Blu-ray Disc inspection for process perfection

A field correlation study based on physical and electrical testers to optimise the BD manufacturing process for both higher yield and quality, by Dr Leonhard Schwab, chief technology officer, dr.schwab Inspection Technologies

BLU-RAY DISC PRODUCTION IS MUCH MORE COMPLEX THAN PAST FORMATS. A careful control of the process as well as the environmental conditions, ie temperature, humidity and cleanliness, is essential.

Together with the format's tighter specifications, inspecting and testing is also far more demanding. For an effective and stabilised BD production process it is necessary to isolate and quantify process deficiencies as early as possible.

A field study was performed on several BD manufacturing sites with an analysis of the main reasons for yield loss using dr.schwab IT physical testers and AudioDev CATS electrical testers.

Physical testers allow a direct inline identification of problems specifically related to the BD process. The relevance of these problems can be confirmed by a good correlation with the signal quality from the electrical tester.

From this a clear strategy for improving and stabilising the manufacturing process can be derived by following this rule: reducing costs by improving quality.

Since its launch, BD has become a mass-production format, doubling in volume year on year. Meanwhile, in contrast, the price for media has come down by 50 percent year on year.

Production lines now run with a 4- to 5-second cycle time and can reach up-time and yields of around 90 percent.

To achieve this a delicate balance and fine tuning of all process steps is necessary. Otherwise the process can become unstable, as is shown in the example in Figure 1 (a diagram of a yield trend of 10,000 discs).

This diagram covers a 12-hour shift with a cycle of 4.5 seconds per disc. Although the production starts with about 80 percent yield, this decreases to about 60 percent and exhibits large fluctuations and instability in the process.

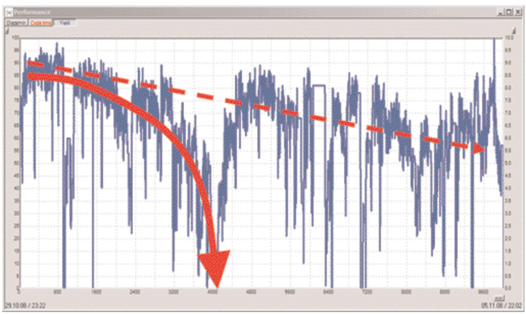

Figure 1: Example of yield trend for 10,000 BDs

This does show that it is possible to run the production with a yield above 80 percent. However, actions taken when the yield dropped did not improve the situation – on the contrary, after about 1,000 discs, the average yield decreases and completely breaks down after around 4,000 discs.

Further attempts to improve the yield are only partly successful. The reason is that the reduction in yield is usually caused by several interrelated factors and changes to single parameters can even make matters worse.

In order to keep the process within the process window very close, monitoring is required. Furthermore, changes need to be made before the process becomes completely unstable and reject discs are produced. By following this not only can the process be stabilised, but also quality can be improved.

Requirements for process control: physical testing

Firstly, all process stages must be taken into account. This includes, of course, all steps in mastering and stamper making. The methods and solutions for these stages will be discussed in another white paper. The present focus is on the replication process.

The replication process of BD, especially BD50, involves many more steps than DVD. Besides moulding and sputtering, additional steps are space layer, pit transfer layer and embossing, followed by cover layer and hard coating. This makes the process highly vulnerable to disturbances either from process variation or from environmental changes.

Physical testers check that the global properties are within specification. This includes thickness and thickness variation of the individual layers, tilt, and acceleration reflectivity. The specs are made to ensure playability: that means spot aberration or radial and axial acceleration should be small enough to ensure a good signal quality with low jitter and allow the PUH (pick-up head) to follow the tracks.

However, there is an equally important second task: physical testers are able to isolate each physical effect. While the signal quality as seen by an electrical tester is a combination of many physical properties (for example, pit replication, sputter thickness, tilt and layer thickness), the physical tester allows these properties to be seen independently from each other. This correlates directly with the corresponding process parameter, enabling a direct feedback to the line for process control and optimisation.

In the same way local defects have to be processed. It is not sufficient to determine their size in order to make an OK/NG decision. It is also necessary to classify them to identify their source. For example from moulding (bump, injection flaw), sputtering (pin hole, mouse bite), coating (flow lines), embossing (L1 bumps), and so on. With corresponding statistics trends can be quickly recognised and a timely correction is possible.

At the same time this classification has another use as it allows the control not to be over-sensitive. The final product has to play: that means it is necessary to know how severe the defects are. For surface defects, a larger size is acceptable and not all bumps lead to a reject disc. Here the electrical tester comes into play: defects have to be weighted with their influence on signal quality or PUH servos. Only defects that clearly affect the signal quality or cosmetics should be isolated. Other, lower threshold effects, may be used for keeping the process stable.

For example, if the disc has information up to a radius of only 50mm, a defect or disc tilt beyond that radius has no influence on playability and a more relaxed quality control can be used. Nevertheless, having defects above that radius indicates that the process is not well controlled so a process correction is reasonable.

This type of classification by physical tester is necessary since an electrical tester cannot realistically perform a 100 percent inspection (time would not allow) and cannot be used in each process stage. Only the physical tester can perform 100 percent inspection in all stages within the cycle time of the production line. (Physical testers support the two key tasks reviewed above and are referenced in the naming of our system: IQPC – Integrated Quality and Process Control.)

Observations from BD production

Process stabilisation demands knowing where a problem comes from. Otherwise the wrong actions are taken, usually making the situation worse. In addition, actions have to be taken at the earliest stage allowing, in most cases, problems to be recognised and corrected within the process window (that is, before making reject discs).

This requires a detailed analysis of the Blu-ray production process taking real production data from several production lines and production locations.

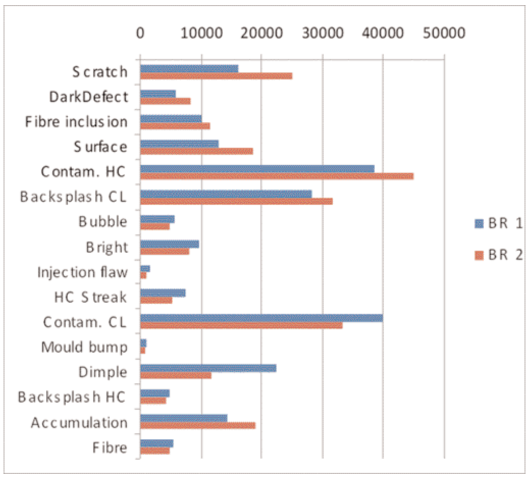

Figure 2: Comparison of line performance: local defects. More than 80 percent of the local defects are caused by contamination. Only a small part comes from injection, handling and sputtering

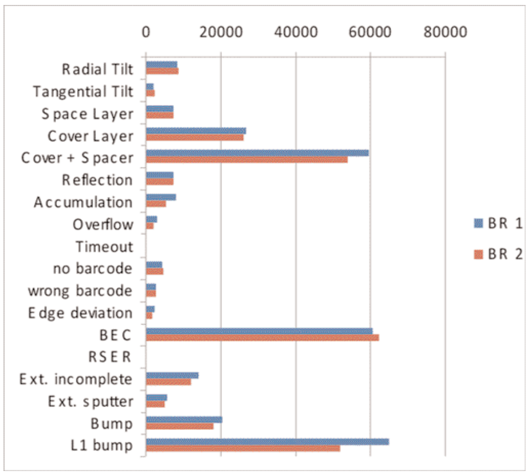

Figure 3: Comparison of line performance: global defects. More than 80 percent of the global defects occur in the coating (cover and spacer) and embossing process (BEC and L1 bump). Many of them are caused by contamination

Figures 2 and 3 give examples of the defect distribution from two identical lines. The defects are divided into local and global defects. Local defects are small isolated defects such as scratches, bumps, dimples, bubbles, inclusions, etc. All of them occur on a random basis. This means that a 100 percent control of both samples and surface is necessary. Global defects are cumulative defects and deviations from specifications, such as layer thickness, flatness or edge deviations.

Looking at the diagrams, it is apparent that the defect distribution between all lines and all manufacturing sites is similar for local as well as for global defects. Three major problems become clear, all of which are related to the new technologies required for the BD manufacturing process.

The first is coating of the space layer, especially the thick cover layer. The second is embossing with the relatively soft silicon pads that cause BEC and L1 bumps. In both of these cases many of the defects are caused by contamination and this is indeed true for most of the local defects. Only a relatively small part comes from injection, handling and sputtering.

This indicates that there is a huge potential for yield and quality improvement by a better control of the coating and embossing processes and by isolating sources of particle contamination.

Coating thickness uniformity: process variation

Figure 4 shows the trend of min-max-avg of cover layer thickness of a BD50 production for

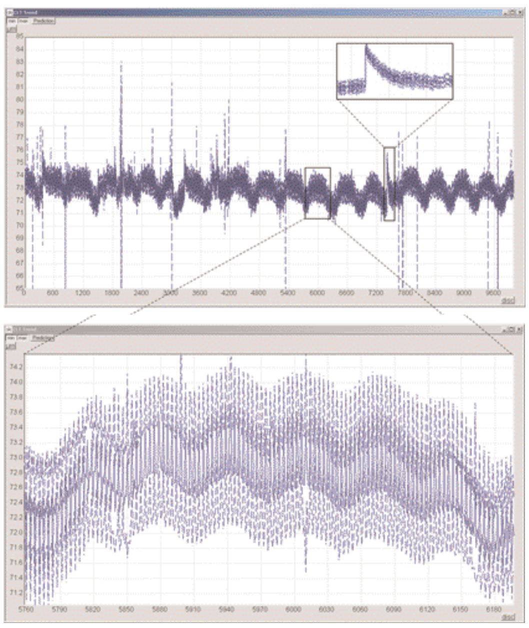

Figure 4: Example of the trend of min-max-avg of cover layer thickness of a BD50

approximately 10,000 discs. The global average is quite stable at about 73µm and there are only a few exceptions, mainly caused by contamination and short line stops.

The 'un-zoomed' picture does not show any trend, but the total width of the band between minimum and maximum is about 2µm and there is a periodic thickness variation within a total band of 4µm. Although only a few micrometres, this is quite large compared with the process window for cover layer thickness. This means that the variation on disc, as well as the variation from disc to disc, already takes up two-thirds of the process window.

The fact that the overall behaviour as shown below is very regular (there is no random variation and no measurement variation) indicates that the process can be considerably improved. Further analysis of the variation from disc to disc shows periodic changes on several timescales. There is a 400-disc period that corresponds to 30 minutes, a 60-disc period (5 minutes) and a four-disc period (18 seconds). The latter comes from the four coating cups in the line, while the longer periods are caused by periodic temperature changes.

It is well established that coating thickness and profile sensitively depend on not only process parameters such as spin speed and time, but also on material parameters, including viscosity and surface tension. The material parameters strongly depend on temperature, therefore a stable state has to be reached for a well-controlled thickness.

Even small temperature changes due to disc cooling during a short pause in production cause a thickness change of a few µm. The time constant to again reach the stable state is about 3 minutes (see zoom insert in Figure 4). If the thickness is measured directly at the coating station, a closed loop feedback to the spin speed could shorten this time further and increase the yield correspondingly.

To reduce the process variation it is important to improve the temperature control or to feed back the variation to the process. It is important to note that it is not the room temperature but the microclimate (temperature and humidity = heat capacity) in the line around the coating cups that is important.

The microclimate in the line is strongly affected by local heat sources such as sputter chambers, UV curing and IR heating stations which are turned on and off within the production cycle and contribute considerably to the local environmental conditions. By taking this into account a reduction of process variation up to 50 percent is possible. This corresponds to an effective increase of the process window invaluable for such complex production processes.

Coating thickness uniformity: profile

As seen on the trend view, the variation from disc to disc as well as the variation on the disc is quite large and occupies a considerable part of the process window. The disc-to-disc variation has to be controlled by stabilising the process conditions. For a small variation per disc the process parameters have to be optimised.

A typical profile of a spin-coating process is shown in Figure 5. It is characterised by a steep gradient at the inner and at the outer diameter (red lines in the diagram). The variation inside these two regions is, as a rule, quite small.

The gradients are caused by the resin material flowing away from the dispense radius and by surface tension at the outer diameter which inhibits the spin off.

Solutions for this include using a centre cap, an outer-edge mask and centre curing combined with outer-edge heating.

By modifying the pre-curing and heating conditions the profile can be modified. Not all parameter changes will lead to an improvement. However, by making arbitrary changes to the parameters and comparing the results with those before, using the comparison module, settings for an optimum profile can be found (blue lines in the diagram). In a short time the variation on disc could be reduced from about

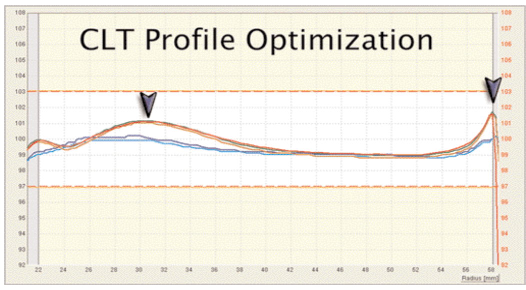

Figure 5: Profile comparison requires a high radial resolution for thickness

3µm to 1µm. This effectively improves the quality, increases the process window and thereby the process stability. Everything can be done while running the process using the comparison module.

Coating thickness uniformity: local defects

So far, these discussions have covered thickness variation from disc to disc and profile variation on a disc. There is a third class of non-uniformities that occur in the coating process: bumps. Actually, this turned out to be one of the most important new inspection tasks for BD production (see defect statistics in Figures 2 and 3) and one of the most important features of IQPC.

Bumps in the coating layers do not directly affect the signal quality. However, they may cause optical aberrations that lead to focus and tracking errors. With an electrical tester they can be quantified using the servo signals 'axial' and 'radial'. Basically bumps are local in nature. L1 bumps are caused in the space layer of BD50 during the embossing process. Due to the soft material of the silicon pads supporting the substrates, their extension is in the mm range and they have very shallow slopes. They can easily be detected by the spectrometer thickness measurement of IQPC. This requires a high spatial resolution combined with low measurement noise that guarantees the measurement repeatability without data smoothing. A spectrometer thickness measurement result is shown in Figure 6.

Again such types of defects are basically caused by contamination, most often particles behind the stamper. They are serial defects – once the contamination is present, the bump will appear on each subsequent disc. A good

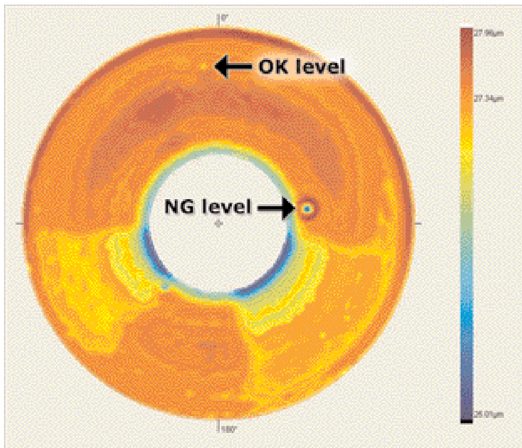

Figure 6: Example of L1 bumps with OK and NG level

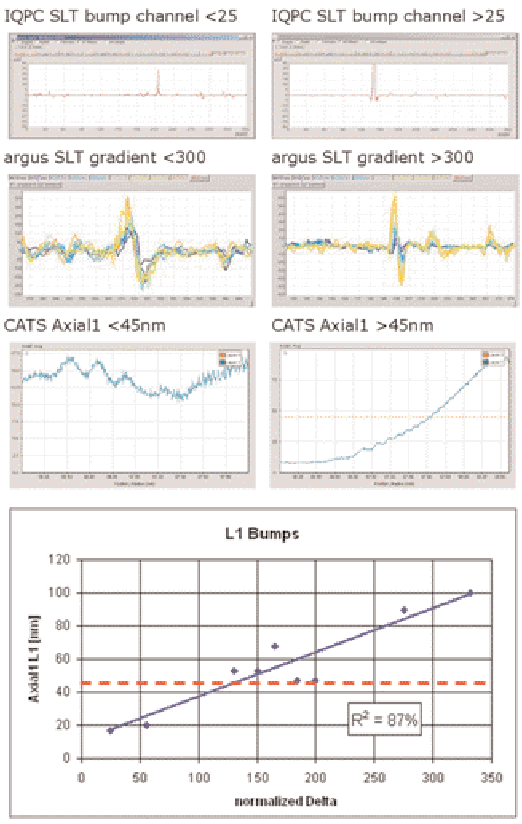

Figure 7: L1 bumps. OK and NG level correlate very well between physical testers IQPC and argus-XE and AudioDev electrical tester

classification and careful discrimination between OK and NG level is required.

A direct correlation between defect length of bumps and burst error cannot be expected. However, the servo signals axial or radial of the electrical tester can be monitored. Figure 7 compares the characterisation of L1 bumps between IQPC, argus-XE and CATS. Although the servo signals of the electrical tester depend on many more parameters, a surprisingly good correlation between physical and electrical testers can be observed. This allows an optimum threshold setting ensuring high yield and good quality of the discs.

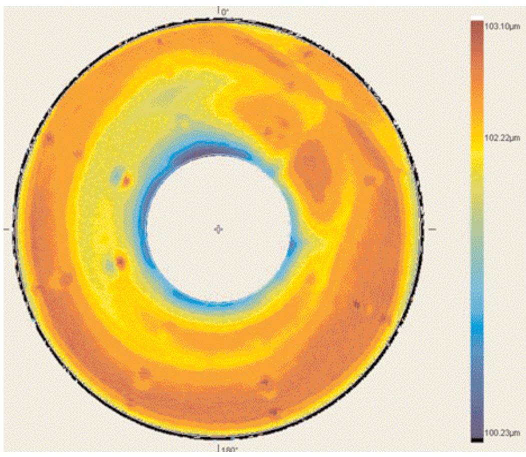

Figure 8: Example of cover layer dimples with OK and NG level

The appearance of dimples and L1 bumps is completely different. Dimples in the cover are typically caused by droplets or (burst) bubbles in the cover surface or by slight local temperature variation. The example in Figure 8 shows a pattern of regular dimples in the cover layer. The eightfold symmetry reveals the handling and underlines again the sensitivity of cover layer thickness with respect to global and local temperature.

Compared to L1 bumps, dimples are smaller with steeper slopes and can clearly be detected by the near darkfield channel (NDF) of the IQPC as

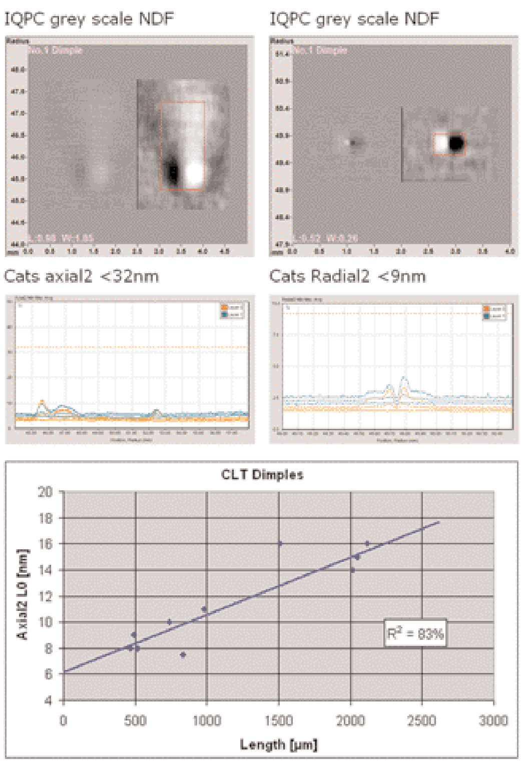

Figure 9: Dimple in cover layer thickness. Direct correlation of IQPC NDF with CATS Axial/Radial

well as by the thickness measurement. Sometimes they are accompanied by a comet. As a rule, they have no contrast part like contaminations or bubbles.

Not all dimples have to be sorted out – a careful classification is required. This makes it necessary to have the combination of good resolution and repeatability of thickness measurement and to identify which layer the defect is located in and to know the effect on the servos of the player. As shown by the comparison in Figure 9, there is again a very good correlation between physical and electrical tester so that corresponding thresholds for quality and process control can easily be defined.

Coating thickness: correlation with tilt

The absolute thickness value and good uniformity of all layers is an important requirement of BD production. However, cross correlation to other physical properties also has to be taken into account. Due to shrinkage, usually each layer has a linear contribution to disc tilt. A variation of the layer thickness therefore directly affects tilt. This can be seen in Figure 10, which shows the tilt trend for the production with cover thickness variations (Figure 4). Even the small thickness variations cause a tilt variation of more than 0.1 degree.

In an optimum production, the individual linear contributions to tilt are kept in a way that they balance each other. This leads to a toroidal profile of the disc with minimum tilt and maximum stiffness (Figure 11).

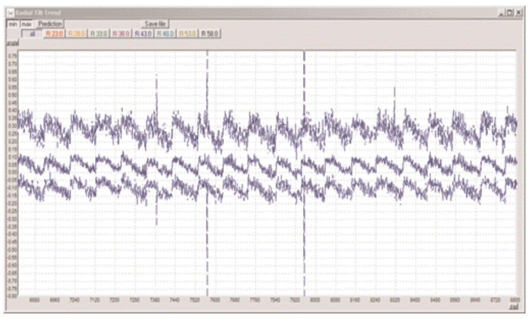

Figure 10: Radial tilt variations caused by layer thickness variations

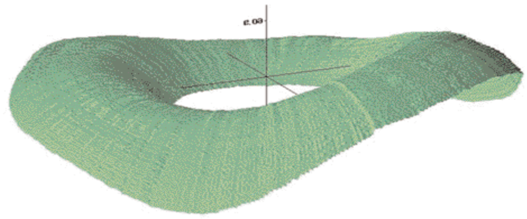

Figure 11: Optimised disc shape with a toroidal profile which exhibits minimum tilt and maximum stiffness

Effect of contamination/local defects

Most of the local defects are caused by contamination. This can be in the material (inclusions of PC, space, cover or HC layer) or in other stages of the process, for example moulding or embossing station. The contamination can come from the machine process (for example, oil stain, cutting dust, particle of the sputter mask, injection flaw) or from the surrounding area.

For most of the local defects there is a direct relation to playability. Contrast defects simply are a damage or masking of the pits, so that the signal is not readable in the defect area. Burst error and defect length are directly correlated.

During production the silicon pad used in the embossing process is exposed to UV and heat leading to rapid ageing of the material. This in turn effects the pit replication. For an aged pad, accumulation of very small defects, especially at the ID, occurs. Although size and contrast of the defects are small, they are usually accumulated at one radius, which causes BEC that can be detected by IQPC and correlated with CATS. Statistical trend analysis of BEC frequency allows an early warning so that the pad can be exchanged pre-emptively before disc failure occurs.

The need for environmental control

As can be seen from the review above, a major part of local defects is caused by contamination. Environmental conditions can be controlled by cleanroom conditions. But implementing a true cleanroom environment is not always possible and, in most cases, would be overkill. In addition, even a complete cleanroom environment cannot guarantee that locally inside the machine there are not sources of contamination. A very well known example is the punch of the cover foil.

Therefore, a more efficient way for improvement is monitoring the cleanliness in the relevant points of the process, that is in the coating and bonding stages. This not only gives an early warning, if conditions deteriorate, but also helps to identify potential sources of particle contamination within the machine and from outside.

Similar scenarios regarding the increase of surface defects and inclusions in coating or bonding layers can be correlated with variations of air purity. By combining the event count with the results of the particle counter the main sources for the contamination are exposed. Figure 13 shows an example of measurement results over 15 hours.

Slightly increasing values for particle count (>3µ and >5µ) correspond to the increasing values of events on the topside of samples. Again, there is a clear indication for the reasons of a quality deviation: the linear growth of topside events is caused by rising contamination of the ambient air.

The same holds for temperature and humidity. Even if the site temperature and humidity are stabilised, the machine itself has a micro-climate that is strongly affected by heat from cycling high-power consumption parts: UV-curing, IR-heating, sputter.

Control of the environmental conditions requires monitoring temperature, humidity and particle count of a production line and use the

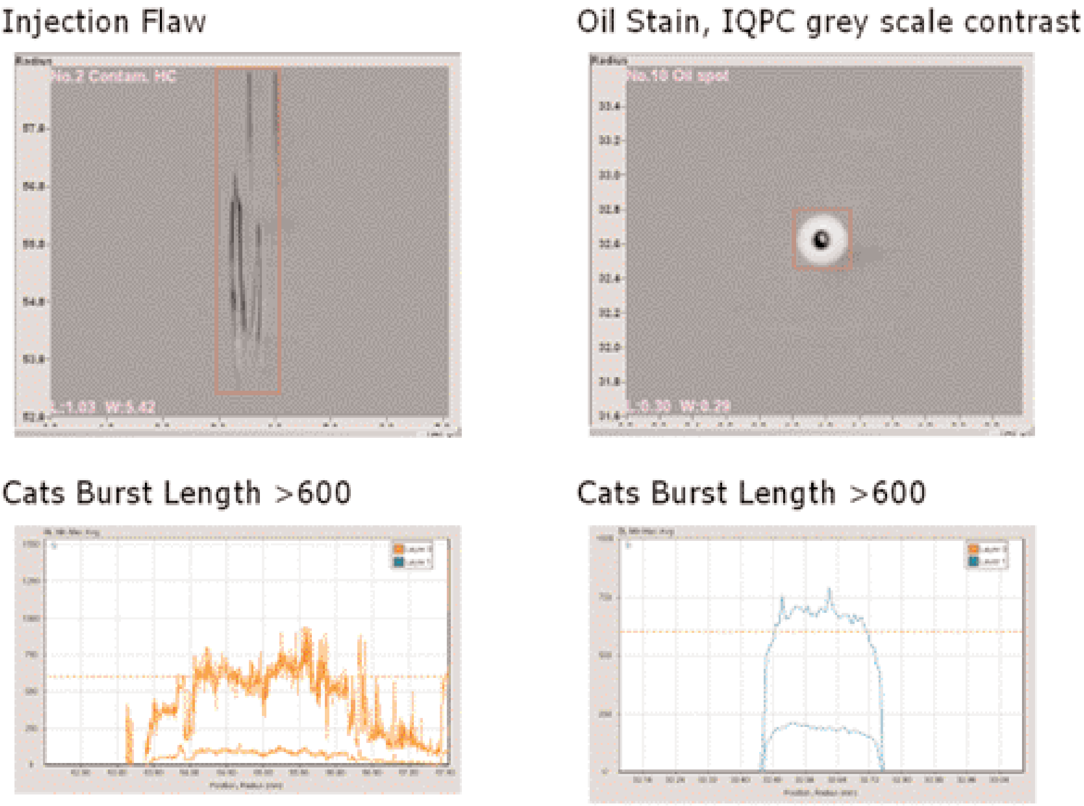

Figure 12: Direct correlation with burst length. Accurate size determination by IQPC

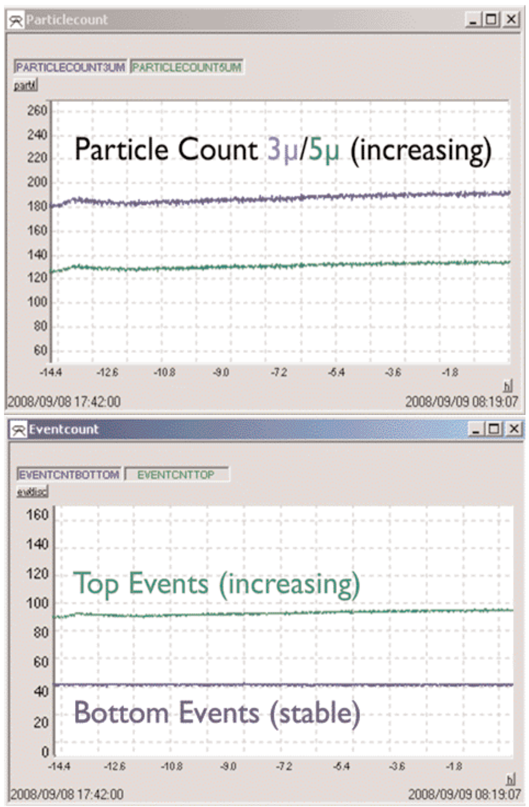

Figure 13: Surface defects (top events) directly corresponding to particle counter results

results as feedback information for process control and optimisation.

Conclusions

Production of Blu-ray Discs is still a demanding task for every manufacturer. Tough specifications and quality demands are directly in conflict with the requirements for high yield. Only a complete inspection solution that is tailor-made for the needs of Blu-ray Disc production, can meet the technical and economical demands.

The combined capabilities of physical and electrical testers reviewed in this study, provide quality assurance as well as process control and process optimisation.

For a full version of the white paper visit:
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