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Pulsed Cooling - optimising BD substrates moulding

Jan Bernards, Peter Simon, Thomas Moosbrugger, Wlodek Mischke

DaTARIUS Technologies GmbH ; Anton Maria Schyrle Str. 7,A-6600 Reutte, Austria,

Introduction

Investigating the substrate moulding process for BD ROM and BD RE (re-writable) substrates moulding process, involved a series of experiments investigating and optimising the moulding process for BD substrates. These studied the relations between the mould temperature, cycle time, moulding process, cooling pulses and the physical properties of the substrates itself, such as birefringence, tangential and radial deviation, diffraction efficiency, AFM measured groove/pit geometry. The investigation showed that, compared to the stationary type of cooling, the Pulsed Cooling method of moulding the BD discs, manufactured substrates with lower birefringence, tilt, dishing, very good groove/pit replication quality with shorter cycle time and using the lower mould temperature.

Body Text

Pulsed Cooled moulding process appeared to be a very efficient and economical method for moulding optical media. The method is relatively new, and was recently very successfully applied for the optical media. The principle relies on dynamic control of amount of mould cooling during the moulding process which is directly linked with the process conditions and its cycle time and the cooling can be also carefully balanced between the two parts of the mould. Usually the method results with substrates of higher quality, moulded within shorter cycle time, and the process improvements are especially evident when manufacturing advanced media such as Blu-ray Discs.

Injection moulding of optical media is a typical cyclic process. During the manufacturing process mould is heated during the hot resin injection, than cooled down before releasing a substrate. Whilst most of manufacturers use the DC type of cooling system for the moulding process, it has been discovered that applying pulsed cooling offers several advantages.

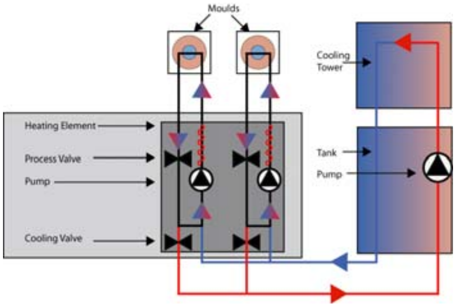
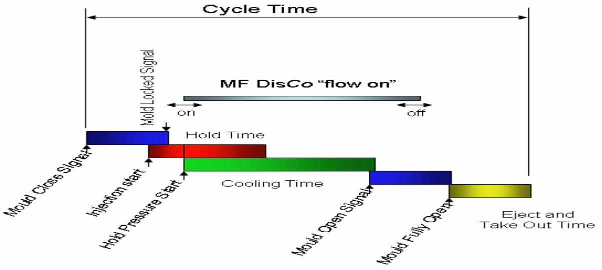


Figure 1: Pulsed cooling system maintains temperature during injection stroke by closing manifold valves and stopping water flow. When injection stops, the valves reopen until the mould cools to the desired temperature.



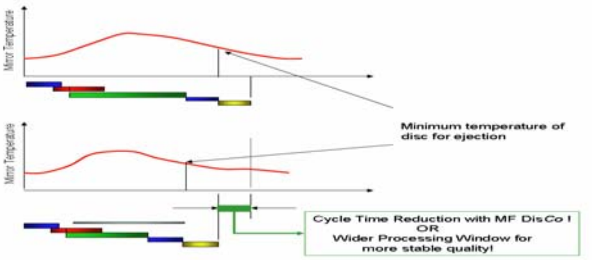


Figure 2. The timing of the Pulsed Cooling with respect to the molding process cycle.

(DaTARIUS MF DisCo description)

Figure 3. Mechanism of the cycle time reduction with the pulsed cooling system

(DaTARIUS MF DisCo description)

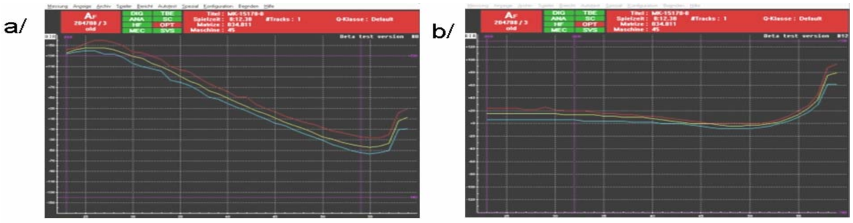


Figure 4.:

Comparison of the substrate birefringence, with continuous type of cooling method (a) and pulsed cooling system (b).

(DaTARIUS MF DisCo description)

Research on various optical disc products indicated that there could be a reduction in cooling time of up to 30% and further investigation showed other technical and costs advantages. Detailed finite element modelling of the moulding process indicates that pulsed cooling is able to achieve better control and stability of the temperature compared to the constant mould cooling principle. Pulsed cooling is used in other special moulding application, but has now been applied to moulding optical storage media. It is seen to be especially suitable for the high density type of formats where mechanical properties of substrates are have very tight limitations..

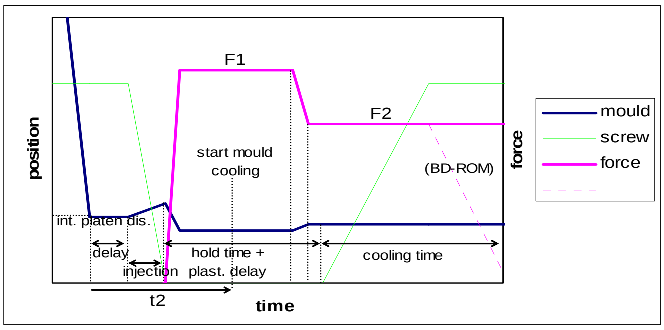


Figure 5: Schematic representation of a moulding cycle. When the mould closes it moves to the inter platen distance. After a delay, the injection starts. Then the clamping forces are applied in two steps. For BD-ROM the clamping force decreases near the end of the cycle. After the hold time and plasticising delay time, plasticising takes place. The total cooling time is the sum of the plasticizing delay time and the cooling time in the diagram (this is the cooling time as used by Injection Moulding Machine). The MF Disco Cooler starts with cooling of the mould t_2 seconds after the mould has closed.

The general principles of the design of the pulsed cooling system and its functioning are explained on figures 1-3. Various experiments with the used of Pulsed cooling shows several improvement for DVD type format discs like improved birefringence (see figure 4), better control of substrates dishing, also improvement of the forming the pit structure, resulting in enhanced measured discs electrical signals (so called HF signals). However in this paper we shall focus on the optimization of the moulding process for the Blu-ray discs (BD). In all the experiments the MF Disco Cooling system developed within DaTARIUS was used. BD substrates were moulded on the line adapted for manufacturing of the commercial BD format media. Both ROM and Re-writable (RE) formats were moulded. The stampers used were of the similar type to the one used for manufacturing normal BD ROM and BD-RE media. Moulding process with pulsed cooling system was compared with the standard process applied for continuous cooling. The process using pulsed cooling was then modified to optimise and investigate influence of various process parameters. The embossed structures were measured with the use of diffraction of the light and also Atomic Force Spectroscopy. Discs flatness properties like radial and tangential deviations were measured as well as their birefringence.

Produced substrates were inspected for the so called clouds and flow lines using diffraction, visual inspection, and AFM as well. Some of the BD ROM discs were completely finished. Electrical signals of the discs were evaluated

PROCESS INVESTIGATION FOR BD-RE MEDIA

The stamper used for manufacturing of the BD-RE substrates had several bands with different groove width. Typical moulding process duration was 12.5 s. With the pulsed cooling system good results were achieved with 15 °C reduced mould temperature and cycle time about 6 s. Under these conditions the radial and tangential deviations were similar to

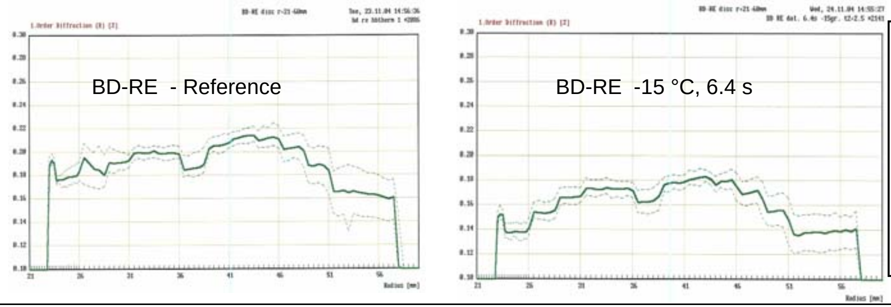
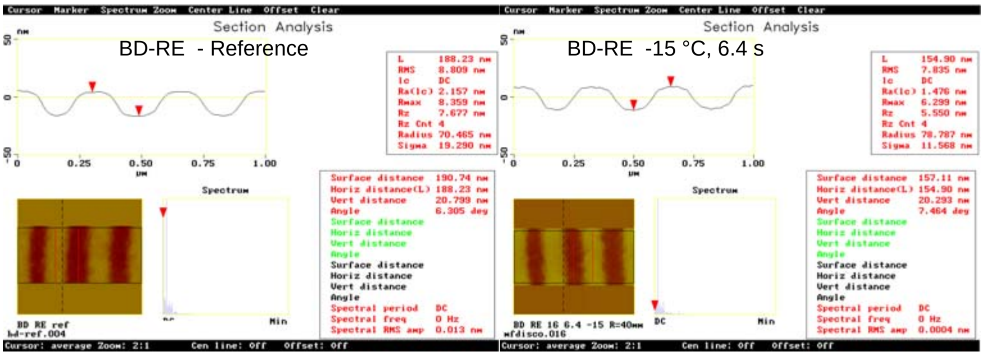


Figure 6: First order diffraction measurements of a reference sample (left) and of a sample moulded at a cycle time of 6.4 s and a mould temperature of 15 °C below the value used for the reference substrate (right). Shown are the minimum, average and maximum value at each radius).



BD-RE - Reference

L	188.23 nm
RMS	8.809 nm
lc	DC
Ra(lc)	2.157 nm
Rmax	8.359 nm
Rz	7.677 nm
Rz Cnt	4
Radius	70.465 nm
Sigma	19.290 nm

Surface distance	190.74 nm
Horiz distance(L)	188.23 nm
Vert distance	20.799 nm
Angle	6.305 deg
Surface distance	
Horiz distance	
Vert distance	
Angle	
Surface distance	
Horiz distance	
Vert distance	
Angle	
Spectral period	DC
Spectral freq	0 Hz
Spectral RMS amp	0.013 nm

BD-RE -15 °C, 6.4 s

L	154.90 nm
RMS	7.835 nm
lc	DC
Ra(lc)	1.476 nm
Rmax	6.299 nm
Rz	5.550 nm
Rz Cnt	4
Radius	78.787 nm
Sigma	11.568 nm

Surface distance	157.11 nm
Horiz distance(L)	154.90 nm
Vert distance	20.293 nm
Angle	7.464 deg
Surface distance	
Horiz distance	
Vert distance	
Angle	
Surface distance	
Horiz distance	
Vert distance	
Angle	
Spectral period	DC
Spectral freq	0 Hz
Spectral RMS amp	0.0004 nm

Figure 7:

AFM measurements at radius 40 mm on a reference sample (left) and on a sample moulded at a cycle time of 6.4 s and a mould temperature of 15 °C below the value used for the reference substrate (right).

the standard conditions (tan. dev. < 0.05°). The first order diffraction was somewhat lower on the entire substrate (see figure 6), indicating differences in groove shape. It is expected that this can be compensated by the choice of the groove

Diffraction data

In figure 6 the first order diffraction sampled at radii 25, 37.5, 40 and 56 mm, is shown as a function of cycle time and relative mould temperature. From this figure it is clear that for all radii the first order diffraction is independent of the cycle time, the main influencing factor is the relative mould temperature. At the standard temperature the same level of first order diffraction can be obtained as for the reference substrate for all radii except for the inner radius.

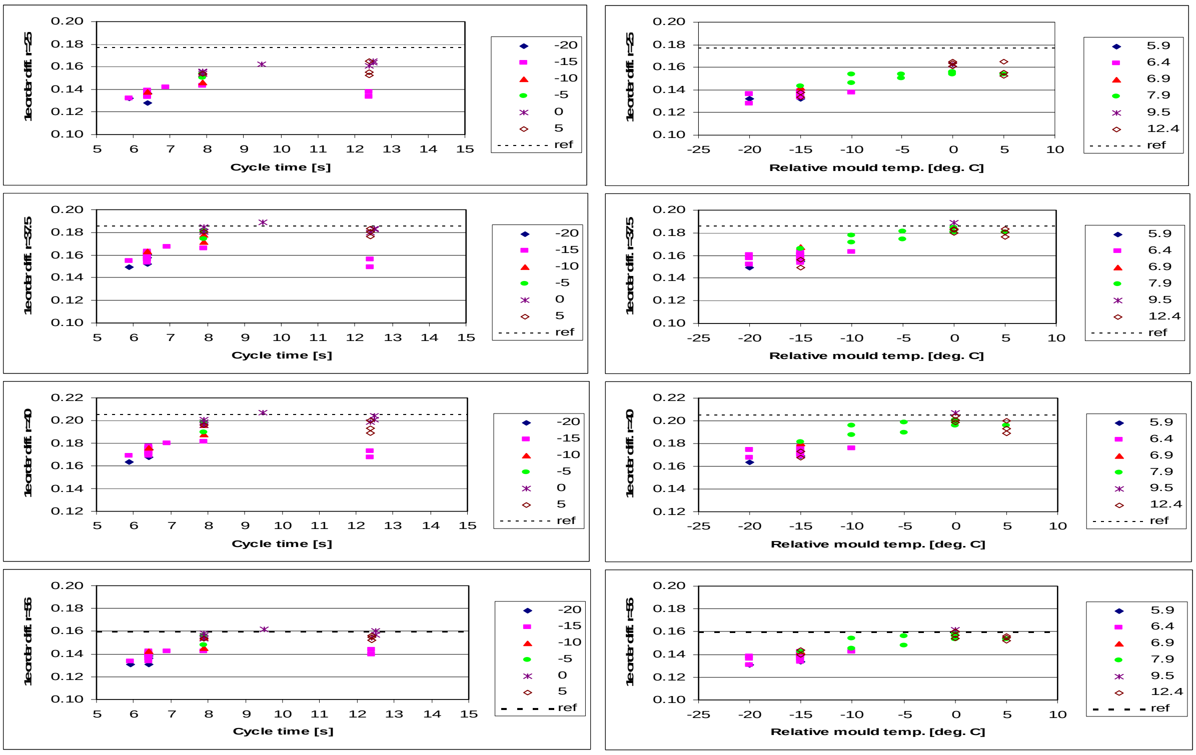


Figure 8: First order diffraction at different radii (r = 25, 37.5, 40 and 56 mm from top to bottom) as a function of cycle time (left) for different relative mould temperatures (see legend) and as a function of relative mould temperature (right) for different cycle times (see legend). The dashed horizontal lines represent the values of the reference substrate.

Because the values from all samples have been incorporated in the figure and values for the samples moulded at the same relative moulding temperature are similar, it can also be concluded that in the investigated range the effects from cooling pulse delay time-t_2, and clamping forces-F_1 and $F_{2,}$ on the first order diffraction are small.

AFM Measurements

Examples of AFM measurements of BD-RE discs are shown on Figure 7. A wide spectrum of measurements of various samples were made at different moulding process conditions. It was found that the values measured on the samples are in good agreement with the stamper measurement, when the values of the widths are corrected by 20 nm (measured tip width). Detailed data analysis showed **also a good relation** between measurements of the first order of diffraction efficiency and the geometrical groove width obtained through the AFM measurements.

Tangential and Radial deviation

We see that the tangential deviation increases in absolute value with increasing mould temperature (see figure 9). This increase is much faster for short cycle times than for long cycle times. The value closest to zero can be obtained at long cycle times or at low mould temperatures, which is as expected because in general it is easier to make flat substrates at lower temperatures and longer cooling time. In either circumstance, the temperature of the substrate is lower at the moment the substrate is taken out of the mould and so less deformation of the substrate occurs.

It has been found that a high value for the force F_1 also results in a better tangential deviation (an improvement of 0.05° over the investigated range). Also an increase of t_2 results in a slight increase of the maximum tangential deviation and a slight decrease of the minimum tangential deviation. This is in line with the expectations because an increase of t_2 results in a decrease of the cooling time.

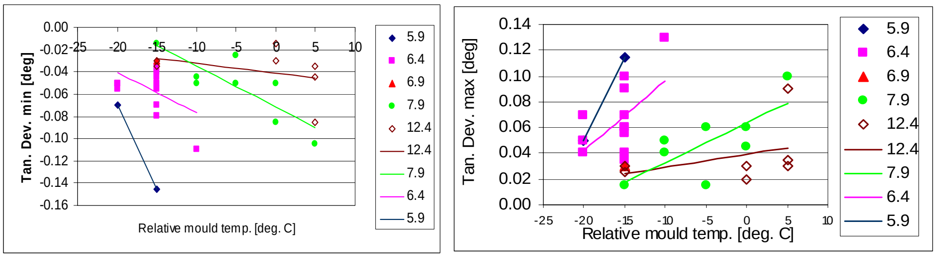


Figure 9: Minimum tangential deviation (left) and maximum tangential deviation (right) as a function of the relative mould temperature for different cycle times (see legend).

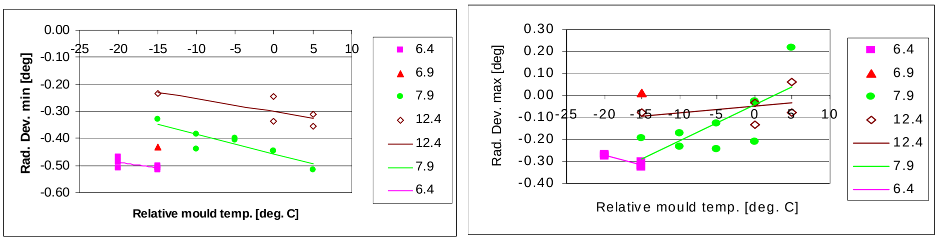


Figure 10: Minimum radial deviation (left) and maximum radial deviation (right) as a function of the relative mould temperature for different cycle times (see legend). Only the results from samples made with the standard values for t_2, F_1 and F_2 are incorporated in the figure

In figure 10 the minimum and maximal radial deviations measured on each sample are shown as a function of the relative mould temperature for samples made with the standard values of t_2, F_1 and F_2. For the maximum radial deviation no clear behaviour is observed, but the minimum radial deviation shifts to more negative values as mould temperatures increase and cycle times decrease. This poses no problem as long as the tangential deviation stays small (in absolute value). Whilst experiments have not been made on this point, we believe that by changing the difference in temperature between the two mould halves the radial deviation can be shifted to the desired value. A shift to more positive values is also obtained by increasing F_2 (about 0.3° in the investigated range).

Birefringence measurements

Figure 11 presents the minimum and maximal birefringence measured on each sample , which is shown as a function of the relative mould temperature. With increasing mould temperature, the minimum birefringence has a tendency to decrease . The maximum birefringence also increases with increasing mould temperature, but decreases with greater cycle times. In addition, the birefringence increases with increasing F_2 and t_2 and the maximum birefringence decreases with increasing F_1 (see figure 12). In most cases the birefringence is maximal near the outer edge of the substrate (see as example page 30, sample 16). It would seem that more stresses are built up in the substrate at the edge at higher mould temperatures, but longer cycle times give these stresses more time to relax.

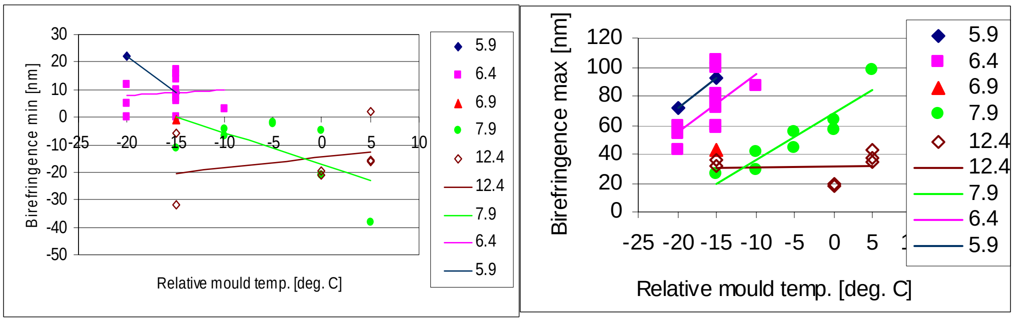


Figure 11: Minimum birefringence (left) and maximum birefringence (right) as a function of the relative mould temperature for different cycle times (see legend).

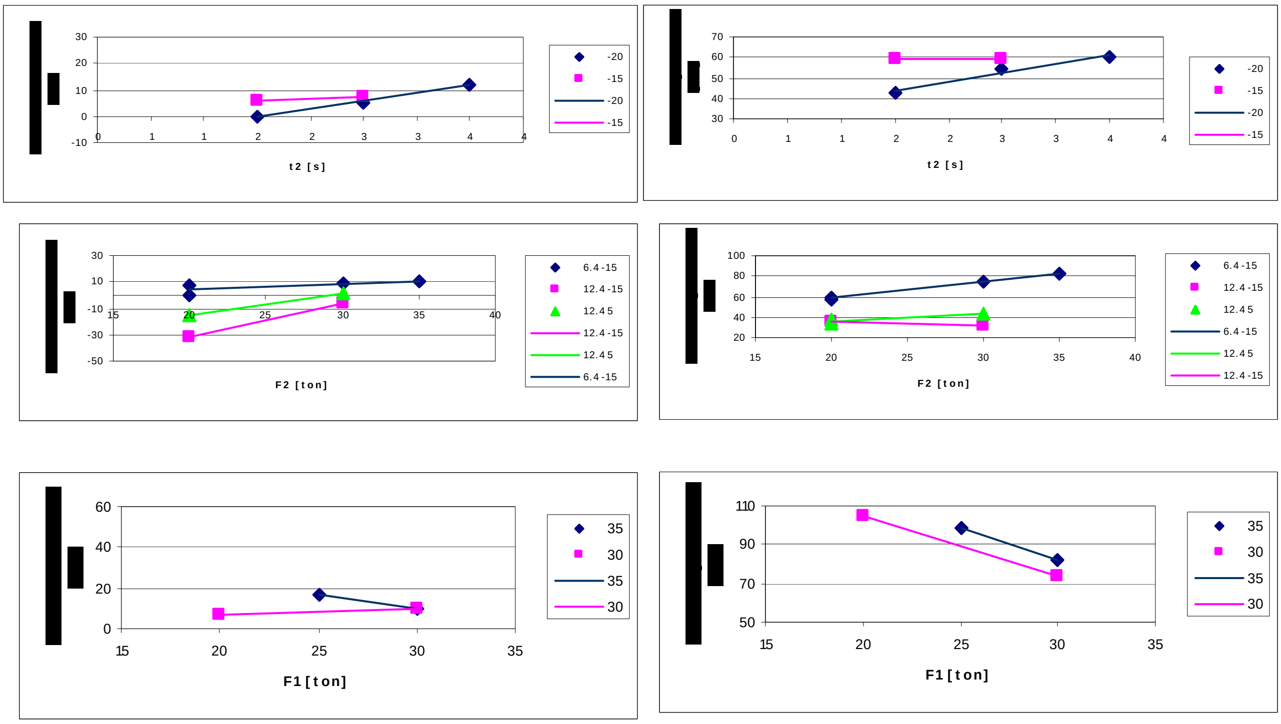


Figure 12 : Minimum birefringence (top) and maximum birefringence (bottom) as a function of t_2 (upper left, for relative mould temperature see legend), as a function of F_1 (left, for F_2 see legend) and as a function of F_2 (above, for cycle time and relative mould temperature see legend).

Profile lines

One of the effects which can show up on the BD-RE substrates are so called ‘profile lines’. These are multiple lines (not flow lines) running across the grooves, giving rise to a disturbance in the signal when using the completed disc in a drive. Most often the lines are at the inner area of the substrates. The cause of these lines is not clear at the moment. It was not possible to find such lines on the substrates made with the Pulsed cooling manufacturing methods, while the defects were frequent and disturbing for standard continuous cooling method.

PROCESS INVESTIGATION FOR BD-ROM MEDIA

A similar broad investigation of using Pulsed Cooling for BD-ROM moulding process was also carried out. Using a standard BD-ROM stamper, a wide range of process conditions were investigated and compared with the discs made using the typical continuous cooling method. Under standard manufacturing process substrates for BD-ROM are being made at a cycle time of 9.5 s. When optimising the process for pulsed cooling, reducing the moulding temperature by 20

°C existing clouding was minimised. At a cycle time of 5.5 s the radial and tangential deviations were similar to the standard process conditions (tan. dev. < 0.05°), but the first order diffraction was somewhat lower, especially near the outer edge (radius > 52 mm; see figure 13). AFM measurements made at radius 40 mm are shown in figure 14. Similarly to the BD RE case the differences in groove shape indicated by the first order diffraction measurements are not evident in the AFM pictures. However, signal measurements on a completed disc did show higher jitter and asymmetry. This is most probably caused by the smaller mark size on the disc: for these effects the lands are smaller and the pits are bigger than they have to be.

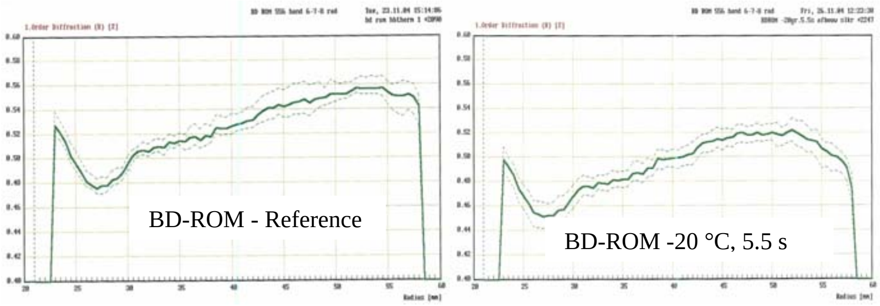
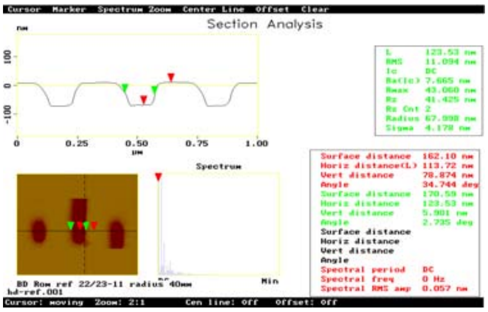


Figure 13: First order diffraction measurements of a reference sample, and a sample moulded with standard conditions and of a sample moulded at a cycle time of 5.5 s with a mould temperature of 20 °C below the value used for the reference substrate Shown are the minimum, average and maximum value at each radius).



```
L          123.53 nm
RMS        11.094 nm
Ic         DC
Ra(Ic)     7.665 nm
Rmax       43.060 nm
Rz         41.425 nm
Rz Cnt     2
Radius     67.998 nm
Sigma      4.178 nm
```

```
Surface distance     162.10 nm
Horiz distance(L)    113.72 nm
Vert distance        78.874 nm
Angle                34.744 deg
Surface distance     170.59 nm
Horiz distance       123.53 nm
Vert distance        5.901 nm
Angle                2.735 deg
Surface distance
Horiz distance
Vert distance
Angle
Spectral period      DC
Spectral freq        0 Hz
Spectral RMS amp     0.057 nm
```

```
BD Rom ref 22/23-11 radius 40mm
hd-ref.001
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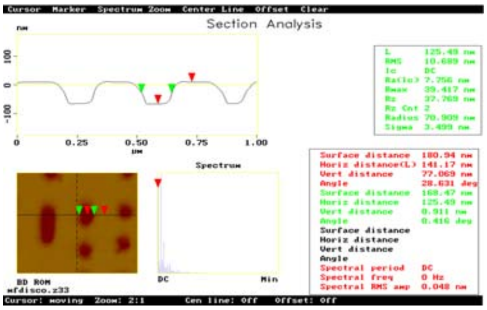

```
L          125.49 nm
RMS        10.689 nm
Ic         DC
Ra(Ic)     7.256 nm
Rmax       39.417 nm
Rz         37.769 nm
Rz Cnt     2
Radius     70.909 nm
Sigma      3.499 nm
```

```
Surface distance     180.94 nm
Horiz distance(L)    141.17 nm
Vert distance        77.069 nm
Angle                28.631 deg
Surface distance     168.47 nm
Horiz distance       125.49 nm
Vert distance        0.911 nm
Angle                0.416 deg
Surface distance
Horiz distance
Vert distance
Angle
Spectral period      DC
Spectral freq        0 Hz
Spectral RMS amp     0.048 nm
```

```
BD ROM
mfdisco.z33
```

With the shorter cycle time there possibility of sticking of the substrate to the wrong side of the mould. This however, can be circumvented by altering certain machine parameters such as timing and amount of air blow and the speed of mould opening.

Diffraction data

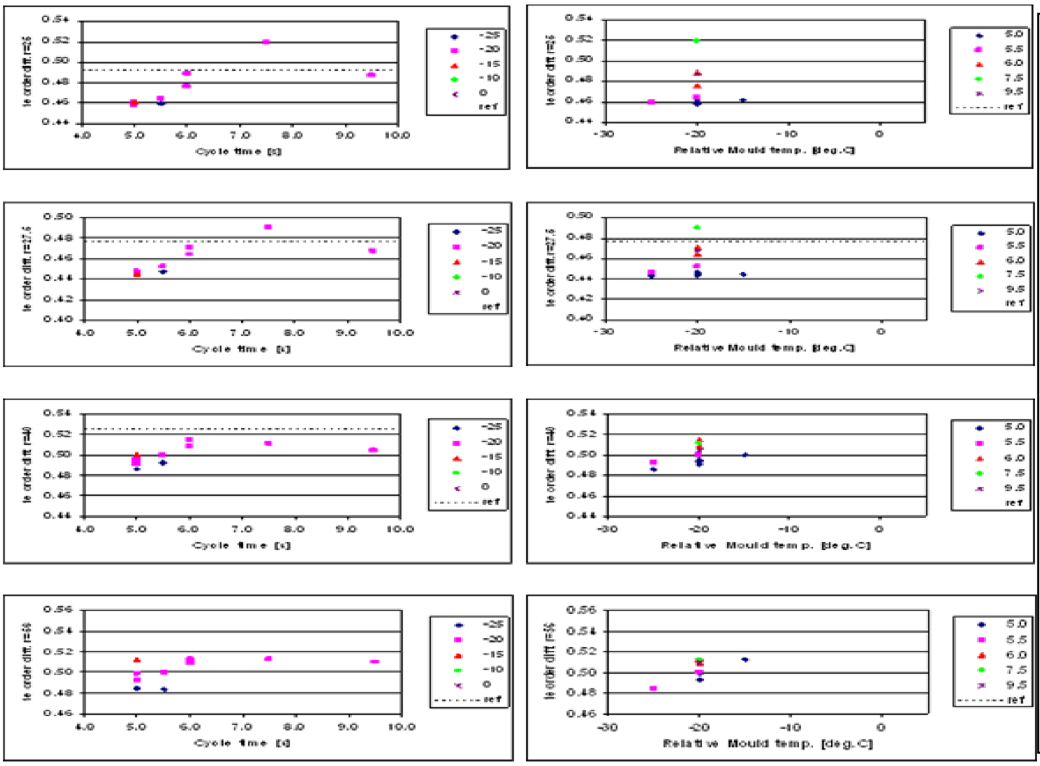

Figure 15:

First order diffraction at different radii (r = 25, 27.5, 40 and 56 mm from top to bottom) as a function of cycle time (left) for different relative mould temperatures (see legend) and as a function of relative mould temperature (right) for different cycle times (see legend). The dashed horizontal lines represent the values of the reference substrate.

An example of a first order diffraction measurement is shown on figure 12. The differences can be caused by dimensions of the moulded structures and the presences of clouds on the substrates. The clouding is caused by pit deformation, which also influences the first order diffraction. This can be removed by process optimisation as seen on the AFM results presented on figure 14.

In figure 15 the first order diffraction at radii 25, 27.5, 40 and 56 mm is shown as a function of cycle time and relative mould temperature. For the inner radii the first order diffraction increases with increasing cycle time and the relative mould temperature has no influence. Towards the outer radius the influence of the cycle time becomes smaller but the influence of the relative mould temperature increases. Also with increasing relative mould temperature, the first order diffraction becomes larger.

For the long cycle times, the first order diffraction at the inner radii equals or even exceeds the value of the reference substrate. For the short cycle times and at the outer radii, the first order diffraction is lower compared to the reference substrate.

3.2. Tangential, Radial deviation, and Birefringence

In figure 16 the minimum and maximal tangential deviations measured on each sample are shown as a function of the relative mould temperature for all samples. As with BD-RE and for the same reasons, the value closest to zero can be obtained at long cycle times or at low mould temperatures.

Similarly, the minimum radial deviation shifts to more negative values with increasing mould temperatures and with decreasing cycle time. This poses no threat as long as the tangential deviation stays small (in absolute value), because by changing the difference in temperature between the two mould halves the radial deviation can be shifted to the required value.

This was some relationship noticed between birefringence and moulding cycle time, but there was no evident relation to the mould temperature

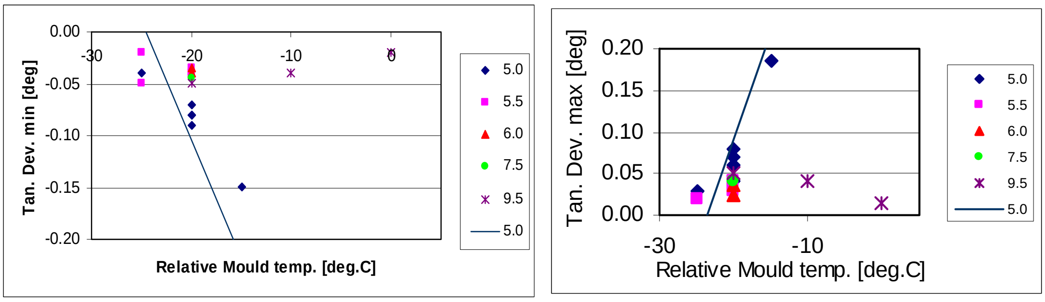

Figure 16.

Minimum tangential deviation (left) and maximum tangential deviation (right) as a function of the relative mould temperature for different cycle times (see legend).

3.3. Signal measurement

The jitter measured on the made samples is about 1.5 to 2% higher than on the reference discs. This can be explained by the higher asymmetry of the pits on the discs. This means that land/pit ratio for the shortest pits (T2) is shifted higher. Moulding of these smallest elements is naturally the most difficult part of the manufacturing process.

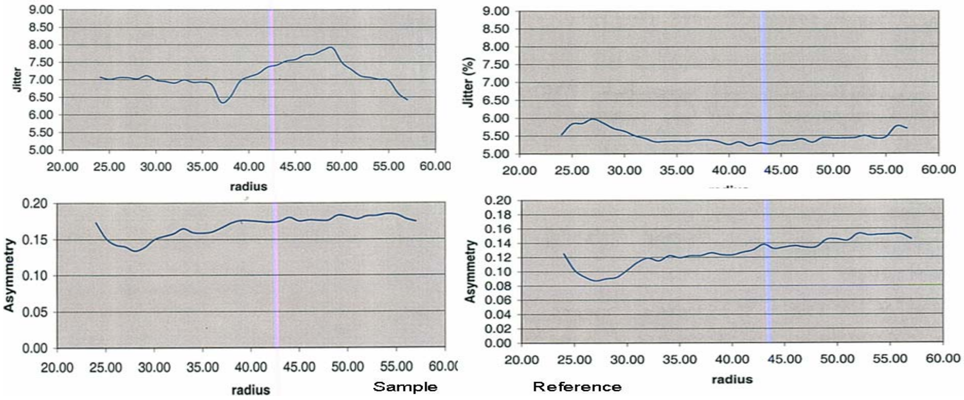

Figure 17:

Signal measurements of a disc from experiment 16 (left) compared to a reference disc (right). The top graphs show the jitter and the bottom graphs the asymmetry.

Conclusions

These experiments shows that by using a pulsed cooling system one may manufacture BD ROM and BD-RE type of discs with much shorter cycle time than with the standard cooling process and with reduced mould temperatures. Pulsed cooled moulding produces substrates with lower birefringence, tilt, dishing, very good groove/pit replication quality. Therefore it can be seen that this type of cooling gives improvements in these areas of the quality of the moulded substrate, whilst also offering the commercial benefits generated by shorter cycles times and lower energy usage.

Acknowledgment

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* wlodek.mischke@datarius.com; phone: +43-676-5812 909; fax: +43-5672 206 730; www.datarius.com