279.541Y165.384I274.449J-173.704
G01X-243.186
Y157.064
X-284.299
G03X-288.739Y148.744I284.299J-157.064
G01X-250.996
G03X-251.307Y146.97I4.888J-1.773
G01Y140.424
X-292.876
G03X-296.722Y132.104I292.876J-140.424
G01X-251.307
Y123.784
X-300.288
G03X-303.584Y115.464I300.288J-123.784
G01X-243.186
Y107.144
X-273.532
G02X-268.83Y98.824I-6.468J-9.144
G01X-243.186
Y90.504
X-271.679
Y82.184
X-314.231
X-243.186
Y73.864
X-316.29
G03X-318.118Y65.544I316.29J-73.864
G01X-243.186
Y62.61
X-246.107
G03X-251.307Y57.41I0J-5.2
G01Y57.224
X-278.396
G02X-274.8Y49I-7.604J-8.224
Y48.904I-11.2J0
G01X-251.307
Y40.584
X-278.611
Y32.264
X-323.194
X-251.307
Y32.15
G03X-248.78Y27.69I5.2J0
G01Y23.944
X-289.194
G02X-288.8Y21I-10.806J-2.944
X-290.175Y15.624I-11.2J0
G01X-243.186
Y7.304
X-293.509
G02X-290.8Y0I-8.491J-7.304
X-290.846Y-1.016I-11.2J0
G01X-279.855
G03X-283.2Y-9I7.855J-7.984
X-283.195Y-9.336I11.2J0
G01X-295.813
Y-17.656
X-324.32
X-279.107
Y-25.976
X-243.186
X-323.76
G03X-322.984Y-34.296I323.76J25.976
G01X-251.307
Y-42.616
X-321.992
G03X-320.781Y-50.936I321.992J42.616
G01X-251.307
Y-57.41
G03X-250.969Y-59.256I5.2J0
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G01X-319.349
G03X-317.692Y-67.576I319.349J59.256
G01X-243.186
Y-73.8
X-245.986
G03X-250.158Y-75.896I0J-5.2
G01X-303.533
G02X-294.151Y-84.216I-1.467J-11.104
G01X-277.591
G03X-279.2Y-90I9.591J-5.784
X-278.909Y-92.536I11.2J0
G01X-295.264
G02X-305Y-98.2I-9.736J5.536
X-309.965Y-97.039I0J11.2
G03X-308.744Y-100.856I309.965J97.039
G01X-270.753
Y-109.176
X-249.084
X-305.901
G03X-302.803Y-117.496I305.901J109.176
G01X-249.154
G03X-251.307Y-121.71I3.047J-4.214
G01Y-125.816
X-299.442
G03X-295.808Y-134.136I299.442J125.816
G01X-251.307
Y-142.456
X-291.892
G03X-287.683Y-150.776I291.892J142.456
G01X-249.65
G03X-246.107Y-152.17I3.543J3.806
G01X-243.186
Y-159.096
X-283.167
G03X-278.329Y-167.416I283.167J159.096
G01X-243.186
Y-175.736
X-273.151
G03X-267.616Y-184.056I273.151J175.736
G01X-243.186
Y-192.376
X-261.699
G03X-255.374Y-200.696I261.699J192.376
G01X-243.186
Y-209.016
X-248.61
G00
Z3
X-306.619Y107.144
Z0
G01X-286.468Z-#1F600
X-306.619F#3
G03X-309.401Y98.824I306.619J-107.144
G01X-291.17
G03X-291.2Y98I11.17J-0.824
X-288.321Y90.504I11.2J0
G01X-311.936
G00
Z3
X-319.719Y57.224
Z0
G01X-293.604Z-#1F600
X-319.719F#3
G03X-321.097Y48.904I319.719J-57.224
G01X-297.2
G03X-293.389Y40.584I11.2J0.096
G01X-322.255
G00
Z3
X-323.916Y23.944
Z0
G01X-310.806Z-#1F600
X-323.916F#3
G03X-324.424Y15.624I323.916J-23.944
G01X-309.825
G03X-304.75Y10.857I9.825J5.376
X-310.491Y7.304I2.75J-10.857
G01X-324.718
G03X-324.798Y-1.016I324.718J-7.304
G01X-313.154
G03X-308.186Y-9.336I11.154J1.016
G01X-324.666
G00
Z3
X-243.186Y-17.656
Z0
G01X-264.893Z-#1F600
X-243.186F#3
Y-1.016
X-264.145
G02X-260.8Y-9I-7.855J-7.984
X-260.805Y-9.336I-11.2J0
G01X-243.186
G00
Z3
X-315.808Y-75.896
Z0
G01X-306.467Z-#1F600
X-315.808F#3
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G00
Z3
X-251.186Y-84.216
Z0
G01X-258.409Z-#1F600
X-251.186F#3
Y-92.536
X-257.091
G02X-265.247Y-100.856I-10.909J2.536
G01X-251.186
G00
Z3
GO100
X-268.8Y98
Z0
G01Z-#1F600
G03X-280Y109.2I-11.2J0F#3
X-291.2Y98I0J-11.2
X-280Y86.8I11.2J0
X-268.8Y98I0J11.2
G01X-274.8Y49
G03X-286Y60.2I-11.2J0
X-297.2Y49I0J-11.2
X-286Y37.8I11.2J0
X-274.8Y49I0J11.2
G01X-260.8Y-9
G03X-272Y2.2I-11.2J0
X-283.2Y-9I0J-11.2
X-272Y-20.2I11.2J0
X-260.8Y-9I0J11.2
G01X-256.8Y-90
G03X-268Y-78.8I-11.2J0
X-279.2Y-90I0J-11.2
X-268Y-101.2I11.2J0
X-256.8Y-90I0J11.2
G01X-288.8Y21
G03X-300Y32.2I-11.2J0
X-311.2Y21I0J-11.2
X-304.75Y10.857I11.2J0
X-313.2Y0I2.75J-10.857
X-302Y-11.2I11.2J0
X-290.8Y0I0J11.2
X-297.25Y10.143I-11.2J0
X-288.8Y21I-2.75J10.857
G00
N100Z3
X-243.186Y180
Z0
G01Y215.304Z-#1F600
Y152.17F#3
X-246.107
G03X-251.307Y146.97I0J-5.2
G01Y121.71
G03X-246.107Y116.51I5.2J0
G01X-243.186
Y62.61
X-246.107
G03X-251.307Y57.41I0J-5.2
G01Y32.15
G03X-248.78Y27.69I5.2J0
G01Y21
G03X-243.58Y15.8I5.2J0
G01X-243.186
Y-26.95
X-246.107
G03X-251.307Y-32.15I0J-5.2
G01Y-57.41
G03X-246.107Y-62.61I5.2J0
G01X-243.186
Y-73.8
X-245.986
G03X-251.186Y-79I0J-5.2
G01Y-105
G03X-245.986Y-110.2I5.2J0
G01X-243.186
Y-116.51
X-246.107
G03X-251.307Y-121.71I0J-5.2
G01Y-146.97
G03X-246.107Y-152.17I5.2J0
G01X-243.186
Y-215.304
G02X-309.965Y-97.039I243.186J215.304
G03X-305Y-98.2I4.965J10.039
X-293.8Y-87I0J11.2
X-305Y-75.8I-11.2J0
X-314.514Y-81.091I0J-11.2
G02X-243.186Y215.304I314.514J81.091
G00
Z10
(IRREGULAR POCKET MILLING)
N10G00X264.683Y150.603
Z3
Z0
G01X250.306Y206.984Z-#1F600
X243.186F#3
Y198.664
X256.959
G02X263.181Y190.344I-256.959J-198.664
G01X243.186
Y182.024
X269.003
G02X274.449Y173.704I-269.003J-182.024
G01X243.186
Y165.384
X279.541
G02X284.299Y157.064I-279.541J-165.384
G01X243.186
Y152.17
X246.107
G02X250.996Y148.744I0J-5.2
G01X288.739
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G02X292.876Y140.424I-288.739J-148.744
G01X251.307
Y132.104
X296.722
G02X300.288Y123.784I-296.722J-132.104
G01X251.307
Y121.71
G02X246.107Y116.51I-5.2J0
G01X243.186
Y115.464
X303.584
G02X306.619Y107.144I-303.584J-115.464
G01X243.186
Y98.824
X309.401
G02X311.936Y90.504I-309.401J-98.824
G01X243.186
Y82.184
X314.231
G02X316.29Y73.864I-314.231J-82.184
G01X243.186
Y65.544
X318.118
G02X319.719Y57.224I-318.118J-65.544
G01X251.307
Y48.904
X321.097
G02X322.255Y40.584I-321.097J-48.904
G01X251.307
Y32.264
X323.194
G02X323.916Y23.944I-323.194J-32.264
G01X243.186
Y15.624
X324.424
G02X324.718Y7.304I-324.424J-15.624
G01X244.308
G02X248.717Y-1.016I-3.728J-7.304
G01X324.798
G02X324.666Y-9.336I-324.798J1.016
G01X243.186
Y-17.656
X324.32
G02X323.76Y-25.976I-324.32J17.656
G01X243.186
Y-26.95
X246.107
G02X251.307Y-32.15I0J-5.2
G01Y-34.296
X322.984
G02X321.992Y-42.616I-322.984J34.296
G01X251.307
Y-50.936
X320.781
G02X319.349Y-59.256I-320.781J50.936
G01X250.969
G02X246.107Y-62.61I-4.861J1.846
G01X243.186
Y-67.576
X317.692
G02X315.808Y-75.896I-317.692J67.576
G01X243.186
Y-84.216
X313.692
G02X311.339Y-92.536I-313.692J84.216
G01X243.186
Y-100.856
X308.744
G02X305.901Y-109.176I-308.744J100.856
G01X243.186
Y-116.51
X246.107
G02X249.154Y-117.496I0J-5.2
G01X302.803
G02X299.442Y-125.816I-302.803J117.496
G01X251.307
Y-134.136
X295.808
G02X291.892Y-142.456I-295.808J134.136
G01X251.307
Y-146.97
G02X249.65Y-150.776I-5.2J0
G01X287.683
G02X283.167Y-159.096I-287.683J150.776
G01X243.186
Y-167.416
X278.329
G02X273.151Y-175.736I-278.329J167.416
G01X243.186
Y-184.056
X267.616
G02X261.699Y-192.376I-267.616J184.056
G01X243.186
Y-200.696
X255.374
G02X248.61Y-209.016I-255.374J200.696
G01X243.186
G00
Z3
Y215.304
Z0
G01Z-#1F600
G02Y-215.304I-243.186J-215.304F#3
G01Y-152.17
X246.107
G03X251.307Y-146.97I0J5.2
G01Y-121.71
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G03X246.107Y-116.51I-5.2J0
G01X243.186
Y-62.61
X246.107
G03X251.307Y-57.41I0J5.2
G01Y-32.15
G03X246.107Y-26.95I-5.2J0
G01X243.186
Y-7.775
G03Y7.775I-2.606J7.775
G01Y26.95
X246.107
G03X251.307Y32.15I0J5.2
G01Y57.41
G03X246.107Y62.61I-5.2J0
G01X243.186
Y116.51
X246.107
G03X251.307Y121.71I0J5.2
G01Y146.97
G03X246.107Y152.17I-5.2J0
G01X243.186
Y215.304
G00
Z10
G69
G00G90Z100
M30
%
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POWER DIVIDER SAMPLE PART

PROGRAM

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O0030(21-12-2004-RAM NEW DIVIDER)
(SINGLE CAVITY SIDE-IST SETTING)
#1=5.08(DEPTH 3MM 4.8AND 5.08MM)
#2=18(TOOL NUMBER DIA 8SSC)
#3=0(FEED 1400&1000F0R FINAL)
IF[#1LT5]THEN#3=1400(FEED)
IF[#1GT5]THEN#3=600(FEED)
#13=[#3/3]
N100#10=56(JOB CENTRE)
#11=1(COUNTER)
(HSS-15000 RPM)
G90G55X0Y0(G55 FIXTURE CENTRE)
G43H#2Z30
N9999IF[#11EQ2]THEN#10=57
IF[#11EQ3]THEN#10=58
IF[#11EQ4]THEN#10=59
G90G#10X0Y0
G68R#500
IF[#11EQ1]GOTO1
IF[#11EQ2]GOTO1
G51.1X0
N1G90X-107.446Y-100.345
Z2.0
G01Z0.0F#3
G01G61Y-90.105Z-#1F#13
G01Y-100.345
G00Z2.0
G00X-107.446Y-77.105
G01Z0.0
G01Y-67.645Z-#1F#13
G01Y-77.105
G00Z2.0
G00X-101.876Y-85.805
G01Z0.0
X-70.0Z-#1F#13
G01X-101.876F#3
X-57.465
G03X-41.035Y-69.375R16.43
G01Y-62.637
G03X-57.465Y-46.207R16.43
G01X-62.465
G02X-78.895Y-29.777R16.43
G01Y0.899
X-70.0Y-2.0
G00Z2.0
Z30.0
X-78.895Y13.899
Z2.0
G01Z0.0
Y44.0Z-#1F#13
G01Y13.899F#3
Y95.970
G02X-62.465Y112.400R16.43
G01X-52.465
G02X-36.035Y95.970R16.43
G01Y80.749
G00Z2.0
Z30.0
G00X-72.325Y1.399
Z2.0
G01Z0.0
X-30.0Z-#1F#13
G01X-72.325F#3
X-21.105
G00Z2.0
X-16.205Y7.399
G01Z0.0
Y40.0Z-#1F#13
Y7.399F#3
G00Z2.0
G00G90X-8.105Y1.399
G01Z0.0
X20.000Z-#1F#13
G01X-8.105F#3
X32.311
G02X48.741Y-15.031R16.43
G01Y-31.378
G03X65.171Y-47.808R16.43
G01X90.601
G00Z2.0
Z30.0
X96.601Y-39.208
Z2.0
G01Z0.0
Y-17.785Z-#1F#13
G01Y-39.208F#3
Y-17.785
G03X80.171Y-1.355R16.43
G01X75.931
G00Z2.0
Z30.0
X96.601Y-52.208
G00Z2.0
G01Z0.0
Y-74.555Z-#1F#13
G01Y-52.208F#3
Y-74.555
G02X80.171Y-90.985R16.43
G01X76.148
G00Z2.0
Z30.0(CENTER CUT COMPLETES)
N20(INSIDE CAVITY WITH 8 DIA TOOL)
G00X-16.205Y30.0
Z2.0
G01Z-#1F#13
G42G62D#2Y40.0F#3
X-4.775
Y13.829
```

```
X-6.275
Y12.829
X32.311
G02X60.171Y-15.031R27.86
G01Y-31.378
G03X65.171Y-36.378R5.0
G01X84.171
Y-37.878
X85.171
Y-17.785
G03X80.171Y-12.785R5.0
G01X69.931
Y10.075
X80.171
G02X108.031Y-17.785R27.860
G01Y-45.208
X96.601
Y-46.208
X108.031
Y-74.555
G02X80.171Y-102.415R27.86
G01X70.148
Y-79.555
X80.171
G03X85.171Y-74.555R5.0
G01Y-57.738
X84.171
Y-59.238
X65.171
G02X37.311Y-31.378R27.86
G01Y-15.031
G03X32.311Y-10.031R5.0
G01X-14.105
Y1.399
X-15.105
Y-10.031
X-67.465
Y-29.777
G03X-62.465Y-34.777R5.0
G01X-57.465
G02X-29.605Y-62.637R27.86
G01Y-69.375
G02X-57.465Y-97.235R27.86
G01X-95.016
Y-96.235
X-96.016
Y-106.345
X-118.876
Y-84.105
X-107.876
Y-83.105
X-118.876
Y-61.645
X-96.016
Y-75.375
X-95.016
Y-74.375
X-57.465
G03X-52.465Y-69.375R5.0
G01Y-62.637
G03X-57.465Y-57.637R5.0
G01X-62.465
G02X-90.325Y-29.777R27.86
G01Y6.899
X-78.325
Y7.899
X-90.325
Y95.970
G02X-62.465Y123.830R27.86
G01X-52.465
G02X-24.605Y95.970R27.86
G01Y74.749
X-47.465
Y95.970
G03X-52.465Y100.970R5.0
G01X-62.465
G03X-67.465Y95.970R5.0
G01Y12.829
X-26.135
Y13.829
X-27.635
Y40.0
X-16.205
Y35.0
G00
Z30.0
G40
IF[#1LT5.0]GO25
N21G90X-107.446Y-100.345
Z2.0
G01Z0.0F#3
G01G61Y-90.105Z-#1F#13
G01Y-100.345
G00Z2.0
G00X-107.446Y-77.105
G01Z0.0
G01Y-67.645Z-#1F#13
G01Y-77.105
G00Z2.0
G00X-101.876Y-85.805
G01Z0.0
X-70.0Z-#1F#3
G01X-101.876
X-57.465
G03X-41.035Y-69.375R16.43
G01Y-62.637
G03X-57.465Y-46.207R16.43
G01X-62.465
G02X-78.895Y-29.777R16.43
G01Y0.899
X-70.0Y-2.0
G00Z2.0
Z30.0
X-78.895Y13.899
Z2.0
G01Z0.0
Y44.0Z-#1
G01Y13.899
Y95.970
G02X-62.465Y112.400R16.43
G01X-52.465
G02X-36.035Y95.970R16.43
```

```
G01Y80.749
G00Z2.0
Z30.0
G00X-72.325Y1.399
Z2.0
G01Z0.0
X-30.0Z-#1
G01X-72.325
X-21.105
G00Z2.0
GO25
X-16.205Y7.399
G01Z0.0
Y40.0Z-#1
Y7.399
G00Z2.0
G00G90X-8.105Y1.399
G01Z0.0
X20.000Z-#1
G01X-8.105
X32.311
G02X48.741Y-15.031R16.43
G01Y-31.378
G03X65.171Y-47.808R16.43
G01X90.601
G00Z2.0
Z30.0
X96.601Y-39.208
Z2.0
G01Z0.0
Y-17.785Z-#1
G01Y-39.208
Y-17.785
G03X80.171Y-1.355R16.43
G01X75.931
G00Z2.0
Z30.0
X96.601Y-52.208
G00Z2.0
G01Z0.0
Y-74.555Z-#1
G01Y-52.208
Y-74.555
G02X80.171Y-90.985R16.43
G01X76.148
G00Z2.0
N25Z30.0(CENTER CUT COMPLETES)
X0Y0
G69
#11=[#11+1]
/#11=[#11+2]
IF[#11EQ2]GOTO9999
IF[#11EQ3]GOTO9999
G50.1X0
IF[#11EQ4]GOTO9999
G00G55X0Y-375
#1=[#1+2]
#3=1000
#13=[#3/3]
IF[#1EQ5.08]GO100
N1000Z100
M30
%
```

APPENDIX-III
PREPARATORY FUNCTIONS (G – FUNCTION)

G-CODE	FUNCTION
G00	Positioning
G01	Linear Interpolation
G02	Circular Interpolation/Helical Interpolation (Clockwise)
G03	Circular Interpolation/Helical Interpolation (Counter Clockwise)
G06.1	Spline Interpolation
G04	Dwell
G05.1	Multi buffer
G07	Hypothetical axis interpolation
G07.1	Cylindrical Interpolation
G09	Exact stop
G10	Data setting
G11	Data setting mode cancel
G15	Polar co-ordinates command cancel
G16	Polar co-ordinate command
G17	Xp-Yp Plane
G20	Inch input
G21	Metric input
G22	Stored stroke check function ON
G23	Stored stroke check OFF
G25	Spindle speed fluctuation detection OFF
G26	Spindle speed fluctuation ON
G27	Reference position return check
G28	Return to reference position
G29	Return from reference position
G30	Return to second, third or fourth position
G33	Threading
G37	Automatic tool length measurement
G38	Cutter compensation c vector retention
G39	Cutter compensation c rounding
G40	Cutter compensation cancel/3-d cutter compensation cancel
G41	Cutter compensation left/3-d cutter compensation
G42	Cutter compensation right
G43	Tool length compensating (+ve)
G43.1	Tool length compensation in tool axis direction
G44	Tool length compensation (-ve)
G45	Tool offset increase
G46	Tool offset decrease
G47	Tool offset double increase
G48	Tool offset double decrease
G49	Tool length compensation cancel
G50	Scaling cancel
G51	Scaling
G50.1	Programmable mirror image cancel
G51.1	Programmable mirror image
G52	Local ordinate system setting
G53	Machine co-ordinate system selection
G54	Work piece co-ordinate system
G55	Work piece co-ordinate system 2 selection

G56	Work piece co-ordinate system 3 selection
G57	Work piece co-ordinate system 4 selection
G58	Work piece co-ordinate system 5 selection
G59	Work piece co-ordinate system 6 selection
G60	Unidirectional positioning
G61	Exact stop mode
G62	Automatic corner override mode
G63	Tapping mode
G64	Cutting mode
G65	Macro call
G68	Co ordinate system rotation
G69	Co-ordinate system rotation cancel
G73	Peck drilling cycle
G74	Counter tapping cycle
G76	Fine boring cycle
G80	Canned cycle cancel/external operation function cancel
G81	Drill cycle,
G82	Drill cycle, counter boring
G83	Peck drilling cycle
G84	Tapping cycle
G87	Back boring
G88	Boring cycle
G89	Boring cycle
G90	Absolute command
G91	Incremental command
G92	maximum spindle speed setting
G93	Inverse time feed
G94	Feed per min
G95	Feed per rotation
G96	Constant surface speed control
G97	Constant surface speed control cancel
G98	Return to initial level in canned cycle

MISCELLANEOUS FUNCTIONS (M – FUNCTIONS)

M - CODE	FUNCTION
M00	Stop program
M02	End of program
M06	Tool change on spindle
M48	Reset M49
M20	Axis lubrication manual command
M21	Head lubrication manual command
M22	Vacuum table activation
M23	Vacuum table deactivation
M30	End of program and rewind the program
M03	Spindle clock wise rotation
M04	Spindle counter clock wise rotation
M05	Stop spindle rotation
M08	Start coolant
M09	Stop coolant
M19	Stop in spindle position