Stamper Quality: the secret of efficient replication

A top-quality stamper is prerequisite for cost-effective optical disc production. Dr Leonhard Schwab (CTO and co-founder, dr.schwab Inspection Technology GmbH) offers an insight into the role of inspection systems in stamper manufacturing, and the importance of controlling the entire mastering process.

Introduction

The optical disc has come a long way since the advent of CD over twenty years ago. As with most good ideas, there has been a proliferation of related applications and – as technological advances continue to open new doors – the pace of development shows no sign of diminishing.

From CD through DVD to the latest emergent formats, Blu-ray Disc and HD-DVD (formerly AOD), successive generations advance by quantum-leaps in storage capacity and functionality. Despite these dramatic changes, the key steps in optical disc production remain constant: manufacturing follows the well-trodden route of master to stamper to replica. Looking forward, this basic formula is likely to persist, offering the practical benefits of familiar – if more exacting – technology, and the commercial attraction of cost-effective mass production.

High-density and structurally complex formats, coupled with an increasingly competitive marketplace, place rigorous demands on the manufacturer. A sound understanding of the entire manufacturing process – and how each element contributes to the finished product - is vital for commercial success.

Overall yield of replicated product is determined almost completely by the quality of the stamper; for optimum performance, stamper quality must be judged very carefully, especially when re-using stampers. However, it is even more important to control the stamper manufacturing process: the mastering process.

In this article, Dr Leonhard Schwab takes a closer look at monitoring and controlling the mastering process which lies at the heart of all current and future optical disc formats.

Mastering Process Control by dr.schwab Inspection Technology GmbH

"dr.schwab Inspection Technology GmbH specialises in off-line and in-line inspection solutions to support every stage of the optical disc production process," says Schwab. "Our development and engineering staff have many years' experience in test technology, and have introduced benchmark equipment such as the Photo Resist Inspection System (PRIS), Diffraction Order Measurement System (DOMS) and Stamper Inspection System (STIS).

"Over the years, our team has worked closely with mastering equipment suppliers and end-users, to establish a clear understanding of the issues that they face on a daily basis, and to ensure that we continue to provide the test tools which are required to help them meet the exacting production standards required by today's – and tomorrow's – formats."

One recent development is an all-new extended version of the established DOMS, the DOMS$^{XE\text{-}blu}$. DOMS$^{XE\text{-}blu}$ is an all-in-one measurement system for monitoring and controlling the stamper manufacturing process as well as providing quality control for finished stampers. Its combination of diffraction order measurement, white light spectrometry and a high-resolution camera module delivers all the functionality of its predecessors (PRIS, DOMS and STIS) from one single system, plus features such as shorter (blue) wavelength illumination, fully-automated operation (including automatic positioning of sensors) and new measurement parameters.

Stamper Manufacturing: overview of the process

The fundamental principle of optical discs is that they utilise information which has been pre-recorded in the form of a height profile which contains, for example, encoded video or audio data, or provides positional guidance for the read or write spot during playback or recording. This height profile enables the relatively simple and cheap mass replication of information using a stamper. However, a good stamper is prerequisite for successful replication, so it is essential to have efficient test tools to check the accuracy of the height profile during the stamper manufacturing process and on the finished stamper.

Information is recorded into a surface relief pattern via the mastering process. "Several different mastering techniques are available, but irrespective of which method is used, the ultimate requirements for the finished stamper are the same: the height profile must be accurate. Errors on the stamper cannot be fixed or compensated during replication; you just get bad discs," comments Schwab.

Mastering

"We focus here on the traditional photo resist mastering process," says Schwab, "which currently accounts for the vast majority of stamper production." The process comprises three basic steps.

- First, the master - a flat glass substrate – is coated with a thin layer of photosensitive material which is then baked.
- Next, the surface relief pattern is recorded by exposing the photo resist using a focused laser beam, the intensity of which is modulated in accordance with the information. Light is absorbed in the exposed areas, changing the solubility of the photo resist material.
- Finally, in the development stage an alkaline solution flows over the photo resist layer and dissolves the material in exposed areas, revealing the height profile.

Electroforming

The height structure in the developed photo resist is very sensitive, and a metal copy must be made for use in the moulding process. First, the glass master is coated with a thin metal layer to make it electrically conductive, and then it is placed in a galvanic bath where nickel is deposited on the surface. When the nickel deposit is sufficiently thick, it can be separated from the glass master.

The structure on the glass master is usually destroyed during separation. The glass substrate can be cleaned and reused provided that the surface is smooth and free from scratches. Although it will eventually deteriorate, with careful handling the glass substrate can typically be recycled up to ten times.

A single stamper cannot produce an unlimited number of discs, so a family of stampers is created during the electroforming process. The first metal copy of the glass master is the 'father'; after separation, the surface of the father is passivated (oxidised), and it is put back into the galvanic bath. The resultant copy is a negative image of the height profile; the 'mother'. To revert back to a positive height profile, the mother is passivated, replaced in the galvanic bath and the 'son' - the final stamper - emerges. Several sons are usually created to ensure an adequate supply of stampers; for exceptionally large production runs, several mothers may be made.

Stamper Finishing

Any residue from the photo resist is removed and the surface of the stamper is coated with lacquer or a protective tape to prevent damage during the finishing process: backsanding to a uniform thickness, polishing to remove any roughness created in the electroforming process, trimming the outer edge, and punching the centre hole.

Stamper Manufacturing: some examples of process and quality control

Comparison between inspection in mastering and replication

"Stamper manufacturing involves a large number steps which are both time consuming and expensive, especially laser beam recording and electroforming. The success of each consecutive step is determined by the quality of its predecessor and – most importantly - the quality of the finished stamper has a direct impact on every disc," explains Schwab. "Therefore the tolerances are much more exacting and the number and size of allowable defects much smaller in mastering than in replication.

"An important practical benefit of the DOMS$^{XE\text{-}blu}$ combining all measurements in a single system is the reduced handling required for inspection in an already complicated and sensitive process. Also, it is very easy to exploit the full range of measurements for every process step. For example, defect detection is necessary not only for finished stampers but also for each step in glass master processing: bare glass (especially when the substrate is being recycled), coated, recorded and developed."

As with replication testing, the distribution of measurement results must be monitored across the entire surface of the sample: shape and symmetry can help identify process characteristics.

The first step: bare glass inspection, photo resist thickness measurement

Before recording can take place the glass master disc has to be polished, cleaned and then inspected for defects. If no defects are found, it is coated with a thin layer of adhesive over which the photo resist material is applied by spin-coating.

The thickness of the finished photo resist layer can be varied by diluting the photo resist material and adjusting the spinning parameters. "The photo resist layer thickness determines the maximum depth of the height profile on the master; it ranges from below 50nm for most rewritable formats to more than 200nm for recordable formats," comments Schwab. "The pit or groove depth itself has to be very uniform with variations of no more than a few nanometres."

Recording and developing: pit/groove measurement, uniformity

"Height profile is the decisive property for success and has to be checked from the earliest possible stage in manufacturing," says Schwab. Several different inspection options are available, operating on different scales:

- Atomic force microscope (AFM). With sub-nm resolution, the AFM is able to reveal minute details of the profile of an individual pit or groove and is used extensively in the development of new formats and production equipment. However, only a vanishingly small area can be evaluated at a time, making the AFM both impractical and inadequate for use in a production environment.
- Optical microscope – the disc player (PUH). The resolution of the optical microscope is of the order of the pit size, in the sub-µm range. Therefore it gives information about signal quality but is inadequate to give direct feedback about the recording and developing process.
- Diffraction order measurement system (DOMS). Typically uses a spot diameter in the sub-mm range (eg 200µm) giving a spatial resolution six orders of magnitude worse than that of AFM. However, because of the averaging process over a large area containing hundreds of grooves and thousands of pits, diffraction order measurement can achieve a pit/groove profile resolution comparable to that of the AFM. At the same time, because of the spatial resolution, diffraction order measurement enables scanning of the complete disc in a matter of seconds. In this respect, the AFM and DOMS complement each other.

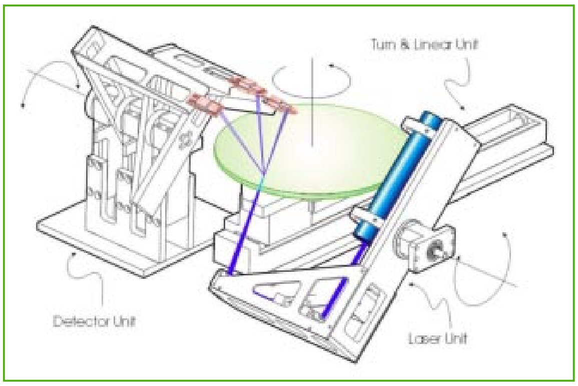

Figure 1 shows the diffraction order measurement module at the heart of the DOMS$^{XE\text{-}blu}$, which supports a measurable track pitch range from 460nm to 2,000nm, with first order measurement down to 230nm. The system is designed such that there are no bearings or rails above the sample, eliminating the risk of abrasion or lubricant contamination. As an option, the system can be equipped with a downflow unit.

Fig 1: DOMS$^{XE\text{-}blu}$ diffraction measurement principle

How can the profile of the groove be determined from diffraction measurements? Schwab explains: "As a rule we can measure zero, first and second order diffraction efficiency for CD and DVD formats with track pitches of 1.6µm and 0.74µm respectively. The diffracted intensities are highly dependent on the groove profile. So from two diffraction intensities, depth and width can be calculated.

"The first order gives groove volume, while the second order is an indicator of groove width; from the measured width and volume we can determine the depth of the groove. However, this is something of an oversimplification: in reality, diffraction intensities also depend on other properties of the groove profile."

By way of illustration, Figures 2a and 2b show the first order diffraction (I_1) and the ratio I_2/I_1 respectively for U grooves (rectangular profile) and V grooves (triangular profile) as a function of the duty cycle (ratio between groove width and track pitch). The diffraction of W grooves (trapezoidal profile) falls between the limits of U and V grooves.

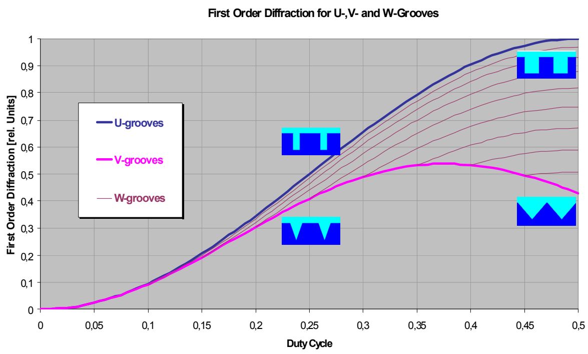

Fig 2a: First order diffraction as a function of duty cycle for U, V and W-shaped grooves

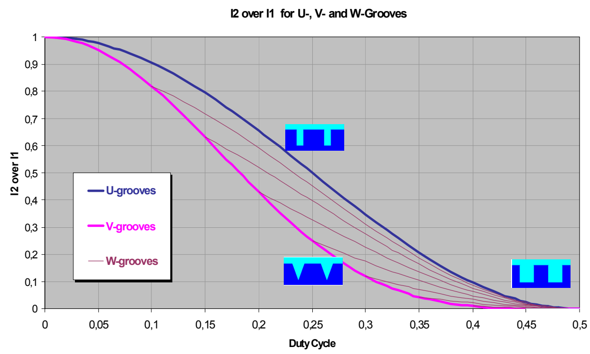

Fig 2b: Second over first order diffraction as a function of duty cycle for U, V and W-shaped grooves

"As these diagrams show, the relationship between diffraction intensities and profile is complex," Schwab continues, "and therefore the profile shape cannot be accurately determined from first and second order diffraction alone. The DOMS$^{XE\text{-}blu}$ solves this problem by using additional information from the spectrometer, which measures zero order reflectance as a function of wavelength (Figures 3a – 3c). Therefore the groove profile can be established, giving clear information not only about groove depth and width, but also about the wall angle."

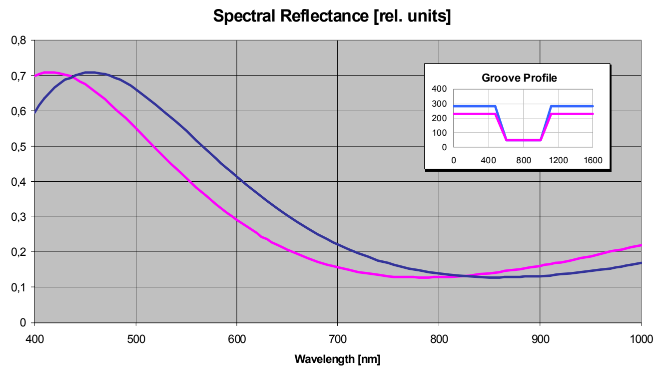

Fig 3a: Effect of depth variation on zero order spectral reflectance

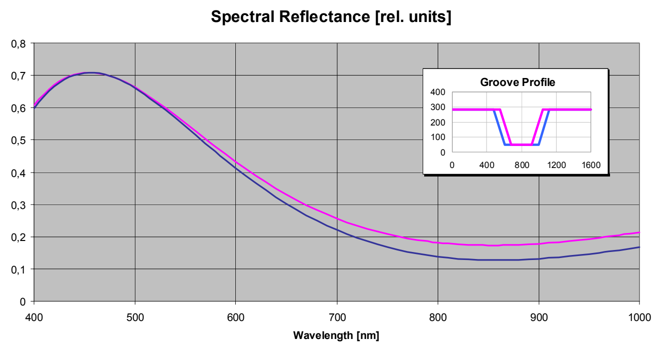

Fig 3b: Effect of width variation on zero order spectral reflectance

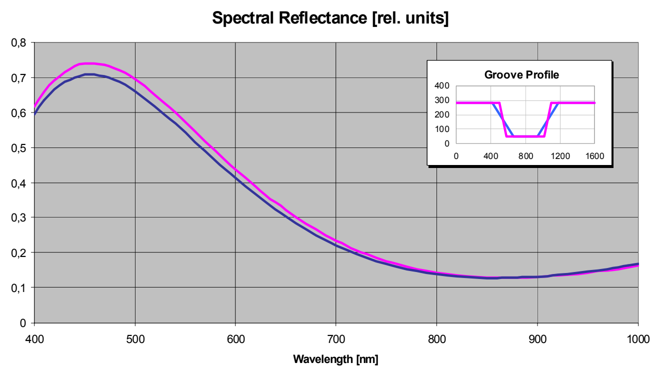

Fig 3c: Effect of wall angle variation on zero order spectral reflectance

Figure 4a shows first and second order diffraction measured on a banded glass master. "In the different bands, either the laser's intensity or its focus is varied in order to adjust the settings of the LBR," comments Schwab. "From first and second order diffraction the corresponding depth and width of the grooves can be calculated with nm resolution.

"Although the bands are only 1 mm wide they can clearly be resolved by the DOMS$^{XE\text{-}blu}$. This is because a spiral mode is used instead of a circular mode for scanning the surface of the disc. With a spiral mode we can achieve an excellent radial resolution whilst maintaining a good angular resolution."

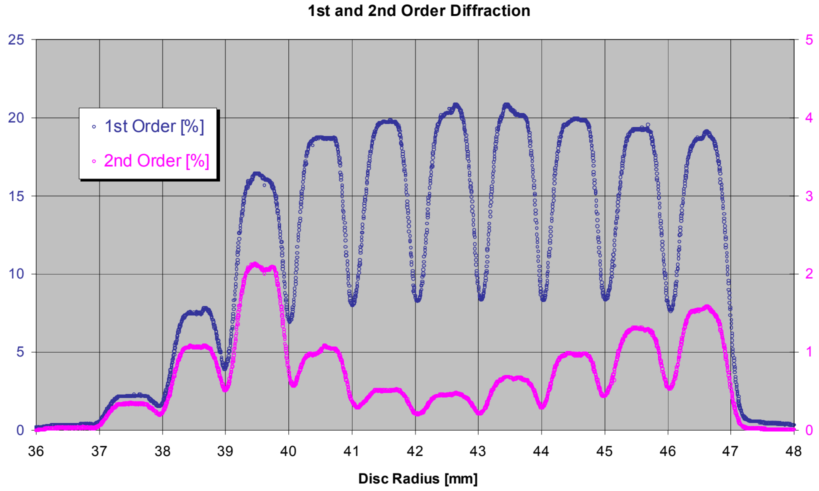

Fig 4a: First and second order diffraction measurements on a stepper master

The DOMS$^{XE\text{-}blu}$ offers an extra measurement cycle which evaluates plus and minus first order diffraction to identify differences between inner and outer wall angles. Figure 4b shows plus and minus first order diffraction measured on a banded glass master. "The normalized difference indicates deviations between inner and outer wall angle of the grooves," says Schwab. "This information is particularly important for the quantitative control of abrasion caused by the injection flow of polycarbonate and by the separation of the disc from the stamper during moulding. This kind of abrasion will have a direct impact as clouding on the finished disc. It cannot be measured and controlled with any of the previously described methods."

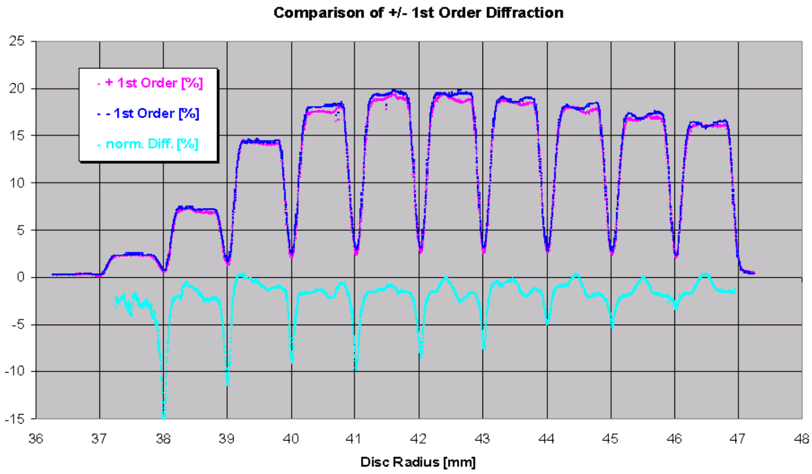

Fig 4b: Plus and minus first order diffraction measurements on a stepper master

As Schwab explains, the optimum groove shape varies from one format to another: its form and tolerances are determined during the lengthy process of format and production process development. "For recordable media, the final groove profile is determined not only by the pre-groove in the substrate but also by the dye filling characteristics. So in order to achieve the correct final profile on the finished disc, the pre-groove and the dye coating process have to be adapted accordingly. For example, the pre-groove of a DVD+RW stamper is V-shaped, only 200nm wide (duty cycle less than 0.3) and approximately 40nm deep, while that of a DVD+R is W shaped, approximately 370nm wide (duty cycle 0.5) and more than 200nm deep. To further complicate matters, different profiles are required for different write speeds."

Stamper finishing and used stampers: eccentricity, surface roughness, damage, wear

After sanding and polishing the back of the stamper, its outer edge is cut to size and the inner hole is punched. The inner hole has to be centered exactly with respect to the tracks; eccentricity of the inner hole gives rise to radial runout on the disc and will affect playability, an especially important consideration for high-speed DVDs.

The DOMS$^{XE\text{-}blu}$ features a fully integrated camera module coupled with powerful image processing software for accurate defect detection and classification. However, as Schwab points out, the camera module has another essential application: "In addition to defect detection, it can be used to verify the position of the stamper hole after punching: any eccentricity would clearly prove disastrous in replication."

The inclusion of a camera option within the DOMS$^{XE\text{-}blu}$ allows the mastering engineer to monitor for defects throughout the process, without incurring the overhead of additional handling, test time and the potential for damage. Schwab comments: "The DOMS$^{XE\text{-}blu}$ is a unique all-in-one mastering process control tool; for the first time, the mastering engineer has all the physical and optical parameters that he needs at his fingertips, from a single system.

"While inspection for defects on the finished stamper is an obvious quality assurance tool prior to committing to mass replication, regular examination for defects throughout the mastering process helps pinpoint the source of any contamination which may detract from the final quality of the stamper."

Typical stamper defects include scratches, stains and bumps – see examples in Figure 5.

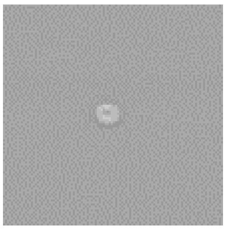

Fig 5a: Oil stain

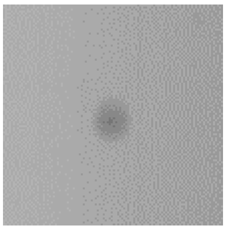

Fig 5b: Black spot

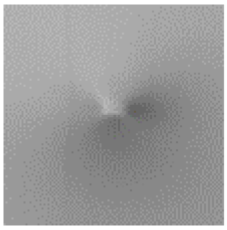

Fig 5c: Bump

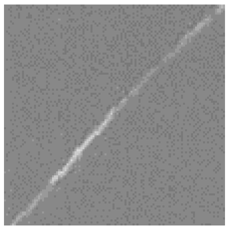

Fig 5d: Scratch

The DOMS$^{XE\text{-}blu}$ uses a high resolution CCD camera for detecting local defects, coupled with powerful image processing software for accurate defect classification. Samples can be evaluated from every step of the process: glass masters (bare, coated, developed, metallised), stampers, substrates and finished discs. A special optical arrangement utilising two wavelengths at opposite ends of the spectrum guarantees simultaneously excellent spatial resolution – to detect fine scratches, for example - and angular resolution, essential for the detection of defects such as small bumps.

A second class of defects – which includes surface roughness, clouds, comets, stripes and wear - is of particular significance when considering used stampers. These defects usually have a quite large extension but are invisible to the CCD camera due to lack of contrast in zero order reflection. "They may arise from handling, from contamination, from cold slugs in the polycarbonate material, or as a result of unsatisfactory release of the moulded disc from the stamper, or simply by abrasion during regular use," says Schwab. "CCD camera and diffraction measurement complement each other: while the camera is sensitive with respect to defects which require high spatial and/or angular resolution, we can use diffraction measurement to pick up areas with extremely low contrast in different diffraction orders.

"Examination of the used stamper can offer valuable feedback about its performance in replication," Schwab continues, "knowledge which helps the mastering engineer fine-tune his process to produce more efficacious stampers."

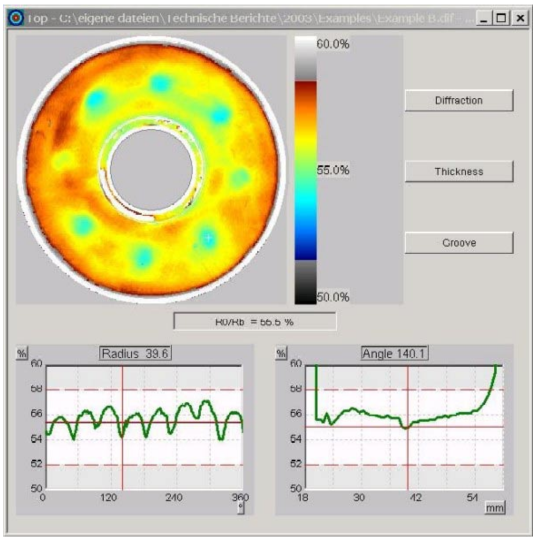

Fig 6: Stamper wear

An example of stamper wear is given in Figure 6, which illustrates the importance of displaying the distribution of measurement results over the entire surface of the sample. The eight-point pattern indicates wear caused by injection flow and reflects the structure of the injection nozzle.

Schwab offers a pertinent example of the importance of consistent stamper quality from the rapidly growing market for recordable DVD formats. "Feedback from manufacturers of recordable media indicates that while a CD-R stamper can typically be used for over 100,000 shots (finished discs), the lifetime of a DVD±R stamper is much shorter, less than 100,000 shots. In this highly competitive market, process efficiencies become very important. The lifetime of the DVD±R stamper must be maximised, reducing the number of stamper changes – and system downtime – to a minimum.

"Inevitably, each father must generate significantly more sons than would have been the case for CD-R production. So the galvanics process must be closely monitored and optimised to minimise deterioration in quality between father and son. The DOMS$^{XE\text{-}blu}$ can evaluate non-punched masters as well as finished stampers, making it ideal for father-son comparison," notes Schwab. "This comparison is useful on two counts: to monitor the condition of used stampers and to help improve groove design so that DVD±R stamper lifetime can be extended."

Conclusion

Applying the following principles during mastering will support cost-effective production of top-quality stampers and provide a solid foundation for replication:

- Every process step must be monitored and adjusted continuously: the success of each step is determined by the quality of its predecessor.
- Every property must be measured accurately.
- Distribution of measurement results must be monitored across the entire master or stamper: shape and symmetry help identify process characteristics and assess uniformity.
- In addition to structural parameters, inspection for local defects is important at every step in the process to ensure quality and to identify sources of contamination.
- Inspection by camera is essential to check stamper eccentricity in the finishing process.
- Monitoring the quality of used stampers provides valuable feedback for fine-tuning the mastering process towards replication.

In summary, it's better to avoid mistakes than try to correct them. "Stamper production is a time consuming and expensive operation, which underpins the success of the replication process. It is worth safeguarding the effort expended on mastering and stamper forming by regular inspection throughout the process to ensure that the end result – the starting point for mass production - is satisfactory," concludes Schwab.

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