Research report 54

DFM(A)- ASPECTS FOR A FIXED ELECTRICAL ATTENUATOR DESIGN

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Keywords: Manufacturability analysis, design for manufacturing and assembly, microwave mechanics, electrical attenuator, reverse engineering

ABSTRACT

The goal of this paper is to describe a complete and extensive prototype design of a fixed electrical attenuator. The paper starts by describing the function and by giving some basic information about the attenuators. After a comprehensive description of the component, the facts of reverse engineering are discussed. The method itself is applied to ease manufacturing and design stages of this component. Information about materials and applied manufacturing technologies are also included in this report. By applying some specified DFMA-aspects the final design turned out to be a potential prototype device to be manufactured and for further analyse.

CONTENT LIST

1 INTRODUCTION

In this research manufacturability analysis will be made for a fixed electrical BNC -attenuator. Possibilities to utilize reverse engineering both for design and for making manufacturability analysis for MW-/ RF -components will be discussed.

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

Practical guides and instructions for easy manufacturing are collected especially for machining and heat treatment. In this report we will focus in researching components, which are made of different coated 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

There are two different kinds of attenuators: waveguide and electrical, and both of them can be divided into fixed and variable types. In this research we will concentrate on fixed electrical attenuator. The component will be designed by using the reverse engineering, which basic elements are described later in chapter 4.

In this design the attenuation is based on a utilization of a ready attenuator component. More extensive research for its suitability for higher frequencies and comparison with other commercial attenuators will be covered in other research. A personal goal for this research is also to gain more information concerning microwave mechanics and characteristics of the microwave components themselves.

3 COMPONENT

3.1 Function

An ideal attenuator passes part of the signal power and other part is absorbed. In other words the amplitude, thus the delivered power is decreased. Its input and output ports are fully adapted, so that the distortion caused by reflections are minimized. It can also be used in infinitely wide bandwidth. A real attenuator causes distortion to the passing signal and its bandwidth is limited by the passive component and joints of the connections.

An electrical attenuator is a component that can be used in low frequencies as well as in microwave frequencies. All ready mentioned power absorption is one of the tasks, but it can also be used for restoring the adaptation rate, and in that way to minimize the distortion of signals. Attenuators are commonly used in antenna applications.

By using a ready surface mounted attenuator component the parasite capacitance and inductance are minimized. Distortion caused by noise is also minimized. The thin film technique that is used within the component makes the characteristics over temperature very stable. When choosing a right kind of attenuator the input impedance matches the characteristic impedance of the transmission line, thus the reflections are minimized. In spite of the good chip properties the bonding wires from the attenuator chip to the connectors causes some parasite inductance, which is undesirable. Basically these are the characteristics that are not covered in this research, but which are yet essential.

The attenuator circuit GAT-6 is manufactured by Mini-Circuits and it is selected so that it causes attenuation of 6 dB to all frequencies up to 2 GHz. The manufacturer gives [6] the information that the attenuation may vary ±0.3 dB, and the flatness between 1 – 5 GHz is 0.20 dB. The VSWR (Voltage Standing Wave Ratio) is between 1.15:1 and 1.30:1. The maximum input power at 25 ^{o}C is 0.5 W. Both BNC –connectors have at maximum 1.3:1 of VSWR and they can be used with relatively accuracy up to 4 GHz.

3.2 Dimensions

In Fig. 3.1 is shown a picture of a commercial attenuator manufactured by Radiall. The attenuator chip does not belong to the original component, but it presents this particular design in this research. The dimensions of the component are ∅14 x L45 (mm). The eventual component will most likely look a little bit different, but in any case it will have one male and female connector. The diameter of the cylindrical cover between the connectors will be determined by the size of the circuit inside. The dimensions of the GAT-6 chip package are 3x3 mm.

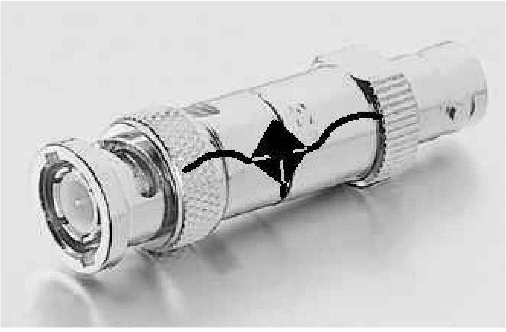


Fig. 3.1 Fixed electrical BNC attenuator manufactured by Radiall. The shown circuit is not Radiall's design [6].

The picture shows that there is a great change for differential-mode interference, because the signal wires and the ground lead forms relatively large wire loop. Future research will show, if the circuit should be designed differently.

4 REVERSE ENGINEERING

4.1 Introduction to Reverse Engineering

The term “reverse engineering” can be explained like what the term implies: the interpretation of an already existing artefact by an analysis of the design considerations that must have governed its creation. It can be said that reverse engineering begins with the product and works through the design process in the opposite direction to arrive at a product definition statement (PDS). In doing so, it uncovers as much information as possible about the design ideas that were used to produce a particular product.

In some situations, designers give a shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to enable the manufacturing of the part. As products become more organic in shape, designing in CAD may be challenging or impossible. There is no guarantee that the CAD model will be acceptably close to the sculpted model. Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the part-to-CAD process.

Basic type of reverse engineering involves producing 3-D images of manufactured parts when a blueprint is not available in order to remanufacture the part. To reverse engineer a part, the part is measured by a coordinate measuring machine (CMM). As it is measured, a 3-D wire frame image is generated and displayed on a monitor. After the measuring is complete, the wire frame image is dimensioned. Any part can be reverse engineered using these methods. New and improved techniques in reverse engineering include laser scanning, which as the name implies, uses laser beams to scan across the surface of components of any shape and display the results in real time. In MW-mechanics an antenna or filter construction could e.g. be manufactured from cost-effective foam or plastic which is then platted with a specific material to test antenna's or filter's performance. If any changes are needed to the geometry they are easy to produce to the soft material. When this first prototype is ready, the raw geometry can be read with the CMM-technique and the exact geometry can be optimised by filtering the data to the CAD-modeller. Finally the required CNC-code for a real product is compiled with the CAM-module.

The process of duplicating an existing component, subassembly, or product, without the aid of drawings, documentation, or computer model is in many cases called as "reverse engineering". Probably this is the way in which people traditionally and typically understand the term's content.

From this point of view reverse engineering can be viewed as the process of analysing a system to:

1. Identify the system's components and their interrelationships
2. Create representations of the system in another form or a higher level of abstraction
3. Create the physical representation of that system

This type of reverse engineering is very common in such diverse fields as software engineering, entertainment, automotive, consumer products, microchips, chemicals, electronics, and mechanical designs. For example, when a new machine comes to market, competing manufacturers may buy one machine and disassemble it to learn how it was built and how it works. A chemical company may use reverse engineering to defeat a patent on a competitor's manufacturing process. In civil engineering, bridge and building designs are copied from past successes so there will be less chance of catastrophic failure. In software engineering, good source code is often a variation of other good source code. However, this process is illegal in many countries. In general, hardware reverse engineering requires a great deal of expertise and is quite expensive. In this case this explanation is far from what is meant with “reverse engineering” in this paper.

In MW-mechanics much more sophisticated way to apply and explain reverse engineering is to start e.g. from antennas required radiation pattern. If we are able to draw at least a raw draft of the pattern it usually gives the first ideas of antennas geometry. So the designing process starts from the “results” of a “measured” antenna – also this could be called “reverse engineering”.

Following are reasons for reverse engineering a part or product:

1. The original manufacturer of a product no longer produces a product.
2. There is inadequate documentation of the original design.
3. The original manufacturer no longer exists, but a customer needs the product.
4. The original design documentation has been lost or never existed.
5. Some bad features of a product need to be designed out. For example, excessive wear might indicate where a product should be improved.
6. To strengthen the good features of a product based on long-term usage of the product.
7. To analyse the good and bad features of the product (either own or competitors’).
8. To explore new avenues to improve product performance and features.
9. To gain competitive benchmarking methods to understand competitor's products and develop better products.
10. The original CAD model is not sufficient to support modifications or current manufacturing methods.
11. The original supplier is unable or unwilling to provide additional parts.
12. The original equipment manufacturers are either unwilling or unable to supply replacement parts, or demand inflated costs for sole-source parts.
13. To update obsolete materials or antiquated manufacturing processes with more current, less-expensive technologies.
14. To support prototype design.
15. Enable the design of complex geometries by utilising demonstrative handmade product models.

4.2 About the suitability of Reverse Engineering for MW-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 organisation-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 organisation-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 MW- and RF-component or system design.

If a new product is under developing reverse engineering can be applied to MW-product's design. Especially if there are no rapid prototyping (RP) systems in use the prototype can be handmade by using reverse engineering technique. However, the computer aided RP-system would decrease the design time significantly. The other version of reverse engineering, which utilises the performance curves of the product, is useful if the exact values for systems performance are available and if it is possible to derive the requirements for a single product starting from these values. However, sometimes it is possible to at least limit the acceptable e.g. antenna geometries for further design by using "limited" reverse engineering. From this point of view items 7, 8, 10, 14 and 15 in the previous list are the most essential aspects for applying modern reverse engineering for MW-design. [4], [5]

5 DFM(A)-QUESTIONNAIRE FOR THE COMPONENT

5.1 General instructions to generate the questionnaire

To help to establish the special requirements of the MW- 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 [5].

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 MW-/ 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 stage 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 [5].

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 < 12,5μm 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	yes no

example: butt joint/air gap 0.15 mm ,t<10 mm, misalignment<0.3 mm)	
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 fixing 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 were 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:

- Minimise 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.
- Minimise 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 standardised 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 summarised 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. [4], [5]

5.2 Special questionnaire for the component

Table 5.3. A preliminary questionnaire for helping to form the requirement list of mechanical microwave subassemblies.

Question	Answer
1. What is the operating frequency range?	DC – 2 GHz
2. What is the maximum radio frequency power to be handled?	26 dBm
3. Will the component a) receive, b) transmit, or c) both?	Both
4. Are semiconductor components involved?	No
5. Preferred transmission line?	Coaxial
6. What is the attenuation?	6 dB
7. Is the component a) sealed for life, or b) should there be possibility for service and repair?	Sealed for life
8. Characteristic impedance a) 50 Ω or b) 75 Ω?	50 Ω
9. How is the inside component attached?	Soldered
10. How is the cylindrical cover attached?	Fitted

Table 5.4. Special DFM – questions for manufacturing processing.

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
2.Could the carbon content of steel be kept under 0.2 % (or at least not higher than 0.3%)?	Yes
3. If the material's hardenability properties must be taken into consideration, are the most appropriate joint geometry utilised?	Yes
4. If jigs are needed, are the fixing of jigs designed and marked on the drawings? (in case when the workpiece is moving in front of the beam)	No
5. Is the possibility to use various material combinations considered?	Yes
6. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	No
7. Are the adjusting holes or fits marked on the drawings? (or are other additional geometries necessary for adjusting the parts together)	Yes

6 REQUIREMENT LIST FOR A FIXED ELECTRICAL ATTENUATOR

This research is focused to the fixed electrical attenuator with BNC-type joints in both ends. Connector body, which is a metallic cylinder, is made of nickel plated stainless steel. The only electrical component is suspended by the connecting wires, which is then placed into the cylinder. Connecting wires are between the two BNC-connectors are assembled by using two lead-throughs. Basic geometry of the construction was previously presented in Fig. 3.1.

6.1 General requirements

Geometry

Two standardized BNC –components are jointed to the cylinder (attenuator's body), by using a heat expansion for firm fit. From the list of geometric tolerances, the requirement of cylindricity is therefore needed. The jack (female part) needs to be processed so that a fit can be used for it as well. A lathe must be used to carve a groove in the end of the jack, where the cylinder is fitted. The width of the groove depends on the thickness of the cylinder. The diameter of the cylinder should be approximately 9.5 mm, because of the structure of the plug (male part) BNC –connector. This diameter is large enough, because the maximum dimension of the attenuator chip is less than 4.3 mm. The length of the cylinder should be somewhat shorter than the total length of the signal wires and the attenuator chip. Later on, the lengths of the wires are defined, but let’s define the length of the body at this point. If we leave approximately 7 mm extra space for tools to attach the other connector pin to the connector, the length of the body ought to be 25 mm. The tolerance of the length does not need to be very accurate since the wires are anyway longer than the cylinder.

Three wires are soldered onto the chip. The signal wires are clamped to the gold plated pins and directed to the connectors. The ground wire is fed through a small hole (diameter 2 mm) of the cylindrical body and glued onto surface of the cylinder. The ground wire should be tightened so that ground impedance could be minimized. The length of the wire should be long enough, so that it won’t escape back to the hole. The extra wire can always be cut apart. It is well known that the asymmetry of the cylinder raise the stray inductances, but to be sure of their magnitudes some measurements need to be done.

The signal wires should have insulation on some parts of the wire and the ground wire can be without insulation. The wire is silver plated copper, which diameter is 0.5 mm and the AWG number is 24. The same wire can be used as a ground wire, on condition that the insulation is removed. The total length of the both signal wires and the chip should be this much longer than the cylinder that there would be enough room to attach the other signal wire to the BNC –connector, and after that attach the cylinder to the connector. If the wires are too long the chip may touch the body and cause unwanted short circuit. More precise dimensions of the insulations and wires are shown in Fig. 6.2.

The dimensions of BNC-connection are fully standardised and these dimensions establish a great deal of product's dimensions. The dimensions that were available were the connector interfaces and total lengths and diameters. More dimensions are needed so the methods of reverse engineering had to be used to gain more essential dimensions for this particular attenuator design. These dimensions are presented in Fig. 6.2.

Perhaps Fig. 6.3 gives a better picture and the relation of the dimensions of the attenuator. The dark square between the connectors is the attenuator microchip. It is well known that since the diameter of the signal and ground surfaces change, it will have weakening effects to the impedance matching. There are some experimental equations available, but the real information concerning the impedance matching will be gotten after some measurements.

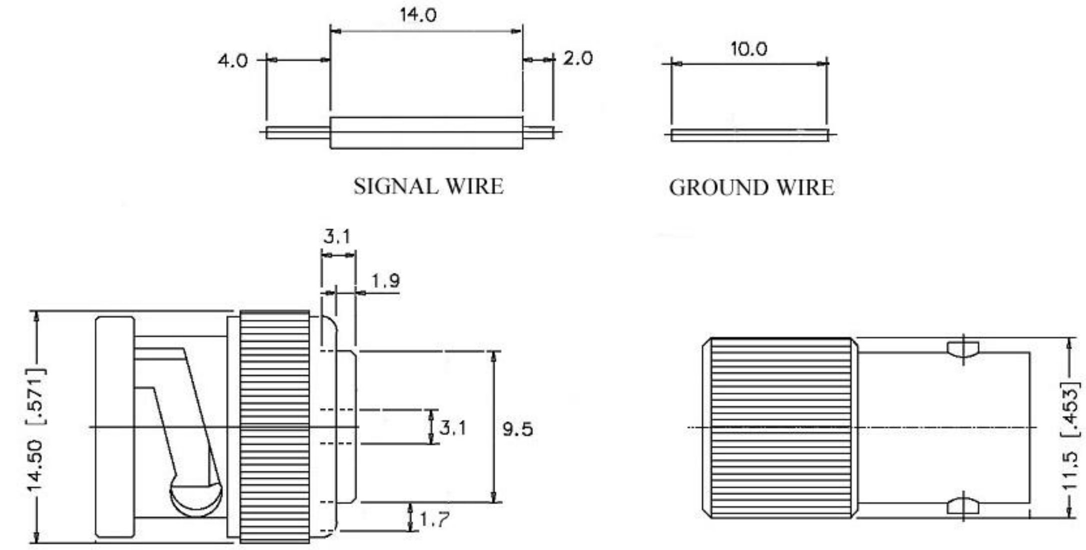


Fig. 6.2 BNC-connector interface, which standardised dimensions have tolerances added to them and other dimensions are measured. The dimensions of the cylinder are described in the text (modified from [6]).

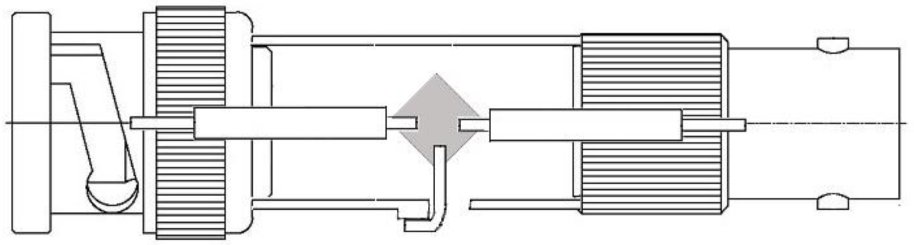


Fig. 6.3 A sketch of the BNC-attenuator interface, which has all the elements that the real attenuator will eventually have. The structure of this design will need some more research, so that it will become more suitable for higher frequencies.

The dimensions of this component are somewhat small, but still it is possible to attache the parts by using heat expansion methods. Some calculations were made, and they showed that, if the cylinder is heated up to 203 ^{o}C, it will expand enough to form a proper joint. The distress, which was achieved is 30 µm. The only problem that we may face during the manufacturing process is that will the length of 2 mm be enough for the maximum allowable tensile force of the cylinder.

Forces

It is required that component structure can withstand the maximum tensile load allowed for the cable, which will be joined with BNC-connectors. If this design is taken into volume production the force aspect is among the most important issues to be taken into consideration.

Material

Due to required performance of the attenuator the materials, which are used, should have at least good conductivity characteristics. Since the operating voltage range of the attenuator is not high, the insulation of the conductive parts is not required. The material is austenitic stainless steel AISI 303 (1.4305), which is plated with nickel. Some information concerning these materials is collected in Table 6.1

Table 6.1 Information about the AISI 303 and its coating material.

Alloying	%C: 0.02 – 0.05 %Cr: 17 – 19 %Ni: 7 – 26 %Mo: 2 – 5 Others: Mn, Si, Nb, Ti
Tensile strength	500 – 900 Mpa
Nickel thickness	0.8 – 1.3 μm
Electroless coating process to ensure even plating	

Environment

This attenuator should be used mostly at room temperature, but the required environmental requirements at this research limit the operating temperature from -45 ^{o}C to 85 ^{o}C.

Production

During this research we will focus to use different machining technologies to be able to produce a small series of specialised attenuators. 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 6 in details. Some other production aspects of the attenuator were explained rather extensively earlier in the chapter that describes the geometry of the attenuator.

The chosen BNC –connector limits the maximum frequency to 4 GHz, so to widen the frequency range, the easiest way is to change to connectors to SMA –connectors. In addition the attenuator microchip and some other dimensions should also be changed. The attenuator family that is used in this research has attenuators up to 30 dB and 8 GHz, so the change of the electrical characters is rather simple. SMA –connectors are smaller than BNC –connectors, which forces to change the dimensions of the body also.

Quality control

The quality of the attenuator could be measured by analysing its performance by using spectrometer, which informs clearly the rate of attenuation and the matching of the impedance. Other measurements are not so important.

Recycling

Connector body is made of nickel plated stainless steel (AISI 303) and the centre pin is brass or hardened copper alloy with gold plate and they could be re-used.

Costs

During industrial manufacturing special automated machines could be used for production. When specialised attenuators are manufactured, main costs consists of three main aspects:

- writing the required CAM-data for machining (attenuator's body).
- assembly of components and
- if BNC-connector's geometry should be manufactured high precision and multi-axis manufacturing technologies are needed.

6.2 Electrical requirements

Some specialised electrical requirements are presented in table 6.1.

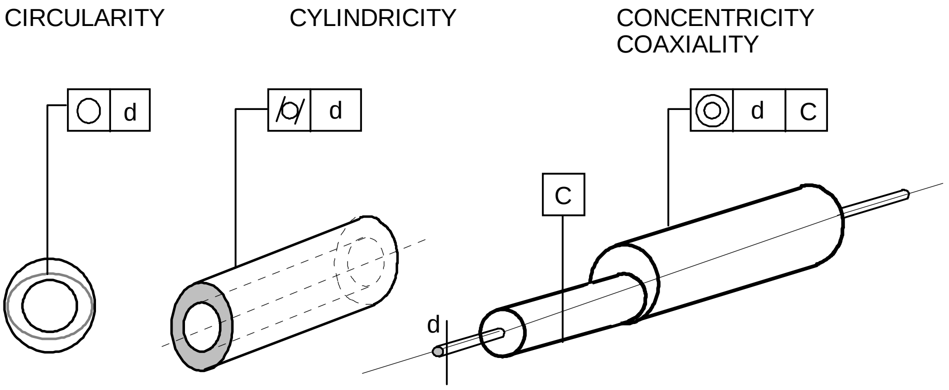
Table 6.1. Electrical requirements

Influencing factor	Material characteristics	Required value
Maximum power consumption	Radio frequency power	26 dBm
	Power	0.5 W
Contact resistance	Allowed oxide film and contaminants	< 2 mΩ
Insulation resistance	Resistance of the insulation	≥5 GΩ

The generated power is absorbed in the surrounding air or medium, which can be used to strengthen the convection of the heat.

6.3 Requirements for geometric tolerances

To ensure a proper attachment with BNC-connectors the shape of the body's cylinder is critical. To ensure the quality this component either circularity or cylindricity could be used. However, it seems that the requirement of concentricity is not necessary (see fig. 6.4).



CIRCULARITY

CYLINDRICITY

CONCENTRICITY
COAXIALITY

Tolerance area is inside two "circles".The distance between the outlines is "d". The true surface should lie between these two circles.

Tolerance area is defined with two "tubes". The true surface should lie between them. The distance between the tubewalls is "d".

Tolerance area is a fine tube (diameter is "d") inside which the theoretical centerlines of both cylinders should lie. A datum surface "C" is necessary.

Figure 6.4. Explanation of circularity, cylindricity and concentricity.

If soldering is used for joining the pin, materials solderability must be checked (related to possible platting of the pin).

Numerical estimation for the required dimensional and geometric tolerances could be estimated from table 6.2 according to the operating frequency range.

Table 6.2 Estimation of the required tolerance grade according to the operating frequency.

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	IT9-10

6.4 System requirements

After the component has been manufactured, some measurements can be made to find out how well the component works. If the component works as assumed, then it is possible to continue research and try to find better technical and electrical solutions for the problems that this research has shown. Earlier, in the chapter that described the facts of the production, some changes to the structure were mentioned. When the frequency range needs to be changed, the changes of such as the connector type must be considered.

7 MANUFACTURING TECHNOLOGIES

Machining, coating and heat treatment processes are used to manufacture the BNC attenuator. The advantages and disadvantages of the mentioned technologies are described briefly in the following.

Cutting

In this research the cutting is very simple task and it is only used to cut a standardized stainless steel pipe to its quantitative measurements. The production quality is not in an essential role in this stage of manufacturing, but of course the sawing edge must be at least of satisfactory level.

Machining

Machining, which in this research covers only drilling and carving, is usually cheap when the technique is used for rather simple tasks, such as drilling. In this particular design also a lathe must be used for carving that requires some fixing aspects to be taken into consideration. Disadvantages that are not essential in this project are the surface roughness requirements that are in some cases hard to meet.

Coating

The coating stage is most likely the most expensive process. The pipe made of stainless steel is plated with nickel in electroless coating process so that the thickness of the nickel is the same all over the cylinder. Coating process needs to be accurate so that the fittings match. The advantage of the coating is for example the fact that the whole part does not have to be e.g. gold, but some cheaper material. For instance in a high frequency applications the current flows near the surface rather than in the middle of the wire. Clear disadvantage is the costs of the process and the coating materials.

Heat treatment

The fittings made by the heat treatment are simple way to make attachments between parts. Some disadvantages are the precise dimensions of the parts and the heating or cooling systems that are needed. The method is not suitable for parts that have sensitive components involved, whose temperature range is limited. Heat treatment is possibly the second biggest source of costs after coating process. Possible alternatives for heat treatment attachments could be screw joints, which in this case is out of question, because the cylinder and the connectors can not rotate related with each other.

7.1 Assembly

At first the wires are cut and peeled, after which the gold plated connector pins are crimped at the ends of the two signal wires. The signal wire and the ground wire, which is totally pealed, are soldered onto the attenuator chip. The first assembly stage is shown in Fig. 7.1

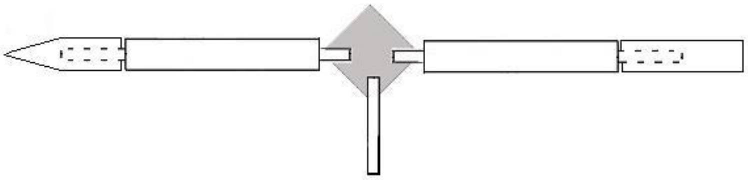


Fig. 7.1 At the first stage of the assembly the inner parts of the attenuator are attached to each other.

The next stage is to cut a stainless steel pipe, which diameter is standardized, to length that is described earlier in the report. The R_a value of the cut edge is not very critical. After cutting process a feed-through hole of a diameter of 2 mm is drilled in the middle of the cylinder.

The third stage is coating, which is done with nickel. The coating thickens the dimensions that should be taken into consideration when choosing the standardized pipe. A nickel coating is usually 0.8 – 1.3 mm thick and for this occasion the largest possible thickness should be chosen. The coating should be equally divided to all over the surface so electroless coating techniques should be considered.

The fourth and the fifth stages are shown in Fig. 7.2. The smaller cylinders of the connectors need to be cut apart. This stage is possibly the most critical, since the ground dimensions change dramatically. This stage will directly affect to impedance matching of the attenuator. After the cylinders are cut, some carving to the corners of the female connecter must be done to ensure a proper fitting with the cylinder.

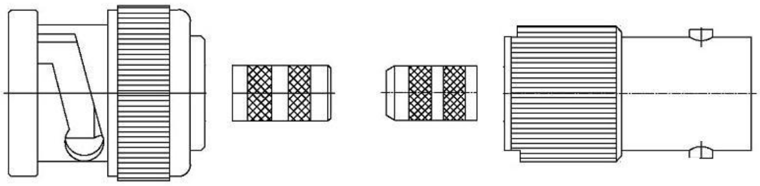


Fig. 7.2 The smaller cylinders of the connectors have to be cut apart and some carving to the corners of the female connector needs to be done.

The sixth and the last stage is to assembly these constructed parts together. This situation is shown in Fig. 7.3. The first thing to do is to place the attenuator inside the cylinder and feed the ground wire through the hole. After that the pins are fed inside the connector until they are locked. Parts are still loose and sensitive to any tensions and twits. The cylinder should now be heated up so that its dimension extends, and that its inner dimension can fit outside the grooves of the connectors. According to the fitting analysis made during this research one possible fitting could be e.g. &9.5 H7/p6, which has deviations quite close to the results of the theoretic optimum fitting (after surface coating). The tolerance analysis has been based on the allowed tensile force of the connecting cable and we have assumed that the fitting joint should be able to carry at least the same force. The cylinder can now be cooled down when they form tight connection with the cylinder. The last thing to do is to tighten the ground wire so that the chip touches the cylinder and minimizes the ground inductance. The ground wire should then be bend and glued onto the outer surface of the cylinder by using isotropic glue.

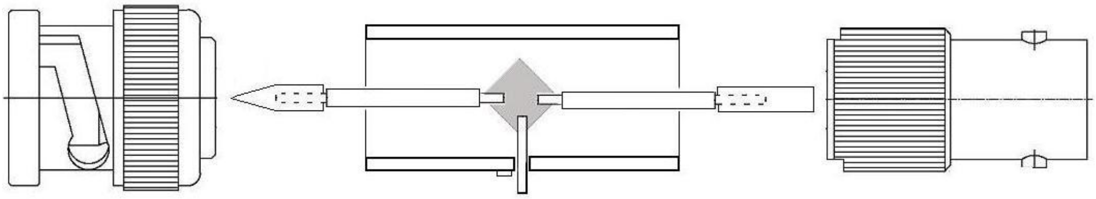


Fig. 7.3 All the parts that are included in the attenuator are shown in the figure.

8 DFMA –ASPECTS

8.1 Changes of the construction

The changes of the construction should be made at early stages of design to avoid expensive redesign. Usually these changes are related to the manufacturing technology, which is selected between the five basic options: welding, casting, machining, forming and sheet metal work. In some cases to ensure easy assembly, also changes of the construction are required.

Because the design of the attenuator has progressed during this research also some changes to its mechanical construction were needed to be able to keep the design simple and easy for manufacture. The construction changed quite a lot starting from the resistor network, which was intended to be the attenuator. As the knowledge of microwave electronics increased the chosen attenuator was changed to be a ready component that already has taken into consideration facts like impedance matching and reactive components of the resistances.

The cylinder between the connectors was at first planned to be welded, but the required high temperatures would have caused damage to the attenuator chip and to the plastic insulators of the connectors. A better way to attach the cylinder with the connectors was found, and the attachment was done by using fittings. In order to form a proper fitting, some carving to one of the connectors needed to be done.

In order to raise the maximum frequency and quality of the attenuator the BNC-connectors have to be changed into SMA-connectors and some other changes are required for right impedance matching. These changes are more essential in the next prototype and not so important at this stage.

8.2 Changes of the geometry

Most of these changes are made to make it possible to use standardised tools for machining or cutting. In some cases the geometry of the product should be changed to enable reliable fastening during manufacturing.

Some geometrical changes were done to the cylinder. At first the cylinder was decided to manufacture from a metal plate and then roll it to a cylinder. Some welding should also have been done to fasten the joints together. This method would have not guaranteed precise cylindrical geometries, which are required in order to attach the cylinder with fittings. The accurate geometric tolerances are achieved by using a standardised stainless steel pipe.

8.3 Choosing more acceptable material

In cases where only one manufacturing technology is needed, this subject is not critical - e.g. it is easy to find suitable alloys from different material groups for easy machining. In cases where two or more different manufacturing technologies are used, it is difficult to make the right compromise between competitive material properties - most difficult are those cases, in which both machining and welding or casting and welding are used.

For the future, if the frequency is raised and the connector is changed to SMA, it requires the body to be plated with gold. Gold plating is better for higher frequencies than nickel, and it therefore increases the costs of the attenuator.

8.4 Detailed changes of dimensioning and tolerances

The following changes, if not accurate, should be made directly to the technical drawings or other documents:

- Indicate where is the allowed “open dimension” for manufacturing inaccuracy.
- Avoid so-called double tolerancing.
- Write allowed dimensional deviations directly after the dimensions.
- Show the required bulk size and geometry, from which the manufacturing should start.
- Group dimensions according to sequential manufacturing stages.
- Use clear dimensioning, which does not lead to any further calculations during manufacturing or quality control to establish the required dimensions of the product

Changes to the dimensioning and tolerancing of the attenuator’s body were neccessary. Almost all BNC dimensions that were needed were not available, and they needed to be measured, which is why the tolerances are missing from the figures. The missing tolerances make the fitting challenging, because in a proper fitting the diameters of the cylinder and the connector must be almost equal. This is the reason, why large tolerances are not allowed. The dimensions of the connecter can be seen in Fig. 6.1.

9 FLOW CHART OF THE DESIGN AND MANUFACTURING STAGES

The Fig. 9.1 describes the design process of electrical attenuator. The flowchart starts from the upper left corner and continues mainly downwards. Some parallel actions are also used, because the design process is never straightforward. The flowchart demonstrates those stages of the design process, which have been at least somewhat important. Some stages are considered to be more important in MW-/RF-mechanics, which is why they are highlighted. Arrow pointing to volume production block is dashed, because the design stresses on prototype and mass production is not considered to be a case.

10 COST ASPECTS

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.

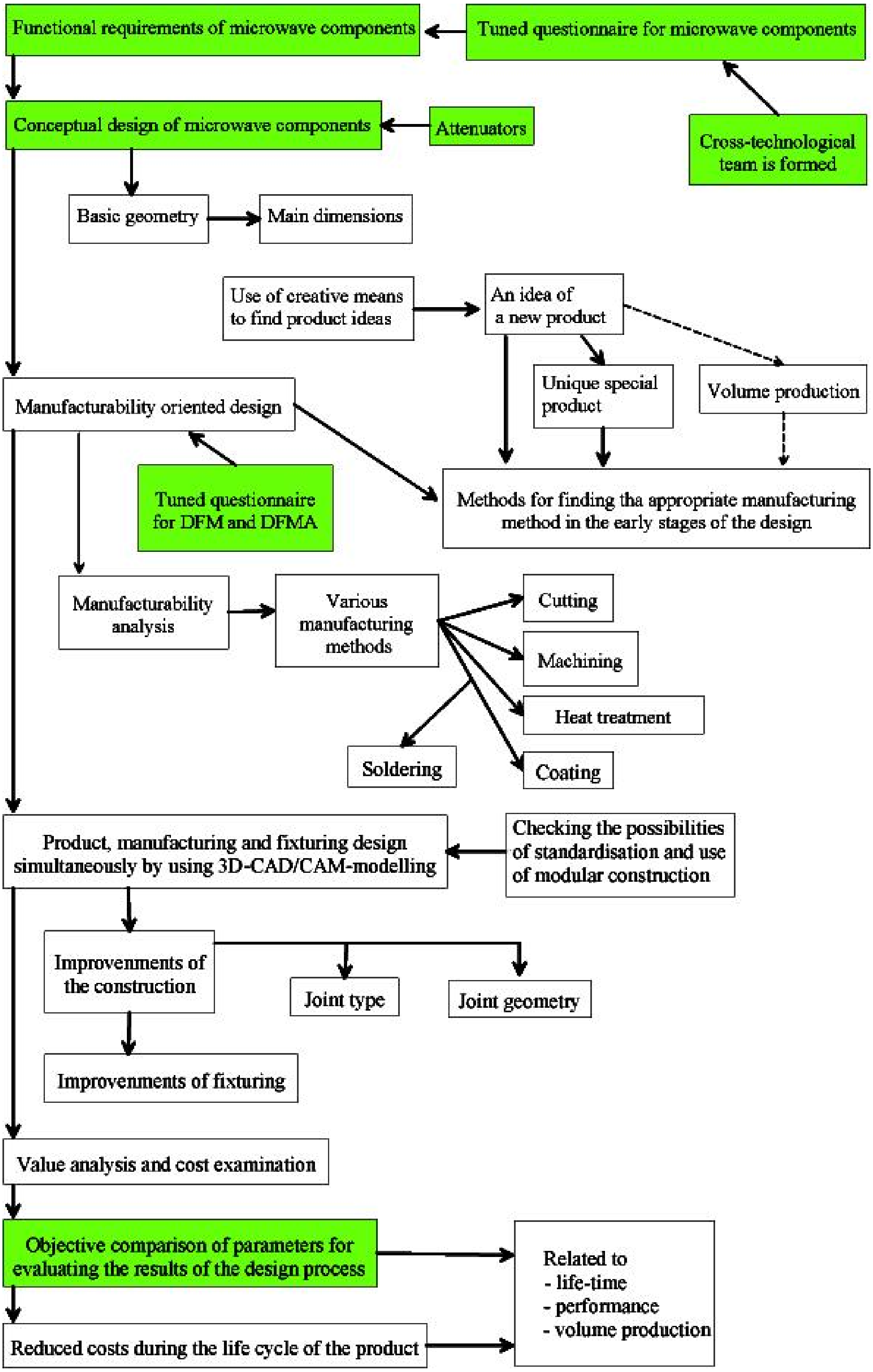


Fig. 9.1 Flowchart of the attenuator design process.

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 this attenuator design we do not need these types of expensive materials.

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 10, which means that the critical allowed dimensional deviations are 58 µm and corresponding required R_a is 12.8 µm. The critical geometry is the diameter of the connector edge and the inner diameter of the cylinder.

There are several commercial semi-products or half-finished materials (like e.g. cold drawn waveguide profiles, flanges or coated raw materials), which could be reasonable alternatives to an in-house start from scratch. For this product the cylinder can be made of a ready stainless steel pipe, which dimensions are standardized.

In MW-/ RF-device production the traditional principles to handle tooling costs, fixed costs, capital costs, labour costs, indirect labour 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. This attenuator construction should not withstand environmental loading. Typical loads are natural wear in which the attenuators are exposed to. The attenuator is in most cases installed and left like it is.

Regardless of technology - as long the dimensional accuracy is met with a standardised 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.

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 tuning 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 tuning. 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 attenuator device will be manufactured. We will use simple milling technology, because it is evident that some changes need to be done to the geometry of the attenuator, before it could commercialized.

Table 10.1 presents the most important cost factors for various groups of manufacturing technologies.

Table 10.1. Cost factors for various manufacturing technologies.

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 (important in this research)	- set-up times - tooling and fixing systems - programming (tool control)
Joining (important in this research)	- 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]
- weight [kg] and dimensions [m^3] 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 attenuation with one single dB-unit. After that the design procedure continues by calculating the cost ratios for 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 phase error and noise but yet gives the desired attenuation 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 optimising ratios are as follows: costs versus attenuation, costs versus noise figure and costs versus phase error. [5]

11 SUMMARY

This research was somewhat difficult at the beginning of the project, because some characteristics of the microwave components were not freshly in mind. Due to this the construction of the attenuator needed to be changed in order to raise the frequency range much higher. Unfortunately some defects in the microwave attenuator could not be fixed and they had to remain in the design. The possible next prototype would be a little bit different and function better, for example the change of connector type would be an issue.

However, this research gave good information concerning microwave mechanics and complete design of devices such as attenuators, and therefore this whole course was very educative. Reverse engineering, which is described in this paper, was only one of the designing methods, and although covering only this particular method, it gave new ways to think different aspects concerning designing and manufacturing of electrical microwave devices.

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