CHAPTER III

ADVANCES IN MANUFACTURING TECHNIQUES FOR UHF RFID ANTENNAS

AVANÇOS EM TÉCNICAS DE FABRICAÇÃO DE ANTENAS UHF RFID

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ABSTRACT

Radio Frequency Identification (RFID) is a technology which can replace a bar code for various applications such as access control, logistics and security management. The RFID system in the Ultra High frequency (UHF) range has the advantage of communication at long distances between the RFID reader and the RFID tag, in addition to the ability to identify multiple tags. Therefore, the UHF RFID system is widely used to identify a wide variety of items and in large volumes, which requires a large number of tags. Consequently, the cost of tags for UHF RFID systems has become an important issue for the implementation of the systems. As a result, different technologies are feasible in different scenarios for volume, processing time, ease of use, cost and applications. In this paper, evaluations and comparisons between different antenna-manufacturing techniques are presented. Characterization methods for each process and a cost estimate were developed in order to obtain the productivity index and to indicate the costs required for the production of antennas for UHF electronic tags (UHF RFtag).

Keywords: RFID. Antennas. UHF. RFtag. Manufacturing Techniques.

RESUMO

A identificação por radiofrequência (RFID) é uma tecnologia que pode substituir o código de barras em diversas aplicações, como controle de acesso, logística e gerenciamento de segurança. O sistema RFID na faixa de Ultra High Frequency (UHF) tem como vantagem a comunicação a longas distâncias entre o leitor RFID e a etiqueta RFID, além da capacidade de identificar múltiplas etiquetas. Portanto, o sistema UHF RFID é amplamente utilizado para identificar uma grande variedade de itens e em grandes volumes, o que requer um grande número de etiquetas. Consequentemente, o custo das etiquetas para sistemas UHF RFID tornou-se uma questão importante para a implementação de sistemas. Como resultado, diferentes tecnologias são viáveis em diferentes cenários em termos de volume, tempo de processamento, facilidade de uso, custo e aplicações. Neste artigo são apresentadas avaliações e comparações entre diferentes técnicas de fabricação de antenas. Métodos de caracterização de cada processo e estimativa de custos foram desenvolvidos a fim de obter o índice de produtividade e indicar os custos necessários para a produção de antenas para etiquetas eletrônicas UHF (UHF RFtag).

Palavras-chave: RFID. Antenas. UHF. RFtag. Tecnicas de Fabricação.

1 INTRODUÇÃO

Radio frequency identification (RFID) is a technology that allows wireless and contactless identification. This identification is possible with tags (RFtags) composed of the chip that is connected to an antenna (metallic geometry on a substrate) both located on the tag itself (Finkenzeller, 2014). This set is also known as “Inlay”.

The information is stored in the chip's memory and read by RFID readers or portals. RFtags can use different frequencies of the electromagnetic spectrum, for example 125 kHz (LF-Low Frequency), 13.56 MHz (HF-High Frequency) or 915 MHz (UHF).

The frequency band most used for logistics applications in general is UHF (Ultra-High Frequency). In Brazil, the frequency range authorized for use is from 902 to 908 and from 915 to 928 MHz (RAO et al., 2005).

The reading range of RFtags is also directly related to the chip's sensitivity, the more sensitive it is, the less energy is required for reading. However, as most tags are disposable, the cost becomes mandatory and obtaining an antenna with satisfactory performance and minimum cost is essential.

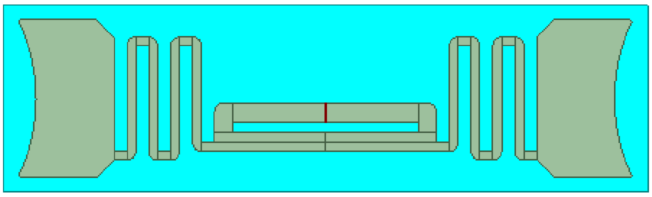
There are several manufacturing processes for UHF antennas (COLELLA et al., 2017; KAHN et al., 2015; SIPILÄ, 2016); however, there are significant differences between the investment required for production (CAPEX), antenna-manufacturing cost (variable cost) and the maximum achievable performance in each technology.

In this paper, a comparison will be presented between the main antenna-manufacturing technologies for UHF RFtags considering these variables.

2 ANTENNA MODEL

To create the cost estimate for all processes, a new antenna model was developed, as shown below (Figura 1) and entitled “JBF model”. This antenna has approximate dimensions of 14 × 70 mm, resulting in 4.32 cm2 of metallic area referring to the geometry of the metallic area. The chip used was the Monza R6 from Impinj (IMPINJ, 2023).

Figure 1 – JBF model antenna.

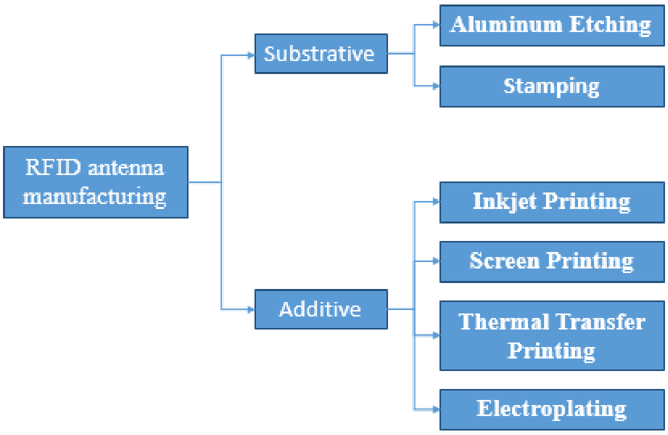


Source: The authors.

3 UHF-RFID ANTENNA-MANUFACTURING PROCESSES

For antenna manufacturing, different processes can be employed. Below are the processes considered in this article (Figura 2).

Figure 2 – Antenna-manufacturing processes.



Source: The authors.

3.1 Aluminum Etching

Currently, it is the process used to remove metal from structures using chemical products, widely used by the electronics industry to manufacture printed circuit boards, being the most used in the manufacture of UHF RFID antennas (EE, 2023; EL, 2023; EPI, 2023), consisting of three stages:

3.1.1 Stage 1: Applying the mask or printing the antenna design on the metallic layer.

This step defines the geometry of the antenna to be manufactured, using different printing techniques such as: photoresist application (photosensitive resin) or direct printing of curable ink by ultraviolet radiation (UV).

The application of photoresist on the metal can be through lamination or screen printing. In lamination, the photoresist (on film) and the material to be laminated (substrate containing the aluminum or copper layer) pass through two cylinders that unite the materials due to the pressure and temperature applied by the lamination equipment. After application, the photoresist is exposed to UV light. The exposure is made through a mask containing the geometry of the antenna to be recorded on the photoresist (photolith). The unexposed part is later removed using a solution (sodium carbonate - $Na2CO3$ or another developer) finishing the mask application process.

In the screen printing application, liquid photoresist is used instead of film in which it is applied through a mask or stencil, using screen printing equipment and then cured before chemical removal of the metal. In the direct impression of the antenna design on the metallic layer, the most used technique is rotogravure. In this technique, a cylinder with the antenna design (cliché) is impregnated with ultraviolet-curable ink that is transferred rotatively to the substrate, through pressure. The process is simple, but the degree of control and precision of the cliché, which contains dimensions of the order of 100 μm, are not trivial, therefore, there are not many manufacturers of these printers available on the market.

Another method of direct printing is by rotary screen printing or Rotary Screen Printer (SPG, 2023), printing is also rotary as in gravure printing, but instead of the cliché, a cylinder-shaped screen or stencil is used, however, the offer of equipment it is limited and costly.

3.1.2 Stage 2: Removal of the metallic layer not protected by the mask.

Material that has not been protected by the mask is removed using a corrosive solution. The removal rate is controlled by the time and temperature the material is immersed in the solution and the concentration of the solution used. In RFID antenna applications, aluminum is usually used as a metal to manufacture the antenna due to its low cost, with a thickness of approximately 10 μm, typically taking less than 1 minute to remove.

3.1.3 Stage 3: Mask removal and cleaning: both processes are done chemically.

For the removal of the mask, potassium hydroxide or another Stripper (remover) suitable for removing the ink or photoresist is used. In the cleaning process, a water rinse is performed to remove contaminants from the previous steps.

In order to obtain the productivity and consequently the necessary low cost, all three steps need to be performed in reel-to-reel equipment (RTRMGC, 2023). In the case of equipment for the manufacture of aluminum antennas over PET (Polyethylene Terephthalate), a roll of laminate (a roll of film containing a 10 μm layer of aluminum on a 50 μm PET substrate) and a roll of PET aluminum antennas comes out. This technology is still the most competitive in terms of cost, but it has limitations. Table 1 shows the main advantages and disadvantages of this process and Table 2 shows a summary of the best technological alternatives.

Table 1 - Main advantages and disadvantages.

Advantages	Disadvantages
Very low cost per antenna	Subtractive method
Production equipment cost is medium to high	Generation of metal removal residues
High production capacity (Reel-to-Reel)	Use of chemicals that need to be recycled
	Aluminum thickness limited by laminate (~ 10 μm)
	Print-defined quality

Source: The authors.

Table 2 - Technological alternatives.

Stage	Technology	Evaluation
Print	Photoresist lamination	Very complex and high cost - in disuse
	Photoresist screen printing	A reel-to-reel screen printer is needed in that case it may be better to print a layer of conductive ink directly by screen printing.
	Rotary Screen Printing	Very limited supply of equipment and high cost
	Rotogravure	Most used - but the supply of good resolution equipment is limited.
Removal	Iron Chloride	It can be regenerated, reducing cost.
	Ammonium hydroxide	The use is increasing because it is currently the solution most used by the electronics industry in the manufacture of PCBs.

Source: The authors.

The main variables involved in this process are the method of printing the antenna design (lamination, screen printing or rotogravure), the chemical solution used in the removal and the time of chemical removal, which depend on the speed and/or length of the line. As there is a minimum printing and removal time, for higher production rates it is necessary to increase the length of the equipment or line.

The corrosive solution, depending on the chemical reagent used and its concentration, may or may not be reused, in addition to defining the process speed.

The possibilities of solutions used for aluminum corrosion are mainly phosphoric acid, acetic acid, nitric acid, iron chloride, ammonium hydroxide and hydrochloric acid. The most used industrially are iron chloride and ammonium hydroxide, both are filtered, have their concentrations adjusted continuously and are recirculated for maximum use. Iron chloride and ammonium hydroxide are also used in the manufacture of printed circuit boards; these solutions remove both copper and aluminum. The quality of the generated antennas depends on the print quality of the standard and the main raw material is PET/aluminum laminate.

3.2 Stamping/Cutting Manufacturing (Cutting System)

A "cliché" or knife is used, which contains the design of the antenna to be manufactured, which is pressed against the underlying laminate by cutting the design of the antennas in it (ACS, 2023). The adjacent material, which is not part of the antenna, is removed while the laminate of the lower layer remains intact leaving a conductive pattern in the laminate. Table 3 shows the main advantages and disadvantages of this process.

Table 3 - Main advantages and disadvantages.

Advantages	Disadvantages
High speed/production capacity	High equipment cost
Process simplicity	Subtractive method
Single input and dry process	

Source: The authors.

The quality of the antenna basically depends on the cutting tool. The most important process variable is the cutting speed. The process is completely automatic.

3.3 Inkjet Printing

Piezoelectric or thermal print heads and inks compatible with these print heads are used to print the geometries on the substrates (MJP, 2023; PIXDRO, 2023; YANG, 2007). It is possible to print thin layers, between 1 μm and 3 μm in thickness, being necessary that the metallic particles in the ink have dimensions in the order of 100 nm to 500 nm (FERNANDES, 2018).

All final properties of the material developed depend on the quality of the paint, such as evaporation, homogeneity of the film, electrical properties, among others. In general, for the formulation of conductive inks, the most used materials are particles and silver nanoparticles dispersed in an appropriate vehicle, allowing good control of ink ejection.

Thus, the control of the synthesis of nano particles is important for the development of the ink. Copper can also be used in the formulation of conductive paints; however obtaining a paint with this material faces the difficulty of its rapid oxidation in the ambient atmosphere (FERNANDES, 2018).

The main advantage of using inkjet printing is that it is a digital technology in which each antenna can be unique without incurring higher costs. Inkjet printing is currently the most researched technology in the field of flexible electronics. It is capable of printing very small lines (up to 10 μm) with excellent resolution, but it still presents several challenges, as it is complex to maintain dense metal particles in stable suspensions.

Another factor to be considered is that these metallic particles, even in the case of nano particles, tend to clog the nozzle during the blasting process.

A potential alternative is the addition of conductive polymers; however, this alternative is severely limited by the low concentration at which the conductive polymers are soluble. Another point to note is that the uniformity of the printed line is poor due to the nature of the points of the arrangement and the kinetics of the surface tension.

In the specific case of the production of RFID antennas, the conductivity necessary for the antennas to have basic performance is relatively high, and conductive polymers do not normally reach the desired conductivity range (FERNANDES, 2018). Table 4 shows the main advantages and disadvantages of this process.

Table 4 - Main advantages and disadvantages.

Advantages	Disadvantages
Additive method	High input costs
Flexibility	Investment in equipment still high
Easily modified print patterns	In practice, it is very complex to print layers with thickness greater than 1 μm
	Technical difficulties for large-scale application

Source: The authors.

Regarding the process variables, the quality of the printed antenna will be directly related to the characteristics of the formulated ink and to the characteristics of the cartridges and heads used for printing. The drying of the paint, spreading, adequacy between properties of the paint and substrate are factors that must be considered in this technology.

3.4 Screen Printing

It is a very traditional, versatile, low-cost technique and widely used by the industry. It is a direct printing technique, which allows application on different types of substrates and the use of inks that have larger particles (CTTR, 2023).

Screen printing is a robust, simple process and can be easily automated. The printing method is direct and additive. In this process, a paint or paste of high viscosity is pressed on a substrate through a mold (canvas) with the aid of a squeegee. The squeegee is positioned on the screen at an angle of 45°.

The speed of ink application on the canvas plays an important role in the amount of ink deposited on the substrate. When the application speed is very high, the ink stays in contact with the screen for a short time and does not fill the opening; on the other hand, low application speeds result in excessive transfer of ink, generating waste. Table 5 shows the main advantages and disadvantages of this process.

Table 5 - Main advantages and disadvantages.

Advantages	Disadvantages
Low investment	Material losses
Additive method	Difficulty in depositing thicknesses below 8 μm -10 μm
	Not suitable for prototype printing

Source: The authors.

With regard to process variables, the quality and characteristics of screen printing are dependent on factors such as ink viscosity, substrate and ink surface tension, printing speed, application angle, mesh size and material. In this process the stencil defines the print quality. It is an additive method, thus generating less waste of materials, these being related to the application of the paste on the canvas, since not all applied ink is used for printing.

For volume manufacturing, the manufacturing line needs to be adapted for the reel-to-reel process. The speed of the line is directly related to the size of the stencil used, but nowadays there is automatic roll-to-roll equipment that uses large masks, with high production capacities.

3.5 Thermal Transfer Printing

It is a digital technology where the antenna is printed by heating and pressing the heads containing thermal needles on the substrate containing the metallic film (Cu or Al), which is released at the heated points (LTA, 2023).

Each print can be unique, allowing the production of prototypes with fast cycles, as well as the production of a small number of units, requiring only a good resolution thermal transfer printer (600 dpi).Table 6 shows the main advantages and disadvantages of this process.

Table 6 - Main advantages and disadvantages.

Advantages	Disadvantages
Capital investment virtually nonexistent or very low	Conductive ribbons costs
Prints on paper and different types of substrates	Subtractive method
Flexibility and ease of use	

Source: The authors.

In this type of process the variables are simpler compared to other types of printing. The print quality basically depends on the print head, the ribbon and the substrate.

3.6 Electroplating

It is an additive process, where the geometry of the antenna is printed on the substrate with a minimum layer of conductive ink that will serve as a seed for the subsequent electrodeposition of copper in chemical baths (the seed needs to be conductive to apply the electric field and the current that attracts and deposits metal ions) (FAP, 2023).

The thickness of the final layer deposited is controlled by the electric current, the time, temperature and concentration of the deposition solution. The limitations of this process are the adherence of the deposited material, which depends a lot on the adhesion of the paint (seed), the seed layer also needs to have a minimum conductivity so that the deposition is uniform and uses chemicals that need to be recycled.

For comparison purposes, the leaf resistance (superficial) of the seed layer needs to be in the order of 300 mΩ/□ (milliohms/square) (BHORE, 2013), while the antenna metallic layer needs 30 mΩ/□. In general, carbon or silver based paints are used for the seed and then a thicker layer of copper is deposited by electrodeposition. Table 7 shows the main advantages and disadvantages of this process.

Table 7- Main advantages and disadvantages.

Advantages	Disadvantages
Additive method	deposited metallic layer
Thickness control	Adherence of deposited material depends on seed adherence
Good quality of the deposited metallic layer	Use of high amount of chemicals
	Needs seed printing using conductive ink
	Oxidation of deposited copper

Source: The authors.

The main variables of this process are the quality of the seed (conductivity, thickness, uniformity and adhesion), concentration and temperature of the deposition solution, the size of the chemical baths or the length of the equipment, the larger the equipment, the greater the production capacity . The process also needs to be reel-to-reel for the manufacture of antennas.

The antenna design needs to ensure electrical contact between all antennas for current flow and this contact is subsequently cut when the antennas are individualized. In general, the equipment is modular and with the addition of more modules (baths) the capacity increases.

4 COST ESTIMATES

Table 8 shows a summary of the relative cost estimates per antenna for the different routes surveyed, taking as a reference the cost of the cheapest antenna in the current market, which is obtained by chemical removal.

Table 8 - Summary of relative cost estimates by antenna.

Manufacturing process	Relative Cost
Aluminum Etching	1
Inkjet printing	2.3
Screen Printing	3
Thermal Transfer Printing	3.9
Electroplating	3.2
Cutting System	1.4

Source: The authors.

4.1 Aluminum Etching

It is the most used process, which dominates the world market, produces the best quality antenna due to the thickness of the aluminum layer. The cost of equipment is average, but there is a significant difference depending on the company/ country of origin of the acquisition, being lower for Chinese equipment.

The quality of the antenna is defined by the quality of the mask impression. The variable cost is dominated by the cost of the main raw material, that is, the Al + PET laminate (about 90% of the total) with a reduction in the total manufacturing cost of more than 10% with a triple of the volume.

As the process is similar to the manufacturing of printed circuit boards, using the same chemicals, a way of reducing costs may be to collaborate with local PCB manufacturers.

Another cost reduction alternative would be to reduce the PET layer from 50 μm to 38 μm. There is this option on the market, but the thinner PET weakens the substrate when curing the chip solder during tag assembly.

The thinner PET is less resistant to temperature, making it easier to wrinkle. It should be combined with fine-tuning of the process and perhaps the use of a faster curing adhesive for soldering the chip.

4.2 Cutting/Stamping Manufacturing (Cutting System)

It is an extremely simple process that uses only one raw material, in this case the same one already used by other techniques such as aluminum etching, and demands just a fully automatic equipment.

The cost of the equipment is high, consequently this makes the initial investment very high, and however, as the production capacity is very large, the cost of amortization, part becomes attractive for large volumes. At a maximum speed of 40 m/min, the equipment is capable of producing antennas of the JBF model (25 mm pitch) indicated in Fig. 1 at a rate of 32.000 pieces/hour. Thus, a single piece of equipment is capable of producing 200 million pieces of this model in one year, operating in three shifts.

4.3 Inkjet Printing

The highest costs, respectively, are: the printer, laminate and ink. What makes difficult the commercial viability of this technology is not the cost of ink, it is the cost of printers, since there are no printers or industrial heads with sufficient speed for high volume production at low cost.

The cost of the equipment depends on the type, size and number of nozzles on the head. However, even a printer with a high number of nozzles would be able to print only about 10 million antennas/year, this increases the investment required for volume production. This technique could compete with aluminum etching if faster printers/print heads are developed.

The substrate cost also has represents a reduction potential, paper substrate can be used, but the paper needs surface treatment to improve ink adhesion, it also needs to be tensile resistant to resist the roll-to-roll manufacturing process and resist temperatures heat treatment (paint curing).

If PET substrate is used, despite not containing the metallic layer, as in the case of aluminum etching, the PET surface needs extra treatment to ensure good adhesion and definition of the impression. This makes the substrate practically the same cost as PET + Al laminate.

Labor and energy costs are very low in this technology, the machines are automatic and the energy consumption is low, so these costs do not interfere in the comparison of technologies. Rotogravure printing can make the process competitive, but printer adaptation/development is needed.

4.4 Screen Printing

It is a simple and commonly used technique in the electronics industry. Investment in equipment is low and production capacity is high. In screen printing, due to the presence of a non-conductive vehicle, high percentages of solids, between 50% and 70% are required to produce paints with adequate conductivity and viscosity.

The vehicle is made up of solvents and additives, which are various chemicals used to give the necessary and desirable properties for the printing process where the results are satisfactory only for percentages from 60% silver. This high percentage of silver means that the costs of screen printing pastes/inks are significantly higher compared to inkjet printing inks.

To reduce the cost, an alternative is to reduce the thickness of the ink layer referring to the irradiating element, being possible through adjustments of the printing process and stencil, reaching 8 μm.

The disadvantage is that through this technique it is not possible to print very thin layers, smaller than 8 μm to 10 μm, for example, which increases the consumption of raw material and consequently the cost.

The cost of the substrate can be considered the same used in the inkjet technique, including the same considerations of surface treatment and resistance. Likewise, screen printing can be done on paper or PET.

Labor and energy costs are very low in this technology, machines are automatic and energy consumption is low, so these costs do not interfere in the comparison of technologies.

4.5 Thermal Transfer Printing

The cost of this printer depends on the speed and resolution and the cost of the ribbons depends on the quantity to be purchased.

The cost of the substrate can be considered the same as the previous techniques. This printing technique can be used on different PET or paper substrates and can obtain a printed metal layer (aluminum) of only 0.5 μm thick with excellent quality.

4.6 Electroplating

Most suitable technique for depositing thicker layers. The cost of electroplating equipment is high. There are several manufacturers of electro deposition equipment, but for deposition in plates or mechanical parts, reel-to-reel equipment is not used, they would need to be adapted.

The process control needs to be very good due to the low thickness. An antenna for UHF tags requires only 2 μm of copper to present ideal radiation characteristics.

This requires equipment with excellent control of concentration, pH and temperature, that is, well above the existing equipment in the national market.

The advantage is that the equipment has a very high production capacity, can be used for the manufacture of antennas for LF and HF tags as well, since it is possible to deposit thick layers, such as 10 μm of copper, just by increasing the deposition time.

As for the variable cost, it ends up being high also because it is necessary to print the layer from seed and then deposit the copper. Even working with chemical replacement and filtration, there is consumption and costs of effluent treatment.

5 CONCLUSIONS/FINAL CONSIDERATIONS

The chemical removal technique proves to be a viable option, since it presents the lowest manufacturing cost per antenna and the most commercially viable process for producing high volumes.

Due to the similarity of processes, materials and equipment, an alternative would be the manufacture of antennas by national manufacturers of PCBs.

Conductive inks, both for inkjet printing and screen printing, have numerous advantages for use in the area of flexible electronics, however, they are not commercially competitive with the technology of chemical removal of aluminum for the manufacture of UHF antennas for RFtags. This is mainly because there has not been enough evolution of the print heads. Even using the largest print heads available on the market, the speed is low, so for large volume production it is necessary to use many print heads or printers, increasing the cost of the equipment. An alternative that can make the use of inks feasible is rotogravure printing instead of inkjet. For that, it is necessary to adjust/adapt a printer, and the plate must be of high definition, about 0.1 mm.

New manufacturing technologies should be considered such as thermal transfer printing and stamping, which can become competitive in some scenarios.

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