

Research report 58

**DFM/DFMA(A) – ANALYSIS AND ASPECTS OF APPLYING
SYSTEMATIC ENGINEERING FOR A MICROWAVE TEST-
FIXTURE DESIGN
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ABSTRACT

In this paper, manufacturability analysis and collection of design aspects is made for a microwave test-fixture. Aspects of applying systematic design for a microwave test-fixture design and manufacturing are also analysed. Special questionnaires for the component and machining are made in order to enable necessary information to ensure DFM(A) – aspects of the component. The aspects of easy manufacturing for machining the microwave test-fixture are collected. Material selection is discussed and manufacturing stages of prototype manufacturing are presented.

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1 INTRODUCTION

In this research manufacturability analysis will be made for a microwave test-fixture. Possibilities to utilize systematic engineering -method both for designing and making manufacturability analysis for microwave component will be discussed.

For helping to establish the necessary guidelines for manufacturing and assembly of the microwave component a specialized DFM(A)-questionnaire will be generated. The questionnaire gives also new information for collaborative designing approach in microwave engineering. Also the advantages and disadvantages of the selected design method are evaluated.

Practical guides and instructions for easy manufacturing are collected especially for a microwave test-fixture. In this report we will focus in researching components, which are made of different stainless steel alloys.

This research is part of the EU-project entitled "Collaboration for human resource development in mechanical and manufacturing engineering (Contract: ASIA-LINK – ASI/B7-301/98/679-023)". Within the same series of publications belong seven reports, which are focused to following design methods:

- systematic design
- reverse engineering
- concurrent engineering
- cross-technological approach
- collaborative design
- use of integrated product teams
- virtual prototyping

All these seven reports will be published at Lappeenranta University of Technology during the year 2004 in the series of scientific reports of the Department of Mechanical Engineering.

2 TASK

The task was to apply and analyse systematic engineering -method for the microwave test fixture design.

3 COMPONENT

Microwave test-fixtures are widely used for evaluation and prototyping of semiconductor devices and microwave assemblies because the measured components cannot be connected directly to measurement instrument. Because fixtures are used in characterization of microwave devices, high quality and flexibility are demanded setting strict requirements for test-fixture's electrical and mechanical characteristics.

Test-fixture includes connector interfaces, which should be compatible to measurement instrument to eliminate the need of additional adapters. Of course fixture should also include some mounting sections when the flexibility for different microwave assemblies and devices could be provided.

The test-fixture designed in this research will be used in network analyzer measurement, which has APC-7 connector interfaces. The APC-7 connector interface is compatible with SMA- or 3.5-connectors.

3.1 Function

To carry out precision microwave measurement, network analyzer has to be calibrated to remove effects due to the measurement setup. The calibration of network analyzer could be carried out by using at least three different calibration standards having different connector interface if the test fixture is not used. Each connector interface has slightly different electrical characteristic because of the manufacturing tolerances of the connector decrease the connector interface repeatability.

The amount of different connector interface can be reduced to two if the DUT can be applied between the connector interfaces of the test fixture. This can be done if the test fixture has adjustable and repeatable mounting blocks for planar transmission line. The mounting blocks are spring-loaded which means that DUT can always be tightened to the specific moment.

The connector interfaces of test-fixture are implemented with standard precision SMA-connectors.

3.2 Microwave Test Fixture

In Fig. 3-1 is presented microwave test fixture including its maximum dimensions. The test fixture consists of four basic parts, which are launcher, mounting block, adjusting rod and body.

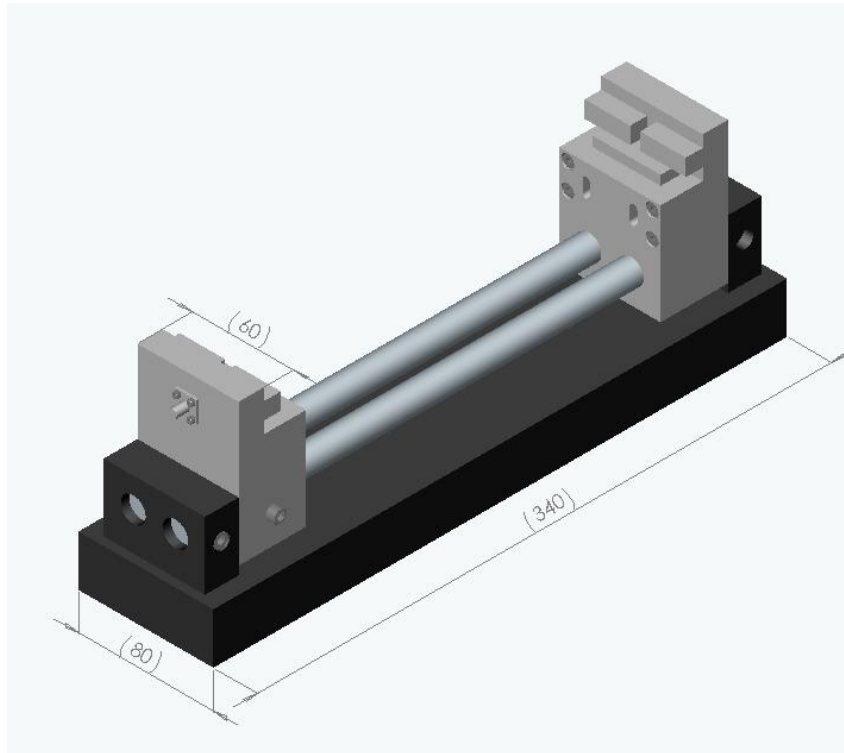


Figure 3-1. A microwave test fixture with its maximum dimensions, which are 80 mm and 340 mm in width and length, respectively.

3.3 Requirement List

In the beginning of microwave test-fixture design, characteristics of fixture have to be specified. These characteristics give fundamentals for mechanical design and material selection. Electrical requirements are presented in Table 2.1. Mechanical and environmental requirements are presented in Table 2.2.

Table 2.1. Electrical requirements for microwave test fixture.

Operating frequency range	DC – 20 GHz
RF power	10 dBm
Characteristics impedance	50 Ω
VSWR	< 1.5
Repeatability	± 0.25 dB

Table 2.2. Mechanical and environmental specifications.

Electrical conductivity	moderate to good
Oxidation resistance	High
DUT substrate height	max. 3 mm
DUT substrate length	max. 200 mm
DUT substrate width	Unlimited
Operating temperature	-30 to +125 °C

4 SYSTEMATIC DESIGN

4.1 Introduction to Systematic Design

Systematic design is a specific methodology, which consists of sequential well-defined steps or phases of the design process, which are used to rationalize the task. The systematic approach of design process is therefore usual presented with a schematic flowchart. The stated principles are used to find solutions for design problems and to make it easy to combine different solutions together if necessary.

Traditionally the flow of work during the systematic design process is dealt in following main phases:

- the first phase is the task clarification and finding the general functions to be performed
- the method moves on step by step from one phase to another
- the solution is developed from qualitative to quantitative properties
- the solution can be found also by developing or combining the variants
- the purpose is to find algorithms or rules to describe the design process
- usually the problems for manufacturing or manufacturability analysis are met in the end of the process

Different researchers have emphasized either their own weightings of specific steps and phases of the design process and they have presented their own methodologies for a systematic approach.

However all models for systematic design are usually detailed and they are easy to follow step by step. These methods can be utilized within most technical research areas. The flowchart of the model includes also feedback in every design phase.

The systematic approach to the design of technical systems and products is presented e.g. in VDI 2221 (1987). Fig. 4-1 presents the most general approach to design according to VDI 2221. Typical to this approach is the underlining of several iterative steps backward or forward, which are, of course, useful to find the optimal solution, but which might as well increase the total time used in design process. This flowchart is meant to be just a guideline and an assisting tool for the designer during the process.

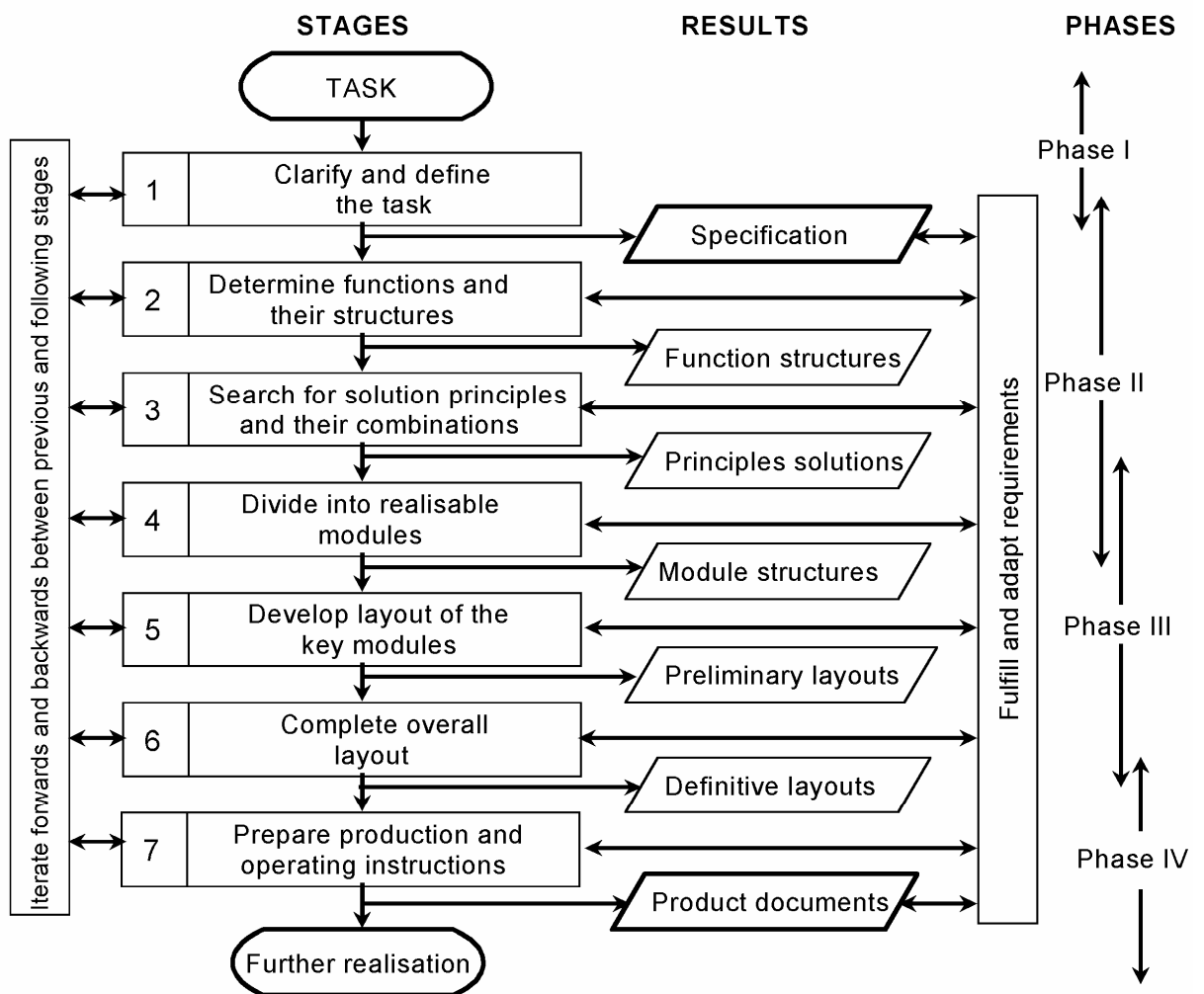


Figure 4-1. General approach to design according to VDI Guideline 2221. [1]

4.2 About the Suitability of Systematic Design for Microwave Design

Common requirements for an effective design method are as follows:

1. The method must be applicable to every type of design activity, no matter in which specialist field.
2. The method should facilitate the search for optimum solutions.
3. The method should be compatible with the concepts, methods and findings of other disciplines.
4. The method should not rely on finding solutions by chance.
5. The method should facilitate the application of known solutions to related tasks.
6. The method should be compatible with electronic data processing.
7. The method should be easily taught and learned.
8. The method should reduce workload, save time, prevent human errors, and help to maintain active interest.

A very simple way to estimate product's manufacturability is to use the following four items:

1. Binary measures (whether or not a specific manufacturing method is suitable)
2. Qualitative measures (products can be classified according to their manufacturability e.g. into groups "poor", "average", "good" or "excellent")
3. Abstract quantitative (some numerical index is counted to describe product's manufacturability)
4. Time and cost comparison

If the design method does not include any of these check points in the early stages of the design process, obviously the method is not too effective for DFM(A)-analysis.

In many cases it is possible to divide the research area of design method into a function-oriented, a performance-oriented or a manufacturability-oriented product design. Alternatively various approaches can be developed for customer-oriented, quality-oriented, cost-oriented and organization-oriented design.

The real need for improvements is between these two extremes. This means that the effective method for the designers should not be too limited (like in the performance-oriented design) or too general (like in the organization-oriented design), but it should, however, include the context of design environment. That is why the traditional design methods are improved for specific design tasks, e.g. for microwave and RF-component or system design.

From microwave mechanics design's point of view the first part of different systematic approaches (task clarification, functional solutions and qualitative analysis) seems to be useful. The method in which design process is regarded as the formulation of the physical process seems to work more effectively than the others do. However, in the end of the design process some common disadvantages were found regardless of the applied method. Because of very special functional requirements, strict tolerances, small dimensions and several material combinations, which are used in microwave mechanics, the manufacturability analysis should have been made earlier (than in any version of systematic design) or at least parallel to the other design steps to avoid tedious redesigns during latter phases. It is also important to notice that some developers of systematic design seem to waste time in "designing the design" than designing the product itself. Each engineering expert should avoid this mistake.

4.3 About the Suitability of Systematic Design for Microwave Test-Fixture Design

The systematic design approach can be easily applied to the design of microwave test-fixture, which consists of several difficult parts. The realizable modules are coaxial to microstrip launchers, microstrip mounting structures and the base, from which the launcher and the mounting structure are quite difficult to design if their functions are not divided to subtasks. Despite the suitability of systematic design method for microwave test-fixture design, the separation of different parts cannot be too sharp and some overlapping has to be applied. If any overlapping is not applied, the combining of different parts to the final component might need redesign.

The flowchart of the most general approach, shown in Fig. 4-1, can be used as a fundamental flowchart for microwave test-fixture design. The suitability of flowchart increases if the stages 5 to 7 are carried out more parallel than sequential. The parallel approach would be more convenient because the design of key modules requires knowledge about the final component and product preparation that might not be specified in stages 1 and 2.

5 DFM(A)-QUESTIONNAIRE FOR THE COMPONENT

5.1 General Instructions to Generate the Questionnaire

To help to establish the special requirements of the microwave or RF-component it is possible to generate a questionnaire, which could be modified from the general presentation shown in Table 5.1. The basic idea is to collect those design aspects, which will later affect on mechanical design and from which the final requirements for design can be derived.

Table 5.1. A preliminary questionnaire for helping to form the requirement list of mechanical microwave subassemblies. [1]

Question	Answer
1. What is the expected operating frequency?	_____ GHz
2. What is the required relative bandwidth?	_____ %
3. What is the maximum radio frequency power to be handled?	_____ dBm
4. Is the unit for a) receive (RX), b) transmit (TX) or c) both?	a) b) c)
5. What is the absolute maximum attenuation allowed?	_____ dB
6. Are semiconductor components involved in the design?	yes no
7. Is the preferred transmission line a) waveguide b) planar c) coaxial d) dielectric?	a) b) c) d)
8. Should the connection to adjacent modules go a) through coaxial connectors or b) waveguide flanges or c) none?	a) b) c)
9. Is the unit a) sealed for life or b) should there be a possibility for service & repair?	a) b)

One example to show how this table guides the design process: if the expected operating frequency of the device is lower than 1 GHz, generally any material could be used and dimensional tolerances can be even > 1 mm. If the operating frequency is <15 GHz, most metals are acceptable, including steel but oxidation is to be avoided, surface and alignment tolerances should generally be generally < 0.1 mm. And finally if operating frequency is over 15 GHz, only highly conductive metals (Cu, Au) can be used, most impurities are extremely harmful, and tolerances should be even better than 5 – 10 μm.

Typically, the questionnaire presented in Table 5.1 should be filled by a microwave/ RF- engineering expert. For specific designs some additional questions might also be useful.

Expert of manufacturing technologies is needed to generate the questionnaire for a specific manufacturing stages to ensure products DFM(A)-aspects. A lot of background information is needed to manage to present the right questions to the designer. However, the designer is the only expert who is able to explain the limits or restrictions due to product's functional aspect for different manufacturing operations. Example of a questionnaire, which is made especially for a laser-processed product, is presented in Table 5.2. Depending on each possible manufacturing technology for the product's geometry, several questionnaires should be generated and filled in.

Table 5.2. Special DFM – questions for laser processing, illustrative examples. [1]

Question	Implementation
1. Are the possibilities to use the fixing systems for machining considered? (typically the requirements of accuracy of fixing in laser processing and machining are almost equal)	yes no
2. Could the carbon content of steel be kept under 0.2 % (or at least not higher than 0.3%)?	yes no
3. If highly reflective materials are welded (for example Cu- and Al-alloys), is the utilisation of Nd:YAG recommended in design documents?	yes no
4. Are the joint preparations for laser welding documented including necessary tolerances and manufacturing methods? (laser cutting or machining are recommended, however $R_a < 12,5\mu\text{m}$ is appropriate)	yes no
5. Are butt welds with raised edges or lap joints with seam welds used whenever it is possible due to constructional aspects?	yes no
6. Are more than two plates welded with the same (seam) weld whenever it is possible due to constructional aspects?	yes no
7. Is the construction possible to be laser processed from one direction or at least in one plane?	yes no
8. Are the values for air gap and allowed misalignment marked in the design documents (for example: butt joint/air gap 0.15 mm, $t < 10$ mm, misalignment < 0.3 mm)	yes no
9. If the material's hardenability properties must be taken into consideration, are the most appropriate joint geometry utilised? (for example the weld is placed mostly on the plates to be welded)	yes no
10. If wires or strings are welded, are the most appropriate joint types used? (power density should be dealt equally to the parts to be joined)	yes no
11. If jigs are needed, are the fixings of jigs designed and marked on the drawings? (in case when the workpiece is moving in front of the beam)	yes no
12. Is the need for grinding the reinforcement marked in the drawings if several sheet metal constructions are welded together?	yes no
13. When jigs are needed for welding partially closed structures, is the possibility of shrinking taken into account when removing the workpiece?	yes no
14. Is the possibility to use various material combinations considered?	yes no

15. Are the possibilities to use different laser processing methods for the same construction or multi-processing methods considered?	yes	no
16. Are the points where laser welding starts and ends designed to meet quality aspects?	yes	no
17. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes	no
18. Are the traditional instructions for designing sheet metal parts taken into account? (needed for example for cut-bend-weld multi-processing)	yes	no
19. Are the adjusting holes or fits marked on the drawings? (or are other additional geometries necessary for adjusting the parts together)	Yes	no

In general the list of actions to put DFM(A) in practice is relatively simple:

- minimize the number of parts in a construction
- design modular constructions
- try to find as many functions for a part as possible
- avoid additional components for joining other parts
- design the construction so that all the parts can be assembled from the same direction
- minimize the number of different manufacturing methods and stages to be used
- obey the rules of easy manufacturing for each manufacturing method (applied into your own production)
- check that there is enough space for necessary tools during assembly, fixing systems during manufacturing and a robotic gripper in automated systems
- use standardized geometry, tools and components
- check the machining allowances
- check the suitability of the material for the manufacturing methods
- use appropriate general tolerances for your own production
- check the summarized errors of the assembly and design a harmless place for manufacturing errors in the construction
- check that the values of surface roughness, tolerances for linear and angular dimensions and geometrical tolerances are adjusted together
- use parts which can be assembled from several directions and still function perfectly (avoid parts which easily assembled in wrong a position or which function only in one position)
- if there are several possible manufacturing methods choose the one, which needs least preparations
- try to repeat the same manufacturing stages, think that each manufacturing stage is also "a module"
- use parametric design

- design the products directly for automated production (in most cases they will be extremely well suitable for manual production too)
- if manual production is used check the ergonomic aspects

During different design stages this list can be used as a checklist to ensure that manufacturability aspect have been taken into account.

5.2 Special questionnaire for the component

To simplify the design of microwave test-fixture the questionnaire is generated and shown in Table 5.3. The generated questionnaire is also answered for giving the fundamental to mechanical design.

Table 5.3. Specific questionnaires generated for microwave test-fixture design.

Question	Answer
1. What is the required frequency range?	DC - 20 GHz
2. What is the maximum power to be handled?	10 dBm
3. Which kind structures will be measured a) waveguide b) planar c) coaxial?	a) b)X c)
4. Which connector type is required?	3.5 or SMA
5. What is the absolute maximum VSWR allowed?	1.5
6. What is the required connector interface repeatability?	± 0.25 dB

Manufacturing technologies, which are researched for the component, are milling and pressure casting, from which, the milling is the main technology. To attain good DFM(A)-aspects with these two manufacturing technologies several questionnaires are generated to specify different manufacturing stages. The generated specific questionnaires for milling are shown in Table 5.4.

Table 5.4. Special DFM – questions for milling.

Question	Implementation
1. Are the possibilities to use the fixing systems for milling considered?	yes X no
2. Is the space for milling tools and fastenings considered?	yes X no
3. Is very hard material used?	yes X no
4. Could cutting fluid be used for cooling tools?	yes X no
5. Is the geometries of construction suitable for common standard tools?	yes X no

6. Is the construction possible to be machined from one direction or at least in one plane?	yes	no X
7. Does the material's hardening during the milling process be taken into account?	yes	no X
8. If the material's hardening has to be taken into consideration, are the most appropriate milling speed utilized?	yes	no X
9. Is there any requirements for specific quality of the surface?	yes X	no
10. Is the surface quality requirements marked on the drawings?	yes X	no
11. Can the drilling be done on a perpendicular surface?	yes X	no
12. Is any coating used?	yes	no X
13. Could every joints be done by using screw joints?	yes X	no
14. Is equal distances for between similar geometries used?	yes X	no
15. Does the surface of construction be cleaned before assembly?	yes X	no
16. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes X	no
17. Are the adjusting holes or fits marked on the drawings? (or are other additional geometries necessary for adjusting the parts together)	yes X	no

The list of the aspects putting DFM(A) in practice is as follows:

- the number of parts in a construction is minimized
- modular constructions is designed
- the number of different manufacturing methods and stages to be used is minimized
- the rules of easy manufacturing for each manufacturing method will be obeyed (applied into your own production)
- checking space for necessary tools during assembly and fixing systems during manufacturing
- using standardized geometry, tools and components
- checking the machining allowances
- checking the suitability of the material for the manufacturing methods
- use appropriate general tolerances for your own production
- checking the summarized errors of the assembly and design a harmless place for manufacturing errors in the construction
- checking that the values of surface roughness, tolerances for linear and angular dimensions and geometrical tolerances are adjusted together
- simplest manufacturing methods is chosen
- using parametric design
- designing the microwave test-fixture directly for automated production (in most cases they will be extremely well suitable for manual production too)

6 REQUIREMENT LIST FOR A MICROWAVE DEVICE TEST FIXTURE

This research is focused to design a microwave test-fixture. The construction consists of two symmetrical adjusting systems, which are used to fix substrates of various lengths for microwave measurements. Standard SMA-type connectors are used to connect the measurement instrument to the microwave test-fixture. Needed components are machined of stainless steel. Basic construction is presented in Fig. 3-1.

6.1 General requirements

Geometry

To make it possible to fix substrates of various lengths it should be possible to adjust the distance between the mounting jaws in a range of 260 mm. The substrate is pressed against connector's center pin, which means that another adjusting system is needed for this. And finally the dimensions of the substrates can vary in a range of 5 x 260 mm. This adjust is made possible by using an adjustable rod between the opposite mounting jaws. Of course the joining dimensions of two SMA-connectors are standardised. The required dimensions of the system with length adjustment ranges are presented in Fig. 6-1.

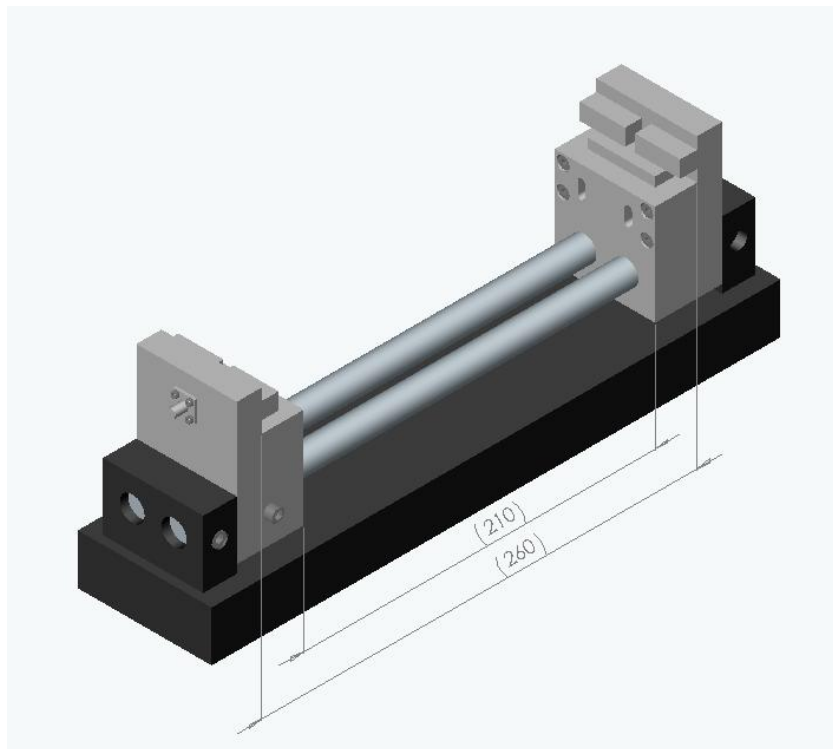


Figure 6-1. Dimensions of the construction with adjustment ranges.

Because the requirements of microwave test fixture are mainly set due to the operating frequency range, which is DC to 20 GHz, the tolerance grade is conveniently to establish respecting the operating frequency. In Table 6.1, the estimation of tolerance grade according to the operating frequency is shown.

Table 6.1 estimation of the required tolerance grade according to the operating frequency. [1]

Frequency (GHz)	Surface roughness	Tolerance grade
300-600	0.8 μm	IT5
150-300	1.6 μm	IT6
75-150	3.2 μm	IT7
35-75	6.4 μm	IT8
15-35	12.8 μm	IT9-IT10

And what is even more important to note here - to ensure a proper measurement - the required tolerances of the measurement device should be at least 5 times tighter than the expected deviations in the product, which will be measured.

The tolerance grade was chosen to be IT9 according to Table 6.1 and it was used to calculate the dimension tolerances. The dimensional tolerances are marked to drawings, which are made for launcher, body parts, mounting block and adjustable rod and are shown in Fig. 6-2 to 6-5.

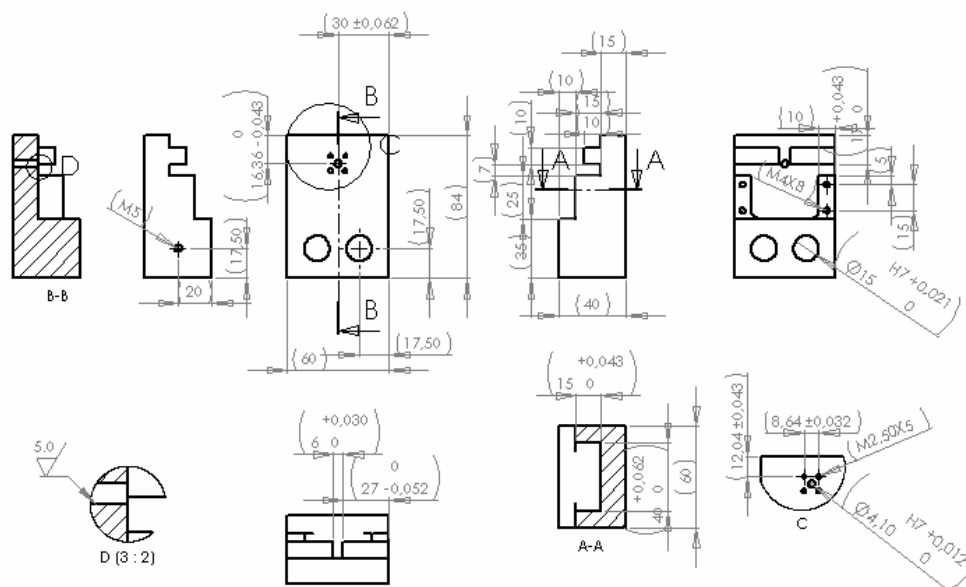


Figure 6-2. Drawings of the launcher including required dimensions and tolerances.

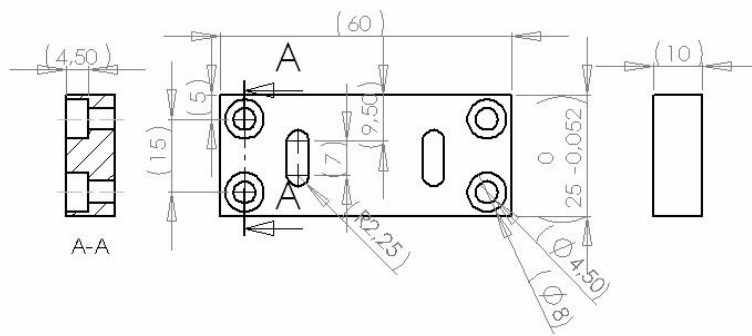


Figure 6-3. Drawings of assembly block including required dimensions and tolerances.

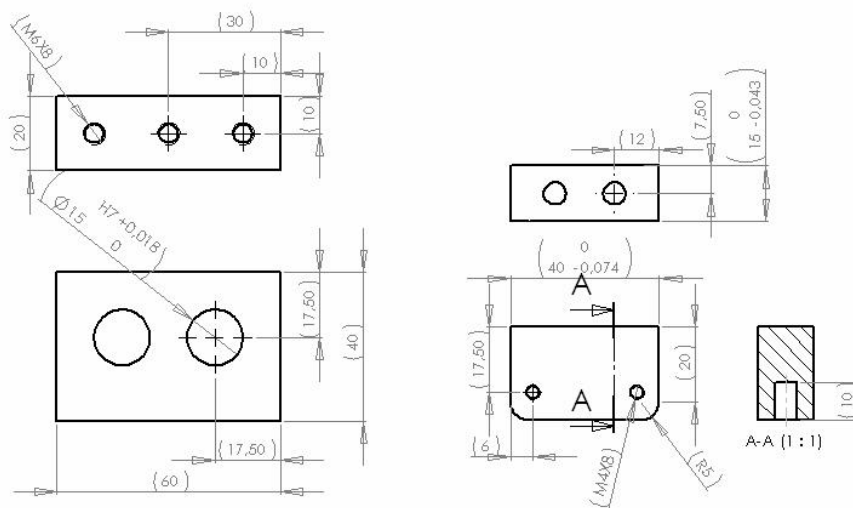


Figure 6-4. Drawings of a) a part of body and b) a mounting block including required dimensions and tolerances.

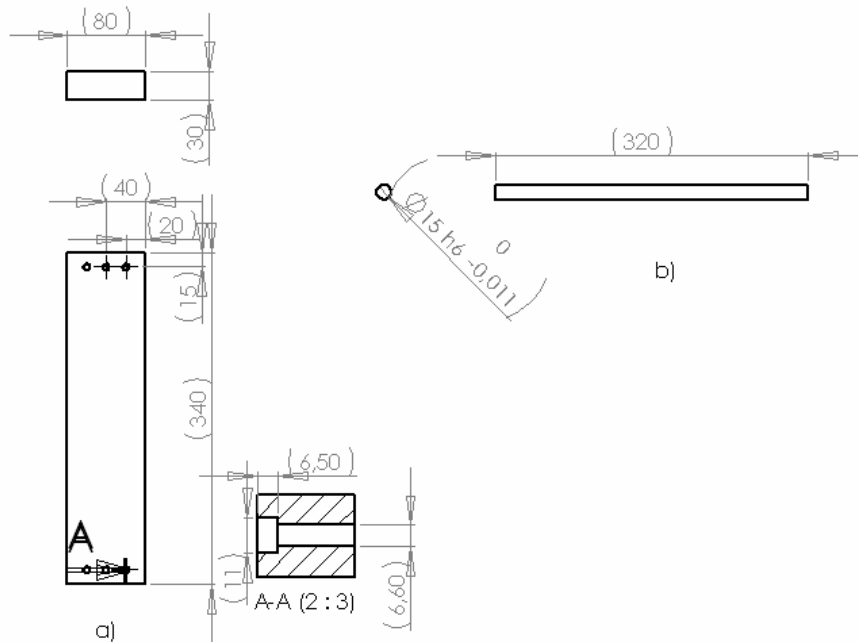


Figure 6-5. Drawings of a) the base of body and b) adjustable rod including dimensions and tolerances.

Forces

Forces, which are needed to press the substrate and the SMA-connectors' center pins to their right positions, are relative small. More important is to take care of adjustment range's accuracy.

Material

There are no special electrical requirements from material because the material of the test fixture is only used to establish the ground connection. Of course the electrical conductivity has to be moderate when the good ground contact for measurement structures should be established.

The limitations of used materials are set by the environmental specifications in which wide temperature and relative humidity range are required. Because of the environmental requirements, materials should have good corrosion and oxidation resistance.

Environment

This test system will be used mostly at room temperature, but the required environmental requirements at this research are as follows:

- operating temperature -30 to $+125$ °C
- operating relative humidity 0% to 100%

Safety and ergonomics

To ensure the easy adjusting attention should be given to mechanism design.

Production

During this research we will focus to some easy machining technologies to be able to produce a small series of test equipment. Materials' machinability is therefore in key-role. On the other hand we must ensure that there will be enough space for machining tools. It should also be possible to use necessary fixing systems and jigs during various manufacturing stages. This aspect will be discusses in chapter 7 in details.

Recycling

The body of the device is made of AISI 303 and it could be re-used.

Costs

When parts for the construction are manufactured, main costs consists of two main aspects:

- writing the required CAM-data for manufacturing processes
- assembly of the parts

However, because we are designing here a new mechanism, usually the time used for the design process is the most expensive stage!

6.2 Requirements for geometric tolerances

To ensure that the substrate is in right position during measurement, it is recommended that the requirement of parallelism and perpendicularity is set for the substrate's assembly between the mounting jaws. This would be better than the use of flatness requirement, because the reference surface could be placed on the measurement devices body (see Fig. 6-6).

Because the standard SMA-connector is inserted to launcher, the circularity and cylindricity should be used to ensure the right positioning of connector's center pin.

Numerical estimation for the required dimensional and geometric tolerances could be estimated from Table 6.1 according to the operating frequency range.

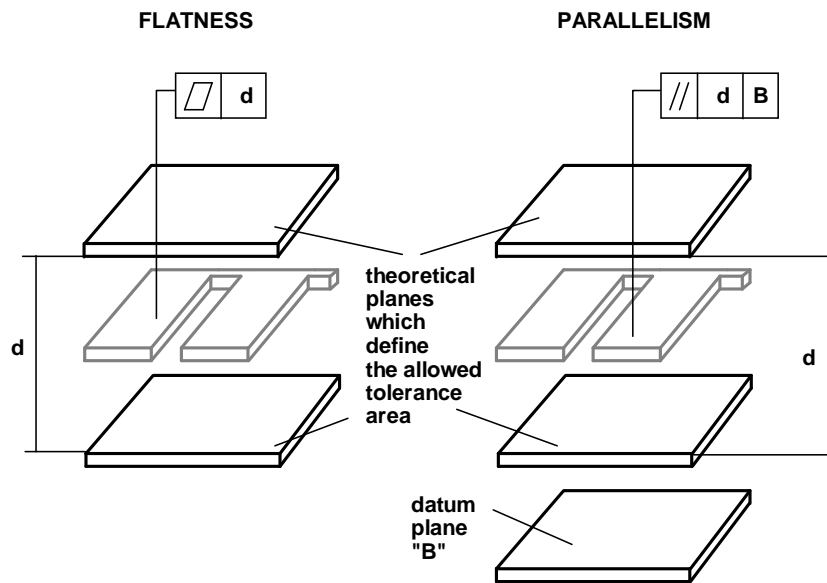


Figure 6-6. Explanation of flatness and parallelism. [1]

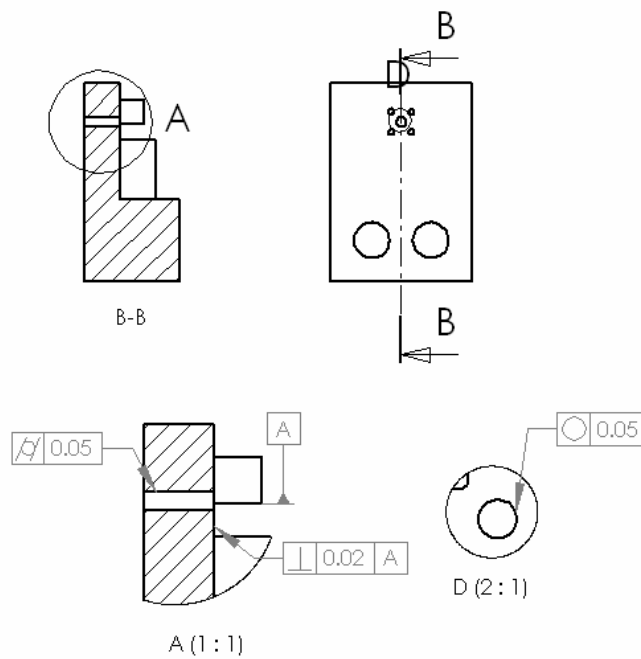


Figure 6-7. Drawings of the launcher with geometrical tolerance.

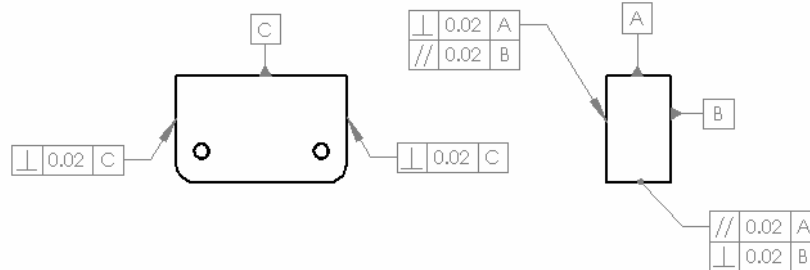


Figure 6-8. Drawings of the mounting block with geometrical tolerances.

7 MANUFACTURING TECHNOLOGIES AND MATERIALS

There are several manufacturing technologies that can be used for processing metals, but only two technologies can be regarded as reasonable ones for manufacturing this specific microwave test fixture. These two manufacturing technologies are machining and pressure casting, from which machining is most attractive. Suitability of machining results mostly from the material selections and small output.

7.1 Manufacturing Technologies

Machining

Machining is a widely used manufacturing process and it can be defined as the process of removing material in the form of chip. Machining includes four different main processes, which are drilling, turning, milling and grinding. From these processes turning and milling are the most attractive ones for this research.

Drilling is the most common machining process and is quite easy to carry out. Some problems in drilling are arising if very narrow and long holes have to be drilled, especially to very hard materials. The term deep-hole drilling is applied to the drilling of holes with a relatively large depth to

diameter ratio [2]. It is normally a question of depths, which are at least 5 times bigger than the diameter.

Milling is versatile for a basic machining process, but because the milling set-up has so many degrees of freedom, milling is less accurate than turning and grinding unless especially rigid fixing is implemented. [3] One advantage of milling is that it can be done almost from any direction but it also generates limitations in means of cutting forces. Especially when hard materials are milled cutting forces should be taken into account to ensure good quality and long tool-life.

Most machining processes have very low set-up costs compared to forming, molding and casting processes. [3] Despite machining is quite expensive for volume production it is necessary when tight tolerances on dimensions and finishing are required. Most important cost factors in machining are setup times, tooling and fixing systems and programming.

Pressure casting

Pressure casting is a process for producing metal parts by forcing molten metal under high pressure into reusable steel molds. The molds can be design to produce complex shapes with a high degree of accuracy and repeatability. Parts can be sharply defined, with smooth or textured surfaces, and are suitable for a wide variety of attractive and serviceable finishes. [4]

Despite in the casting process can be used several metal alloys, stainless steels are seldom used. In stainless steel casting, special alloys are needed whose characteristics are not so suitable for test-fixtures.

Casting process is usually suitable for mass-production, because the process needs always molds, and it is therefore a quite expensive manufacturing technology for single production. In addition of molds and die costs, the most important cost factors are the costs of finishing processes and quality checking. In this research, casting process is not estimated as a suitable technology because only a few prototypes will be manufactured. The suitability of casting is also suffering from the amount of different parts of test-fixture: Different parts would increase the need of molds increasing molds and die costs. Of course the need of different molds could be decreased by milling some parts, but then manufacturing could not be done with one manufacturing technology.

7.2 Material Selection

Stainless steel alloys

Different stainless steel alloys are among the most frequently used metals in mechanical industry. Stainless steels are high-alloy steels that contain large amount of chromium. Due to chromium stainless steel has almost superior corrosion resistance compared to other steels. Stainless steels can be divided into three basic group based on their crystalline structure: austenitic, martensitic and ferritic. [3] These groups have different characteristics especially in hardness, machinability and corrosion resistance as well.

In general stainless steels have very high toughness and poor thermal conductivity leading to the higher machining tools' temperatures compared to carbon steels. These disadvantages impose severe requirements on the high-temperature hardness of the machining tools and on its ability to withstand high temperatures. The machinability of stainless steels is also decreased by low chip-breaking characteristics, which can decrease the quality of machined surface without good cleaning.

Austenitic Stainless Steel

Austenitic alloys include very common 300-series steels and are characterized by their high content of austenite-formers, especially nickel. They are also alloyed with chromium and other compounds such as copper and titanium.

Austenitic steels have excellent corrosion resistance and heat resistance with good mechanical properties over a wide range of temperature. They generally have a relatively low yield stress and are characterized by strong work hardening. The strength of austenitic steels increases with increasing levels of carbon, nitrogen and, to a certain extent, also molybdenum. Austenitic steels exhibit very high ductility and toughness and can be hardened with cold working. [5]

Martensitic Stainless Steel

Martensitic alloys include 400-series steels, which have high carbon content. Because martensitic alloys have high carbon content they are usually used in tools.

Martensitic steels are not as corrosive resistant as austenitic steels and their ductility is also relatively low. They possess excellent hardenability: even thick sections can be fully hardened and these steels will thus retain

their good mechanical properties even in applications where thick sections are used. [5]

Ferritic Stainless Steel

Ferritic alloys are ferritic at all temperatures which is achieved by a low content of austenite forming elements, mainly nickel, and a high content of ferrite forming elements, mainly chromium.

They may have good ductility and formability, but high-temperature mechanical properties are relatively inferior to the austenitic stainless steels. Toughness is limited at low temperatures and in heavy sections. [6]

Machining

Machining of stainless steels is often regarded as a difficult manufacturing stage because of material properties, which result the machining tools being exposed to severe conditions. The problems during machining are primarily arising with the austenitic, ferritic-austenitic and certain of the ferritic-martensitic steels. Pure ferritic and martensitic steels are seldom difficult to machine. [5]

Machinability is a complex concept that embraces several factors, and not just the conditions of tool wear. It is also necessary to consider material effects to the magnitude of cutting forces, which can causes vibrations if the part fixed loosely or too long tools are used. Of course the effects of the material itself to tool wear has to be taken into account when the good quality of machined surface is essential. [5]

Stainless steels suffer considerably from work-hardening, meaning that the hardness increases as material is deformed. It also means that, after a first pass, the machined surface has become harder, changing the working conditions for the cutting edge during subsequent passes, as the edge then has to work in a hard surface layer. The work-hardening is often a phenomenon for thin surface thickness resulting problems for finishing, as the depth of cut is so small and the cutting edge is working entirely in the work-hardened layer. [5]

Aluminum Alloys

There are a lot of different aluminum alloys, but only a few attractive alloys for microwave mechanics. Most attractive is AlMgSi1, which is easily machined and does not require any plating. Limitations of aluminum for this test-fixture arise from its too small modulus of elasticity. Modulus of elasticity is considerably smaller than stainless steels or beryllium copper meaning that aluminum cannot be used when strength combined with high rigidity is needed.

Beryllium Copper Alloys

There are wide variety beryllium copper alloys having different chemical composition and the used heat-treatment methods of the specific alloys. These alloys might be classified and standardized sometimes even under same identification e.g. CuBe2. So, some attention should be paid in alloy selection.

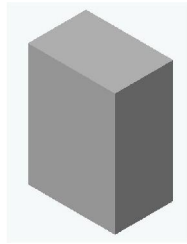
Beryllium copper has a good electrical and thermal conductivity. It can be used without additional plating, because the corrosion resistance is good. The good thermal conductivity and very high tensile strength allow it to be exposed to high temperatures without a risk of melting or deterioration of other factors. [1] Beryllium copper has better machinability than copper but usually heat-treatment is needed for maximum strength.

Beryllium copper could be very attractive material for test-fixture, but it is more expensive than stainless steel that decreases its suitability.

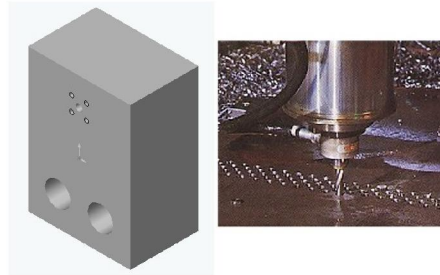
7.3 Machining the microwave test-fixture

Determination of suitability of selected manufacturing technology can be done by examining different manufacturing stages. The examination of the stages can also give new aspects for component design and should be done as early as possible. If the preliminary examination of manufacturing stages is not done at early design stages, some redesign might be needed.

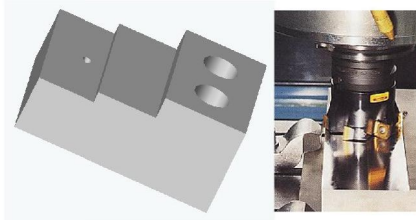
The machining of any component start with the selection of a valid billet having dimensions close to basic dimensions of a machined component. After the billet selection, the component is machined in different stages. The stages are different if fastenings or tools are changed. In this research several different manufacturing stages are needed and five basic stages are shown in Fig. 7-1.



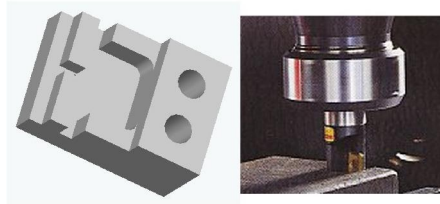
Stage 1. Selecting a valid billet.



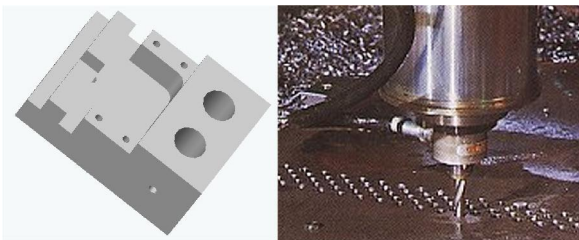
Stage 2. Drilling holes for adjusting rod and SMA-connector.



Stage 3. Facemilling planes.



Stage 4. Endmilling square shoulder, facemilling and long edge milling.



Stage 5. Drilling holes and threads.

Figure 7-1. Five basic manufacturing stages for manufacturing the microwave test-fixture.

8 APPLIED DFM(A)-ASPECTS

8.1 Changes of the Construction

The changes of the construction will usually mean that the shapes of designed components should also be changed radically. Because of the risk of possible radical changes to the components, all constructional decisions should be done at the earliest possible design stages to avoid redesigns. Usually the changes are related to the selection of manufacturing technologies and materials but the assembly of components could also required changes to the construction.

During the early design stages of this device, two main chances of construction were done to make milling and assembly easier. The first chance was the redesign of launchers to be fixed by adjusting the

mounting block. This would make the contact force between connector's center pin and the strip on laminate easier to handle. Of course this change was also loosing tolerances for milling. The other change was redesign an assembly block into launcher. The assembly block, shown in Fig. 6-3, will help assembly of the spring loaded into mounting block.

8.2 Changes of the Geometry

The changes of the geometry of separate components do usually not cause so radical consequences as the possible ones in the construction because most of the changes are made just to make it possible to use standardized tools e.g. for machining or cutting. In some cases, product geometries will be changed to ensure reliable fastening during manufacturing.

In this research, no changes of the geometry were done, because the component ensures already quite good fastening locations. The geometries of component were not also changed for the standardized machining tools because the dissections of standardized machining tools were not done very strictly.

8.3 Choosing More Acceptable Material

Several materials should be compared to choose the most suitable material to meet the DFM(A)-aspects. The comparison has to be done carefully if several different manufacturing technologies are used, because alloys usually have different manufacturability characteristics for different manufacturing technologies. In example, beryllium copper has moderate machinability but has some restrictions in weldability. In the manufacturing of microwave test fixture, only machining technology is used making this aspect almost uncritical.

Considering the properties of different materials, treated in chapter 6, some improvement in electrical properties of the test fixture could be achieved. Despite electrical properties could be improved by choosing different material, it does not give any improvement for DFM(A)-aspects. It might even make manufacturing more complicated than with stainless steels.

Fabrication technology affects to mechanical properties of material that should be taken into account when billet is selected. In this case, suitable billets of AISI 303 stainless steels is restricted to cold drawn square bar

because of dimensions of launcher part. Of course there is more than just one choice to be selected as a billet for other parts, but the effects of fabrication technology is not so critical within these parts.

8.4 Detailed Changes of Dimensioning and Tolerances

These changes are usually made directly to the technical drawings from which they should be easy to read. When the dimensioning and tolerancing are made accurately and clearly, manufacturing will be easier because there is no need to any readjustments. The dimension variation should always be marked after dimensions so that manufacturer does not need to try to search the values from engineering tables. The clear and accurate dimensioning and tolerancing reduce also error possibility.

In the drawings of microwave test fixture, detailed dimensioning and tolerances are used to ensure required specifications. Also the symbols for fittings have to be marked with direct limits so that manufacturer does not have to calculate them from tables. The clear tolerancing is established by avoiding unnecessary geometrical tolerances.

9 FLOWCHART OF THE DESIGN AND MANUFACTURING STAGES

The flowchart of the tuned design methodology for machining is illustrated in Fig. 9-1. It includes manufacturability analysis and the tuned analysis for machining that are done for machined microwave test fixture.

In the first stage of flowchart, the functional requirements of microwave component are established. This establishment creates the basis for microwave component design and of course for the DFM(A)-aspects. After the functional requirements establishment, the conceptual design of microwave component is done. The conceptual design specifies basic geometries and dimensions that are important aspects for selection of appropriate manufacturing methods and materials. The selection of appropriate manufacturing methods and materials in the early stages of the design process will reduce the need of redesign.

In the designing stages, the tuned machinability analysis has been done giving more specifications for material selection and construction of component. The tuned machinability analysis includes also predesign of fixings and jigs and dissection of different machining equipment. The dissection of machining equipment is important, because machining time can be reduced if the passes in milling can be minimized.

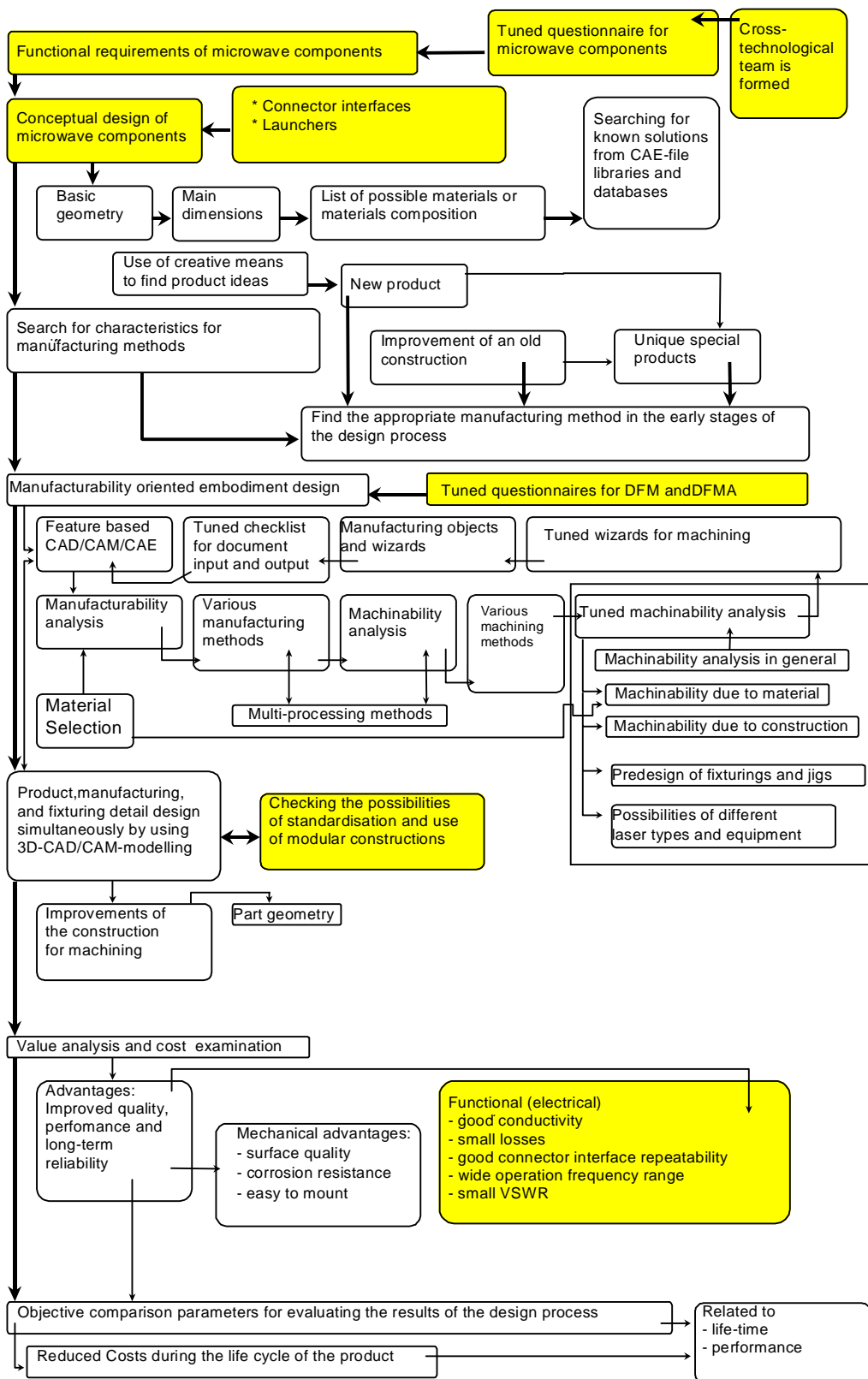


Figure 9-1. A flowchart of the tuned design methodology for machining including manufacturability analysis and the tuned analysis for machining.

The passes in milling can be reduced by noticing the milling tools geometries in the design of milled component. Although the dissection of machining tool could save some time, it was not done very strictly.

The last stages include value analysis and cost examinations, which can give new aspects for designing of microwave components. Of course the cost-effectiveness of the microwave test fixture is not vital and there is no need for precise cost examinations.

10 COSTS ASPECTS OF MICROWAVE TEST FIXTURE DESIGN AND MANUFACTURING

Basically there are four main cost elements, which should be taken into account when evaluating the total costs of a MW- /RF-product:

- design costs
- material costs
- manufacturing costs
- costs spanning over the lifetime of the product

Many MW- /RF- applications include difficult geometries or materials regarding traditional manufacturing processes (e.g. turning, milling or casting). This means that much time is needed to develop the first prototypes to be suitable for production. The design costs of a microwave component can be estimated to be at least double compared to any "non-high-tech" product.

MW- /RF-devices utilize several precious and expensive materials. E.g. gold or silver or some specially mixed powders are needed. It is also usual that the quality grade of alloyed metals used in microwave applications is extremely good and the price therefore higher too. If expensive materials are used their price is essential. In addition to this some of these materials are difficult for traditional manufacturing processes or at least some special arrangements are needed during production. These double the effects of material selection to the price. A direct comparison between a MW- /RF-application and "non-high-tech" product is hard to make, but typically material costs is at least ten times higher. In the designing of microwave test fixture, these types of expensive materials are not needed.

In general MW- /RF-applications need specialized tooling and fixing systems and in some applications, depending mostly of the operating frequency, quite tight dimensional tolerances down to 1 μm . These call for some extra time to make a dedicated set-up into the production system.

Although the manufacturing stages themselves could be quite cost-effective, the long set-up times and specialized tools and fixings increase production costs by about 500 to 800 per cent in prototyping or small series production. In high volume production these cost elements are marginal. There is a tight relationship between manufacturing costs and surface roughness. After the specified surface roughness level the costs will increase exponentially. Nowadays in milling and tuning the limit is 0.8 μm and in grinding 0.4 μm . A better surface finish rapidly adds costs. Many MW-/ RF-applications tend to lead to over-estimated dimensional accuracies. The surface requirements may be set too tight to ensure the products performance though an easier way might have been e.g. to change more reliable connectors to the device. The most important thing is to compose the requirements of dimensional accuracy and surface finish from the operating frequency of the device. In this construction the required IT-grade is IT9, which means that the critical allowed dimensional deviations are 30 μm and corresponding required theoretic value of R_a is 5.4 μm . The critical geometry is the hole for the SMA-connector's insulation material.

In MW-/ RF-device production the traditional principles to handle tooling costs, fixed costs, capital costs, labor costs, indirect labor costs etc. are as usual. The main acts should be focused in decreasing the lead-time - that is to minimize the time required to start production.

In many cases also MW-/ RF-components should withstand environmental loads and there is a reason to compare different materials and their lifetimes. This comparison is typically made between two alternatives:

- a) common base materials with an appropriate coating, a relatively short lifetime, the product must be changed due to a break-through in the coated surface, relatively cheap
- b) specialized base materials, a long lifetime, no changes needed during the lifetime, extremely expensive

To make the comparison a ratio, which shows the price in the form of a "unit" like [performance/ price/ lifetime], is needed. Microwave test fixture should withstand environmental loading like oxidation.

Regardless of technology - as long the dimensional accuracy is met with a standardized process - the costs depend only on the manufacturing time. Immediately if there is a need to change the process to ensure a better accuracy or dimensional tolerances the price rises essentially. To manufacture this construction standardized processes could be used.

The development process of many high-tech products normally includes several prototype phases and tests before the final design. Unfortunately these prototypes can constitute the largest portion of the total developing costs. To minimize the costs of a prototype several manufacturing technologies could be applied:

- the prototype could be made of some soft materials like foam or plastic by using simple milling or turning operations
- the prototype could be manufactured by casting but the mould and the casting model are made of some cheap material
- scale models could be utilized
- rapid prototyping could be used (the geometry of the component is laser sintered according to the computer aided model)

One serious problem is that if the prototype is not manufactured with the final manufacturing technology, at least some of the geometrical limits are compromised. E.g. there are important rules for designing a product for casting or powder metallurgy, which are not necessary if the prototype is manufactured by milling or turning. In practice this means re-design for final manufacturing, which increases cost. Additionally, the surface quality or dimensional tolerances may have a weak basis if the prototyping scheme relies on a different technology. Based on the results of this research a prototype of the microwave test fixture will be manufactured. The simple machining technology is used, because it can reach required dimensions and tolerances.

Table 10.1 presents the most important cost factors for various groups of manufacturing technologies. From these groups, most usable manufacturing technologies for this research are machining and casting.

Table 10.1. Cost factors for various manufacturing technologies. [1]

Manufacturing technology	Most important cost factors
Forging processes	- tool and die costs related mostly to complexity of the workpiece
Extrusion and drawing processes	- tool and die costs related mostly to the selected process (e.g. hydrostatic extrusion needs special equipment)
Sheet metal work	- tool costs related to the geometry of the work piece - costs will decrease if several manufacturing stages can be done with a multi-processing machine - nesting makes it possible to use sheet metal material costs-effectively
Powder metallurgy	- die and model costs - manufacturing processes of the powder itself are expensive - finishing processes - quality checking
Casting	- die and model costs - finishing processes - quality checking
Machining	- set-up times - tooling and fixing systems - programming (tool control)
Joining	- set up times - pre- and post treatment after joining

There are some derived ratios to estimate MW- /RF-component's total costs. These characteristics are describing the effectiveness of production and the investment costs are taken into account as well. Typical ratios could be as follows:

- costs [€] [↓] / attenuation [dB] [↓]
- costs [€] [↓] / noise figure [dB] [usually ↓]
- costs [€] [↓] / phase error [rad] [↓]
- costs [€] [↓] / lifetime [h] [↑]
- accuracy [IT-grade] [↓] / attenuation [↓] or noise figure [↓] [dB]
- distance between electric components [m] [usually ↓]
- weight [kg] and dimensions [m³] of the product [usually ↓]

When utilizing these types of ratios the designer calculates e.g. the costs due to changes, which should be made to the product to improve the maximum gain with one single dB-unit. After that the design procedure continues by calculating the cost ratios for attenuation, noise, phase error

etc. The arrows [↑ or ↓] after each unit describe whether the aim is to maximize or minimize the corresponding property. E.g. the designer is searching the minimum manufacturing accuracy (IT-grade), which still satisfies the performance requirements of allowed attenuation and noise but yet gives the desired gain level. After having collected all the ratios listed above the designer is able to make a numeric and objective comparison between various product alternatives. For this research topic the most important optimizing ratios are as follows:

- costs / lifetime
- accuracy [IT-grade] / attenuation
- costs / attenuation

11 SUMMARY

Usually DUT is integrated in transmission media that is not directly supported by measurement instrument. It means that a microwave test-fixture is needed to carry out precision microwave measurement. If the test-fixture is not used, connector interfaces of DUT have to be implemented with different connectors having slightly different electrical characteristic because of the manufacturing tolerance. These differences will decrease the accuracy of measurement. Using the test-fixture, amount of different connector interfaces can be minimized and the measurement will be more repeatable. This research is focused in designing and manufacturing a microwave test-fixture. Manufacturability analysis is also discussed.

The specific questionnaires are implemented for component requirement and machining to ease design process. These questionnaires and the list of actions to put DFM(A) in practice will also serve as a check list to ensure manufacturability aspects during the design process.

Manufacturability analysis for the microwave test-fixture confirmed the importance of the DFM(A) –aspects, when designing microwave mechanics. If the concentration is only in electrical properties, manufacturability of the component will easily suffer and the costs will increase. The design of a microwave test-fixture needs both electrical and mechanical designing skills and the use of cross-technological design team is highly recommended.

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