New production facility for Air Motion Transformer production by Mundorf

Dieter Michel

Mundorf, the Cologne-based audio components manufacturer, has been considered *the* industry supplier when it comes to top quality in the sector of high-quality components for crossover construction – Mundorf coils and capacitors are considered premium products throughout the world and are used in both high-quality high-end audio and studio loudspeakers and in numerous notable PA systems (see also reports in PROSOUND). Mundorf has also been successfully developing and producing high-quality electro-acoustic transducers – the Mundorf Air Motion Transformer (AMT) – for about 15 years. The most well-known high-end user may be Burmester, the high-end Berlin-based manufacturer, which is known for its top manufacturing and sound quality standards. At this point, however, we are more interested in the versions for professional use: The Mundorf ProAMT series is one of the rare representatives of the magnetostatic transformer principle that easily meets the demands of professional sound systems in terms of power handling and maximum sound pressure level – and not just since today. After Mundorf solved the typical problems of the magnetostatic principle with partly patented processes, an increasing number of manufacturers now prefer the Mundorf ProAMT to the classic compression driver. Mundorf was able to manufacture the components of an Air Motion Transformer, i.e. the magnetic structure and, in particular, the film diaphragm, at quantities of – depending on the model – 500-1000 pieces in the manufacturing plant to the tightest tolerances and planned to convert the manufacturing process to an industrial production process as the next step. That means it should be possible to manufacture significantly higher quantities. The following article explains the challenges/difficulties involved in this conversion and in any company growth.

During a visit to the new production facility in Hürth near Cologne, Managing Director Raimund Mundorf explained to me that this conversion to industrial production is no Sunday stroll. In practically all process steps, close attention must be paid to ensuring that all manufacturing tolerances of the end product remain within the specified limits, even with larger production batches – a requirement that can often only be met by using the most sophisticated technology. To briefly recap first: An Air Motion Transformer works on a similar principle to a magnetostat, but has several advantages over the latter. In a classic magnetostat, a flat membrane radiates the sound directly. Several conductive tracks are usually applied to the insulating membrane foil. This membrane is located in the field of a strong permanent magnet, whose field lines run parallel to the membrane surface. A current flow through the strip conductors causes a force in the magnetic field that acts perpendicular to both the direction of the current flow and the direction of the magnetic field; in this case perpendicular to the membrane surface. This deflects the membrane and allows it to emit sound.

The film diaphragm, strip conductors and magnetic field components are also present in an Air Motion Transformer; however, the geometry is different, which is advantageous in terms of efficiency, among other things. The diaphragm is folded up in a wave-like pattern and the strip conductors run in a meandering pattern so that they come to rest on the flanks of the folds. The current flow runs in the opposite direction for neighbouring flanks or strip conductors. The magnetic structure has been designed in such a way that the field lines are perpendicular to this diaphragm structure. The current flow through the strip conductors now also induces a force that is perpendicular to the current flow direction and the magnetic field. Due to the folded structure of the diaphragm and the arrangement of the strip conductors, the current flow causes the flanks of the diaphragm to move towards or away from each other, thus pushing the air out of the folds or sucking it in. Here too pressure differences are generated that ultimately lead to sound radiation. In contrast to the direct radiating diaphragm, however, the effective diaphragm surface is larger, ultimately resulting in greater efficiency and a higher maximum sound pressure level, as is required for use in professional sound engineering.

In contrast to a compression driver, an Air Motion Transformer gets by without a pressure chamber (high-speed transformer). This has the advantage that, even near the diaphragm, the sound pressure and velocity is not as high as inside a compression driver, which can produce distortion at higher levels – simply due to the non-linear properties of air. At the same time, the effective surface of the current-carrying strip conductors is larger than that of the voice coil of a compression driver, meaning it is easier to dissipate the heat generated during high-load operation. In fact, even forced cooling by a fan, which is very difficult due to the narrow geometry in a compression driver air gap and, to the best of my knowledge, has only actually been done in one commercially available system and hasn‘t become prevalent.

One application in professional sound engineering, which should be the natural domain of Air Motion Transformers, so to speak, is their use as tweeter systems for line arrays. Here, the loudspeaker developer must ensure, with a certain amount of effort, that the sound flow generated by one or more circular or ring-shaped driver diaphragms is transformed into a rectangular sound outlet in such a way that results in conphase emission over the entire surface. In an Air Motion Transformer, this conphase emission is already a result of the working principle of the transformer, meaning that the developer does not have to do anything at this point.
The devil was in the details when it came to developing an Air Motion Transformer to meet professional standards. Of course,

Raimund Mundorf during our conversation at the company's headquarters in Cologne

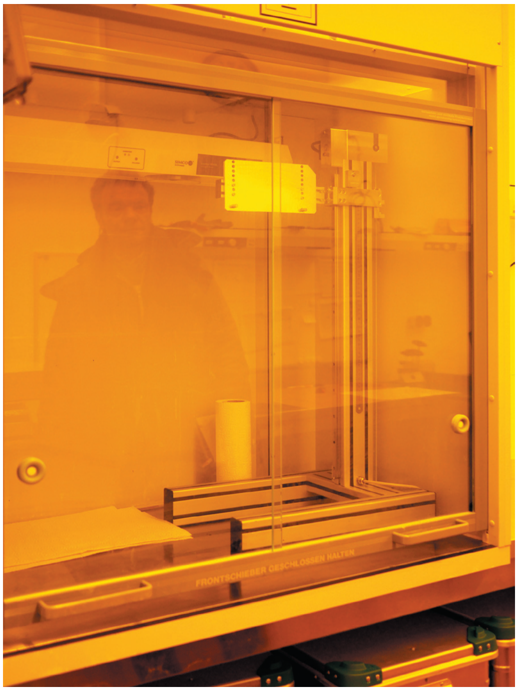
the geometry of the magnetic structure and the shape of the sound outlet in the pole plate affect performance – as do the size and damping of the volume behind the diaphragm. However, this shouldn‘t be the subject of this article as the basic problems have already been solved.

Industrial production

The big challenge when it comes to setting up industrial production is in scaling all the production steps that already work on the scale of a manufacturing plant in such a way that production is at a consistent level of quality, even at larger quantities. When it comes to the magnetic structure, you can still outsource that.
Diaphragm production, however, is the absolute key technology when it comes to AMT manufacturing; at the same time it has so many quality-influencing parameters that scaling up production is a time-consuming and resource-intensive process. After all, this kind of production is breaking new ground – no finished production facilities are available to buy and there are just as few service providers with whom you can outsource such production.

Diaphragm production

The process for manufacturing an AMT diaphragm involves several steps. The diaphragm itself is made from a highly temperature-resistant Kapton film, a polyimide plastic that remains thermally stable up to 230°C in continuous operation (or up to 400°C for a short time). An aluminum film is applied to this Kapton core, from which the strip conductors are later uncovered in a photochemical process. Aluminum is used here because, with a value of 71.8 Ω·kg/m², it has the lowest mass-specific electrical resistance – with the exception of alkaline earth metals, which are not chemically stable in open air. At 149 Ω·kg/m², the value for copper is significantly higher – strip conductors made from aluminum are therefore significantly



Left: Device for immersion coating the diaphragm film with photoresist – shown without cuvette and film. The coated film is tempered in heating cabinets (right), each of which has its own temperature sensor. By the way: Nothing is wrong with the white balance in these and the following photos – rather, all work related to the undeveloped, UV-sensitive photoresist is carried out in yellow light, which contains no short-wave parts that could pre-expose the resist layer.

lighter than those made of copper for a given geometry and nominal impedance. However, you cannot buy Aluminum-Kapton film as a ready-made product, says Raimund Mundorf, meaning it has to be custom made.

The details of the manufacturing process also depend on the aluminum alloy because strip conductors are part of the vibrating system and, as such, are also subjected to mechanical loads and stress. Although the deflections of a tweeter are not particularly large, the frequencies are relatively high, meaning manufacturers need to pay a certain amount of attention to the subject of material fatigue, particularly if the loudspeaker component is to be used for many years in a professional environment. The fact that Mundorf succeeded in meeting these requirements regarding the durability of the diaphragm is shown by applications such as in the in-house system at the Royal Albert Hall. Mundorf AMTs have been in use here without any problems since 2012. Mundorf AMTs have also been in continuous daily use in clubs such as Kulturfabrik Kofmehl in Solothurn without failure for almost a decade now. To prevent problems caused by material fatigue from occurring in the first place, only special aluminum alloys can be used. Of course, they must also be available on the market in the first place in order to use them for AMT diaphragm manufacture.

Mundorf cooperate with a service provider when it comes to the production of aluminum and Kapton film. When batches of the required aluminum alloy with particularly high tensile strength and break resistance are available on the global market, the service provider immediately buys what is required for the year and puts it into storage. This ensures consistent quality of the AMT diaphragms, even with regard to the properties of the base materials.

A particularly important but critical process step is the production of the strip conductors. This is done using an etching process from the semiconductor industry, which could also be used in the production of VLSI chips for integrated circuits. As no finished,

View of the heating cabinets

UV exposure unit with vacuum suction of the exposure mask


System for developing and washing the exposed film

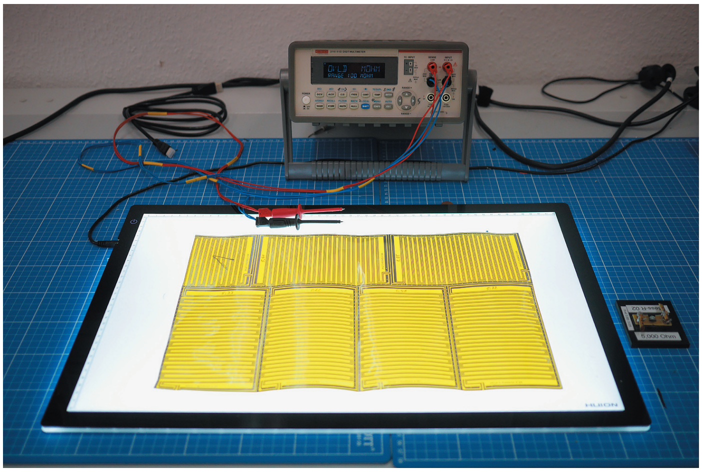

Automatic titration system for determining the etching agent concentration

coated aluminum-Kapton laminate with the required mechanical properties is available for purchase, the first process step involves coating the laminate with photoresist.
At Mundorf, this is done in an immersion process that even makes it possible to coat larger surfaces with a consistent coat thickness. This process holds various pitfalls that a manufacturing process with the aim of consistent product quality has to deal with. This includes an immersion process with constant, vibration-free transport of the medium to be coated in conjunction with control of the air flow over the still-wet photoresist coat because this influences the evaporation behaviour of the solvents in the photoresist and thus also indirectly influences the thickness of the photoresist coating produced during the coating process. Ventilation is of course necessary in any case because the solvents used are potentially harmful substances that have to be extracted and removed into appropriate filter systems in the exhaust air channel.

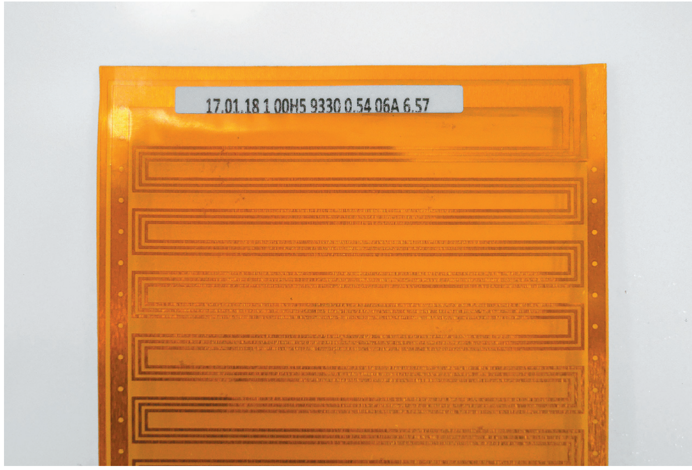

Etching unit with fume hood and exhaust air filter system

Before the actual etching process, the photoresist coat is tempered in special drying cabinets (pre-bake or soft-bake) and the residual solvent content is reduced to below a predefined value. This improves the adhesion of the photoresist to the substrate, prevents the formation of imperfections during exposure and, in particular, reduces the so-called dark erosion during development, a process that inevitably also partially reduces photoresist coating in areas where it should actually remain. In this tempering process, the optimisation of the residual solvent thickness over the depth of the photoresist coat is important, therefore the temperature and the airflow over the film to be tempered must be regulated precisely. The drying cabinets used at Mundorf have temperature sensors on

Controlling the air supply and exhaust air system



Control and documentation of the finished etched diaphragms



Each diaphragm is recorded in a database and receives an individual label, including a serial number and measured impedance.

each individual rack level so that the optimal conditions for the tempering process can be adhered to very precisely. The same applies for the thermal curing of the photoresist coat after exposure and development.

The current thickness of the photoresist coat is only be measured after tempering because it influences the following process steps, for example the effects of the previously-mentioned dark erosion and the extent of the undercutting on the width of the strip conductors actually produced in a subsequent etching process. Mundorf's process control actually goes so far as to use different exposure masks with slightly different strip conductor widths, depending the actual thickness of the photoresist coats, so that the strip conductor width in the subsequent final product is always within the specified tolerances. This is important because there are a relatively large number of strip conductor sections next to each other on the diaphragm, which have a considerable total length, so that deviations in width do have a noticeable effect on the resulting impedance. Which, in turn, is an important design parameter for loudspeaker developers and must therefore be closely tolerated. We are talking about a tolerance range of 2-3% which can only be maintained with a lot of effort because many factors, each with their own tolerances, have an influence here.

Photochemical development and another stay in the heating cabinet follow exposure. Here, the photoresist coat is thermally cured so that it can withstand the aggressive etching chemicals. Here, too, temperature control during the curing process is important so that undercutting during the etching process always has a consistent influence on the final width of the strip conductor.

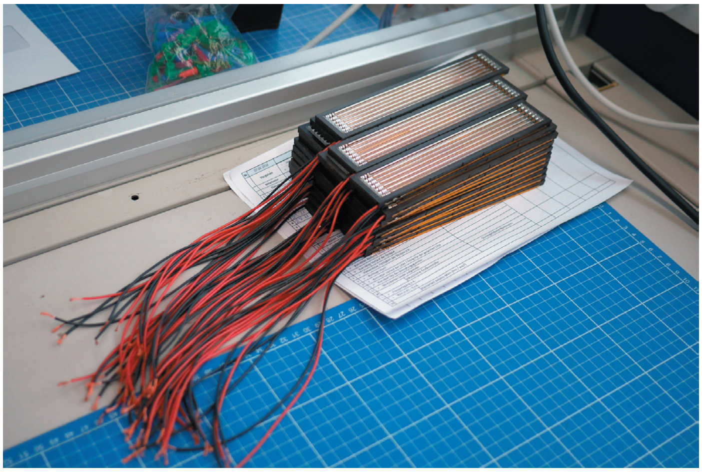
The actual etching process takes place in an etching unit under a fume hood so that the gases produced can be extracted and fed to a filter stage that removes harmful substances from the exhaust air. To achieve a consistent result, the etching agent – a combination of various substances – is circulated during the etching process. As some of the chemicals are converted during each etching process, the actual concentration of the etching agent in the various chemical components is determined in an automatic titration system and used quantities of chemicals are replaced in order to ensure that each batch is processed with the same strength/concentration of the etching agent components.

After the etching process, the photoresist coat is removed from the diaphragm film and the finished panel, which contains several AMT diaphragms on one sheet, is sent for final inspection. Here each diaphragm is inspected for etching defects and the resistance of the strip conductors uncovered in the etching process is checked. Each individual diaphragm that passes this test receives a label with a serial number and the actual measured impedance. The information from the final inspection is stored in a database together with a lot of information from the manufacturing process; this ensures that complete quality documentation is obtained and that, in the case of future quality checks or services, it is always possible to trace whether process parameters during manufacture or properties of the base materials could possibly be the cause of parameter deviations or failures in the end product.

... Control is better

So, it turns out that in a supposedly simple production process – in the past, many of our electronics-savvy readers have probably etched their own circuit boards – an enormous number of parameters can influence the end result. On the one hand, if you want to deliver consistent product quality in significant quantities in an industrial manufacturing process, you have to keep all process parameters that have an influence on the end product under control – and there is an astonishingly large number of them, says Raimund Mundorf on our visit to Hürth. On the other hand, quality control of the end product must be such that production defects are quickly detected and can be reliably traced back to their cause in order to avoid

Soldering the connecting cables to the aluminum strip conductor



A batch of finished AMT diaphragms with production protocol

producing a lot of rejects before the source of the problem can be remedied.

As stated at the beginning, AMT diaphragm production is not a standard production process in which the production steps and production equipment are known from the outset. Setting up production of this kind is not just a question of financing production equipment of a known design, rather, it is also a matter of development work, in which the individual production steps for all the necessary equipment must be designed, built, tested and, if necessary, modified until a production process for larger quantities with consistent and documented product quality is achieved.

Occupational safety and protecting the environment

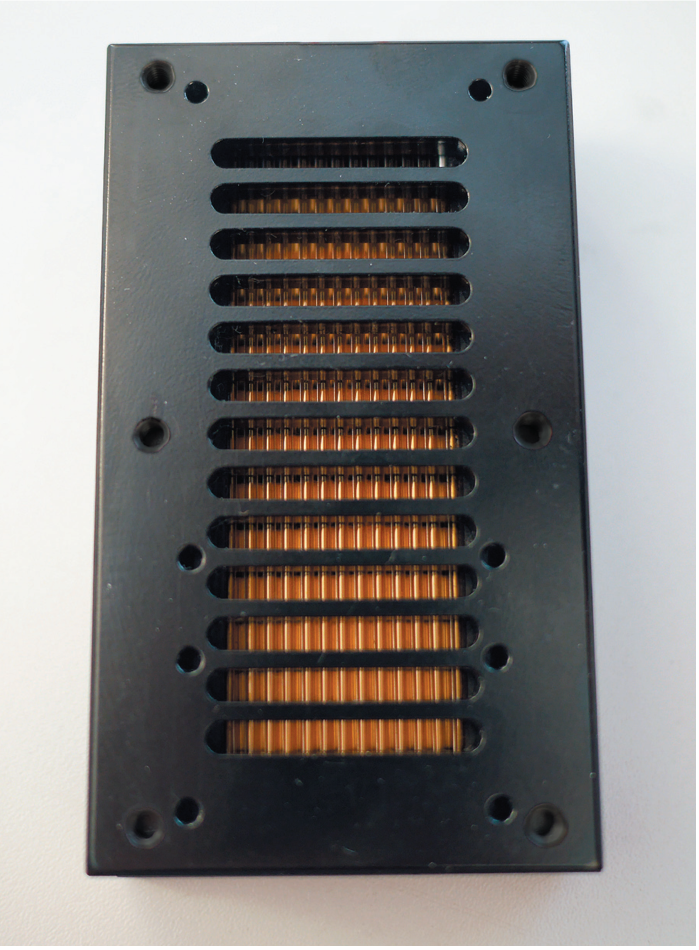
It goes without saying that the relevant occupational safety and environmental protection regulations must be complied with and, if possible, exceeded because the production process uses and produces substances that are potentially harmful to health. To take all of this into account, the production facility must be designed appropriately; this may involve enormous investment in the necessary infrastructure, such as aeration and ventilation equipment, filter systems, etc.

When designing the equipment relevant here, Mundorf worked together with an external office for occupational safety, because details which a loudspeaker component manufacturer wouldn‘t normally have much experience with, are of great importance here too. For example, room air conditioning must be regulated in a way that ensures that there is always positive pressure in rooms, even if air is being extracted in a fume hood. This serves the purpose of preventing that exhaust gas enters the room but is instead actively pushed into the fume hood and extracted. The room air conditioning must constantly readjust in order to maintain the internal room pressure despite the pressure loss due to the extraction in the fume hood.

After a lengthy search, says Raimund Mundorf, the company finally found a site in a business park in Hürth near Cologne, which had previously been used by Degussa and a chemistry lab, and already had an aeration and ventilation system. Although this could not be used directly in the AMT production process, some components and the existing piping, as well as the connections to the heating system could still be used for the purpose of providing a regulated, constant supply of air. However, a good six-figure sum had to be invested here alone for the necessary control and regulation of the air-conditioning technology.

Anyone who has ever set up an industrial production process – whether that‘s in electronics manufacturing or in the chemicals industry – will surely be able to confirm that something like that cannot be completed in a few days if you want to make sure that all the influencing variables that can affect the quality of the final product are under control. If, in addition, the aim is to develop the manufacturing process for a new product for a new industrial scale, you will find that various steps over the course of the project have something of a trial-and-error character for as long as the type and extent of all the influencing variables of the up-scaled processes are not yet completely known and under control. In this context, Raimund Mundorf speaks of a pilot-plant scale, which in the chemical industry is an intermediate step between the laboratory scale and large-scale industrial production, in order to develop scalable production facilities.

In this context, one must bear in mind that practically every manufacturer in our industry (i.e. professional sound engineering) is, at best, an SME by the standards of the chemicals industry, for example. In other words: Manufacturing on a much larger scale would only be needed if every loudspeaker in the professional sound engineering sector were equipped with a Mundorf AMT. The current system has been implemented in



such a way that further up-scaling would be possible without significant changing the process steps.

Some time has passed since the successful testing of the AMT products for professional use, which Mundorf used to implement the industrial production process. With the current production process, Mundorf have now reached a level that allows them – depending on the diaphragm size – to produce up to 4,000 to 10,000 AMTs per month (after the upcoming overhaul of the etching equipment, this will be about double).

As a result, Mundorf has invested significantly in scaling the production process and the necessary manufacturing equipment – chapeau, by the way, for this decision and the associated commitment – so you can look out with excitement for further developments.

Prototype of a Mundorf AMT from the extensive range of AMT products, which has a particularly flat design with a magnetic structure depth of only 21mm. It would be suitable, for example, as a component in loudspeakers for flat-panel displays provided that you also use very flat mid-bass drivers.

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