Improve Yield of the Replication Line for DVD9/DVD5 for a Technology Company

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Abstract *— Replication process is used to mold the disc via injection molding, this process is used for high volume runs due to process stability. Currently the yield of the replication line is around 85-90%, the objective of this project is determine why the line can't operate at a yield of 90% or greater, if the process is qualified to operate at a 90% process yield in a 4 hours job. The Company needs to determine if the process yield variation shown by the replication line are due to a manufacturing model that forces the equipment operates within transient (unstable) zone for most of the orders processed. The frequency and extend of technology changes, order size and idle time between jobs could be major factors within manufacturing model that affects the process yield.*

Key Terms *— Injection Molding, Replication process, Transient Zone, Yield.*

INTRODUCTION

Optical media manufacturing could be conducted in two different manners. Disc can be replicated, which implies that the pits and lands that are used to create the digital signal (0's and 1's) are molded into the disc during their manufacturing via injection molding. Replication is designed ideally for high volume runs due to process stability. This process requires large and complex equipment that is very expensive and requires a considerable amount of utilities such as power, water, and argon, among others.

The other method is called duplication which is basically the same method that typical users do in their personal computers. A blank media with a temperature reactive dye (ink) is burned and the color difference between the areas that are burned and the ones that are not, are the equivalent to the pits and lands (called pseudo-pits and pseudo-lands) in a replicated disc. This process is ideal for high mix and low volume runs given that the equipment is less expensive which allows more flexibility.

RESEARCH DESCRIPTION

Currently the company is using both techniques, but it depends on the quantity of the order. If an order is greater than two hundred units, then it will be replicated, otherwise it will be duplicated.

The Company needs to determine if the process yields variations shown by the replication line are due to a manufacturing model that forces the equipment to operate within a transient (unstable) process zone for most of the orders processed. Machine transient zone is defined as the time period required for a replication line to achieve operational stability, under normal conditions and continuous operation. The frequency and extent of the technology changes (DVD-5 vs. DVD-9), order sizes, and idle time between jobs could be major factors within the manufacturing model that affects the process yield.

Most of the efforts will be placed in the transient phase of the downstream process, base on the hypothesis that the machine of molding process should ensure stability before allowing the machine to manufacture. A series of experiment will be conducted in order to determine the transient state length.

RESEARCH OBJECTIVES

The objective of this research is identifying the mayor causes that are impacting the yield for the Replication Line, for that is important to characterize the length of the downstream transient time for both technologies. Also measuring the impact of changes in the molding process, the process yield and the cooling in the transient time. Currently the line is qualified to operate at 90% of process yield in a 4 hour job, but the line operates between 85-90% of yield. The goal is that the line operates always a yield greater or equal to 90%.

RESEARCH CONTRIBUTIONS

With this research the major contribution will be to identify what is affecting the process yield. When the company determines the major causes it will be more feasible to optimized the machine utilization. Another important contribution will be to reduce the time to stabilized the machine (reduce transient time), when they achieve this goal, the quality of the disc will be improved for both technologies and probably reduce scrap quantities. Improving the process yield to grater or equal to 90%, the defects units will be reduced and the scrap cost will be less.

RESEARCH BACKGROUND

During mid 1990's Sony and Philips announce that they were working with a new highly-density medium know as Digital Video Disc (DVD), they face many battles with Toshiba and others competitor. At the beginning they develop two prototypes: Multimedia Compact Disc (MMCD) by Sony and Philips and Super Density Disc (SD) by Toshiba and others partners. In order to avoid competition and affect the client, they decided to develop one standard format that includes both previous formats, this is the way that the DVD was born [1].

Replication Process Definition

Replication process consist of transferring the data from the source master to CD or DVD by pressing copies of a DVD glass master onto aluminum/polymer blank disc. The glass master is performed in a cleaning room, the glass is used as a substrate to hold the CD/DVD master image while it is created and processed. This glass is very sensitive, even a microscopic scratch will affect the quality of the disc, pressed from the master image. Once the glass is ready for mastering, it is place in a laser beam recorder (LBR), a laser is use to write the information with a wave length and numerical aperture chosen to produce the required pit size. Depending on whether the laser hits a pit or land, the leaser bin is reflected and received by a photoelectrical cell. The disc data is converted into electrical pulses (the bit stream) by reflection of the laser beam off a photoelectrical cell. In Figure 1 is an example of the pits and land.

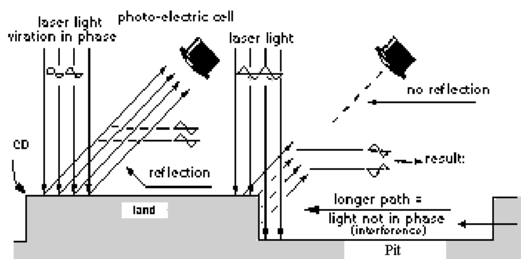

Figure 1
Drive Reflection of a Pit and Land

Replication Process Step by Step

Replication process start with Polycarbonate dry, this material is plastic and highly static generator. Dryer process is critical and important for the CD/DVD generation, if the Polycarbonate material reach the injection molding heating area without dry, many defects will appear in the disc. After the pellets are dried the injection molding process starts, this process is responsible in melting the Polycarbonate material, injecting it in the mould at high temperature (210 to 320 degrees Celsius) and pressure. Once the material is injected to mould it has to face the stamper where the data is and the mirror creating the CD/DVD. When the mould is full, cool water running through mould halves, outside the cavity and cools the plastic in order to solidify the disc. The mould then opens and the disc is removed with the data, this process is performed each 3.5 seconds, creating approximately 1,000 disc/hr. Currently this data is the process time under study.

The Downstream process is the one in charge to take the Polycarbonate clear disc form the injection molding machine and make it reflective to allow the laser reader to read it, the process is the sputtering (reflective by aluminum) and lacquering to protect the metal. Once the disc is metalized by the sputtering process, it becomes reflective, and then the lacquering process is performed to complete the disc. The purpose of placing the lacquered is to: protect the metallization (aluminum oxidation, scratch and protect the data) and create a flat surface for the printing process. All this stages are represented in the Figure 2.

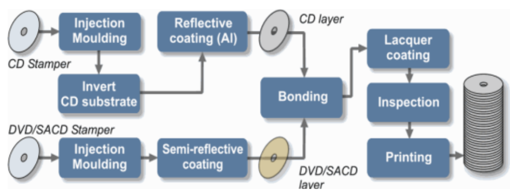

Figure 2
Replication Process Summary

RESEARCH METHODOLOGY

This section will be focus on the process that needs to be follow in order to achieve the objectives.

- Analyze historical data
  - This data is from the past year: September'10 to August'11
- Measure Transient Time for the Downstream
  - Characterize replication line
  - Measure yield during runs
  - Measure disc temperature in the downstream process
  - Measure spin station temperature
- Make cooling time variations
  - Characterize the process for the new cooling time
  - Understand the impact in the cycle time
  - If necessary study the possibility to add a device in the downstream, in order to control the temperature
- Study the possibility to have a moving yield target
- Cost analysis

RESULTS AND DISCUSSION

Current process have a cycle time of 2.3 seconds per disc, this time was modified in order to increase the cooling time and attempt to stabilize the yield. Cycle time was increase on November 2011 to 3.0 seconds; the main objective is to move more cooled disc to the input conveyor, where the discs are moved to the downstream process. Months under study are from July 2011 to February 2012.

ANOVA

The first analysis that was completed was an ANOVA, this approach is used to test the significance of regression, also to prove that there is no relation between order size before and after the change. There is a need to prove that the order size is not a variable that affects the study, meaning that the change in cycle times is the real impact on the study. Below are the results for the ANOVA, were the comparison is between order size and month (before/after). In Figure 3 are the results for the hypothesis tested:

One-way ANOVA: Order Size versus Before/After					
Source	DF	SS	MS	F	P
Before/After	1	21563549	21563549	1.1	0.296
Error	422	8296534048	19660033		
Total	423	8318097597			
S = 4434	R-Sq = 0.26%		R-Sq(adj) = 0.02%		

Figure 3
ANOVA Results

The P-Value for the test is 0.296 greater than the alpha value of 0.05, means that there is no evidence to reject the null hypothesis. Below in the residual graph, the normality of the residuals can't be proven, the residual didn't follow a normal distribution. The residuals are important because they measure the variability in the response (Y=Order Size) not explained by the regression model. Residual plot are very effective way to investigate how well the regression model fits the data [2] and to check the assumptions that the regression should follow, listed below:

- The relationship between the response y and the regressors is linear, at least approximately;
- The error has zero mean;
- The error has a constant variance;
- The errors are uncorrelated;
- The errors are normally distributed.

The residual graph below show that the previous conditions are not met, this regression doesn't fit the model.

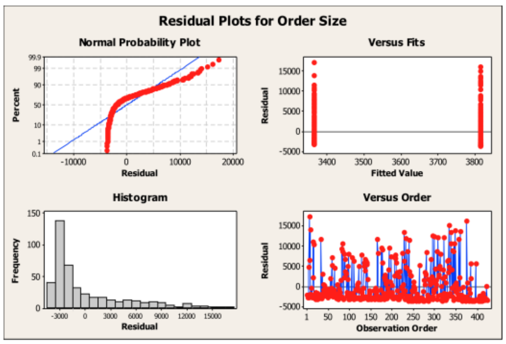

Figure 4
ANOVA Chart

In order to find a more accurate model a transformation Box Cox was applied to the response variable (Order Size), the intention is to normalize the residual. This method is a power transformation to stabilized variance and makes the data more normally distributed. In Figure 5 are the results after transformation:

One-way ANOVA: BoxCoxTransData versus Before/After					
Source	DF	SS	MS	F	P
Before/After	1	0.28	0.28	0.13	0.715
Error	422	897.19	2.13		
Total	423	897.48			
S = 1.458	R-Sq = 0.0003	R-Sq(adj)=0			

Figure 5
ANOVA Results

ANOVA results didn't varied much from the previous results, the P-value is 0.715, greater than the previous, resulting in an inability to reject the null hypothesis, there is no evidence that the order size change before and after the study. An important observation is that the residual, now are more normalized. This regression fits better to the model; even though the null hypothesis can't be rejected (see Figure 6).

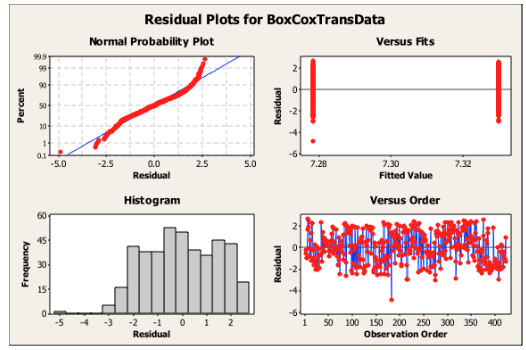

Figure 6
ANOVA Chart

Proportion Test

This method was used with the intention of compare two populations to determine whether they are significantly different. This procedure uses the null hypothesis that the difference between two population proportions is equal to a hypothesized value and tests it against an alternative hypothesis. Below is the hypothesis use for this analysis, with an alpha level of 5%.

- H_o: $P_1 = P_2$
- H_1: $P_1 \neq P_2$

The data was segregated in different ranges, in order to measure the Yield before and after the cycle time changes. The ranges selected based on experience of the Process Engineer, were the data have similar behavior dependent on the order size; the comparison is between amounts inspected and amount good. Below are the ranges for different order size under study, also multiple graphs with the count of order per ranges.

- 1-500
- 501-2000
- 2001-4000
- 4001- grater

For the first range (1-500), as shown in Table 1, there is a significant changed between the Yield before 72% and Yield after 81%, this results also can be prove with the following Proportion Analysis, were the P-value (see Figure 8) is smaller than the alpha of 5%. There is sufficient evidence to reject the null hypothesis and conclude that there is a significant difference after the cycle time was increased (see Figure 7).

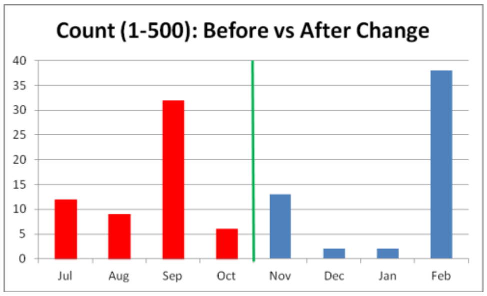

Figure 7
Count per Orders Before vs. After

Table 1
Range 1-500 Amounts Inspected vs. Amount Good

1-500	Amount Inspected	Amount Good	Yield
Before	15291	10941	72%
After	14405	11597	81%

1-500 Proportion Test

Test and CI for Two Proportions

Sample X N Sample p

1 10941 15291 0.715519

2 11597 14405 0.805068

Difference = p (1) - p (2)

Estimate for difference: -0.0895488

95% CI for difference: (-0.0991917, -0.0799058)

Test for difference = 0 (vs not = 0): Z = -18.20 P-Value = 0.000

Fisher's exact test: P-Value = 0.000

Figure 8
ANOVA Results: Proportion Test

For the other ranges the behavior was similar to the previous, there is an improvement in terms of Yield. The results are summarized in the Table 2.

Table 2
Yield before vs. Yield after

Group	Yield Before	Yield After	P-Value
1-500	72%	81%	0.00
501-2000	77%	82%	0.00
2001-4000	87%	87%	0.00
4001- greater	94%	93%	0.00

In Table 2 the results shown that the biggest changes were for those orders that are less than 2000 units. These are the results that the management expected, because for small orders the process is very unstable and the discs rejected for different quality reason are a high volume. Orders that are greater than 2000 units, the machine have more opportunity to stabilized all the parameters and run with a better yield. The limit is 91% Yield, but this is the biggest impact to the process that all the Yields were greater than 80%, in the past there are Yield below 80%, as the table shown.

Transient Time Analysis

In order to know how long the machine takes to stabilized, the Transient Time was measured, 4 runs were performed. The first 2 runs were with 2.3 seconds of cycle time and the last two were with the new cycle time of 3.0 seconds. To create a new recipe where the cycle time was increased, the technician modified the time and pressure of injection, plasticizer temperature was decreased, and increased cooling time from 1.3 sec to 1.7 sec. These adjustments took into consideration all quality parameter, the recipe preparation wasn't in the project scope. The machine plasticizer remains in standby mode at 165°C, in order to avoid humidity and that the material at the plasticizer wouldn't be degraded. Approximately the machine takes 20 minutes to achieve the temperature desired in the plasticizer, to start the production. After that it is necessary to purge the plasticizer 50 times to discard all the melted material, and then substitute with new material. At the same time the operator installs the stamper (where the data is stored), to start the run. Temperature in the plasticizer could be ±20°C; it will depend on the material (different suppliers). Currently the company has 2 suppliers for Polycarbonate, one is the preferred and the second one is the alternate in case of emergency.

For the first two runs some parameters remained the same, such as room temperature ranged between 19-20°C, mold temperature in standby mode equal to 165°C and the mold high temperature is 345°C. For the first 2 runs the transient time was stabilized approximately after 25 minutes, achieving approximately 90% of Yield, the target. An example of the results are shown in Figure 9, for both runs the input conveyor temperature start approximately at 22°C and when the Yield was achieved the temperature was 27°C, the data prove that the downstream temperature increase gradually during the run, as hotter disc input during the process. In Figure 10, we can see for the first 25 minutes a positive slope, then the Yield was stabilized, as well as the temperature.

		Temp (°C)	
Time	Yield	Spin Coat	Input Conveyor
0	0.00%	21.6	21.7
5	84.60%	23.4	25.0
10	86.87%	23.9	25.8
15	88.61%	24.0	26.1
20	89.27%	24.2	26.6
25	89.75%	24.4	26.8
30	90.02%	24.4	27.0
35	90.19%	24.5	27.3

Figure 9
First run Transient Time Data

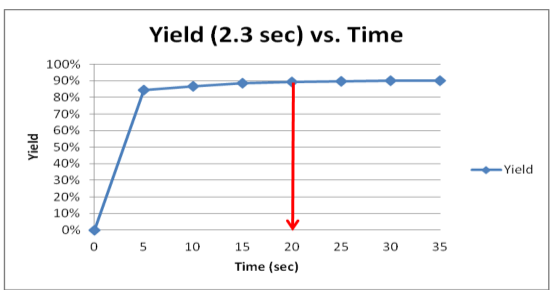

Figure 10
Yield (2.3 sec) vs. Time (sec)

For the last two runs some parameters remained the same as well, such as room temperature round between 19-20°C, mold temperature in standby mode is 165°C and the mold high temperature was decrease to 340°C, in order to have more cooled discs. For the last 2 runs the transient time was stabilized approximately after 5 min, achieving 90% of the target Yield. The data is shown below in Figure 11 as an example. For both runs the input conveyor temperature started approximately at 22°C and when the Yield was achieved the temperature was 24.5°C, the data proves that the downstream temperature for the new cooling time decreases 2.5°C for the run, more cooled disc input during the process, helps to stabilized the Transient Zone faster and the quality of the disc was improved, reducing the scrap cost. In Figure 12, we can see for the first 5 minutes a positive slope, then the Yield stabilized, as well as the temperature.

		Temp (°C)	
Time	Yield	Spin Coat	Input Conveyor
0	0.00%	23.4	22.0
5	89.18%	23.7	25.0
10	90.53%	23.9	25.8
15	90.67%	24.2	26.4
20	91.30%	24.4	26.7
25	91.28%	24.4	27.0
30	92.34%	24.5	27.3
35	92.55%	24.4	27.5

Figure 11
Third run Transient Time Data

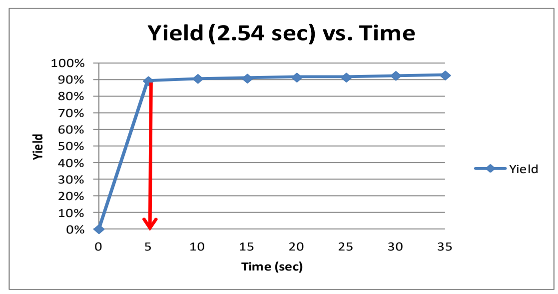

Figure 12
Yield (3 sec) vs. Time (sec)

Downtime Analysis

Finally to prove that the change in Cycle Time had an important impact in the orders, especially in orders that are less than 2000 units, an analysis of how the machine stabilized the Yield (90% or higher), after a downtime was performed. The machine is stopped for different reasons, such as: stamper change, which takes approximately 20 minutes, technology change, unplanned downtime, lack of orders, among others. An analysis was performed before the change, with 2.3 seconds of cycle time (data is shown in table below). Column Test represents the day where the run was performed and column Run, represents the different runs in the same day, std time, is the time that the order took to complete the order. For this cycle time the Yield after every stop was below the target

90%, for almost all the runs. This is due to the variability in transient zone temperature and different defects cause by these variations, such as surface spot, scratch, black spot, among others. The data is summarized below (Figure 13).

Before Cycle Time Change					
Test	Run	Std Time (min)	Amount Inspected	Amount Good	Yield
A	1	10.96	286	199	70%
	2	20.20	527	419	80%
	3	12.15	317	49	15%
B	4	69.88	1823	556	30%
	5	6.94	181	127	70%
	6	12.15	317	230	73%
C	7	7.78	203	111	55%
	8	17.37	453	391	86%
	9	97.67	2548	2382	93%
	10	4.37	114	109	96%

Figure 13
Downtime Data before the Cycle Time Change

The same analysis was performed after the cycle time change to 3.0 second, were the cooling time was increased, in order to place more cooled disc into the downstream zone. The impact in the Yield was significant, the machine's stabilized time was faster, after almost every downtime. The transient time was reduced to 5 minutes, before that change the transient time was approximately 20-25 minutes. The data is summarized below (Figure 14).

After Cycle Time Change					
Test	Run	Std Time (min)	Amount Inspected	Amount Good	Yield
A	1	36.00	190	150	79%
	2	13.00	232	225	97%
	3	13.38	242	231	95%
B	4	13.20	233	231	99%
	5	10.01	261	254	97%
	6	9.97	260	258	99%
C	7	103.19	2692	2559	95%
	8	63.98	1669	1485	89%
	9	141.11	3681	3548	96%
D	11	621.50	12430	12030	97%
	12	715.00	14300	14129	99%

Figure 14
Downtime Data after the Cycle Time Change

COST ANALYSIS

To quantify the potential cost impact of the new cycle time a cost saving estimate was developed. Many assumptions were taken into consideration in order to provide some dummy values to the real cost and total year production, below are the values utilized for this analysis.

- Disc weight = 22g
- Polycarbonate = $0.003/g
- Disc material cost = $0.07/disc
- Operators rate = $22/hr

The savings for the project were calculated base on 100% Yield vs. current and new Yields for orders that are less than 2000 units. These types of orders had a major impact in terms of Yields vs. the orders that are greater than 2000 units where the Yield was more stable, due to the run time; the machine had more opportunities to stabilize.

Below is a calculation for a Yield of 100%, this is the best case scenario, which is not the normal state of the machine, but this will be used as a base. Another assumption is that for a year the company produces 439,178 discs.

$$\frac{Hrs}{Yr} = \frac{439{,}178 disks}{Yr} * \frac{2.3\sec}{disk} * \frac{1hr}{3600\sec} = 280.59 hrs/year \tag{1}$$

From equation 1 there are 280.59 hrs/year if the line runs 100% of Yield, now the same calculation will be made, but with a Yield of 74%, which is the average Yield for orders that are less than 2000 units. For this Yield its necessary to calculate how much disc is necessary to produce in order to replace all the scrapped material.

$$\frac{Scrap}{Yr} = \frac{439{,}178 disks}{Yr} * (1 - 0.74) = 114{,}186 diks/year \tag{2}$$

In order to complete the requirements it is necessary to produce 114,186 discs per year, this over production required 72.95 extra hours (Equation 3), that were reflected in an additional cost of $9,598.06 per year.

$$\frac{Hrs}{Yr} = \frac{114{,}186 disks}{Yr} * \frac{2.3\sec}{disk} * \frac{1hr}{3600\sec} = 72.95 hrs/year \tag{3}$$

$$\frac{\$}{Yr} = \frac{114{,}1186 disks}{Yr} * \frac{\$0.07}{disk} + \frac{72.59 hrs}{Yr} * \frac{\$22}{hr} = \$9{,}598.06/year \tag{4}$$

It is necessary to performed the same calculation for the new Yield with an average 81% for order that are less than 2000 units, as mentioned previously these were the orders, more impacted by the change in cycle time. Below are the calculations for the new Yield.

$$\frac{Scrap}{Yr} = \frac{439{,}178 disks}{Yr} * (1 - 0.81) = 83{,}444 diks / year \quad (5)$$

As shown in order to complete the requirements it is necessary to produce 83,444 discs per year, there is a delta of 30,742 discs compared with a Yield of 74%, they will need less hours to complete the requirements. This over production required 69.54 extra hours (Equation 6), which were reflected in an additional cost of $7,370.96 per year.

$$\frac{Hrs}{Yr} = \frac{83{,}444 disks}{Yr} * \frac{3.0 \sec}{disk} * \frac{1hr}{3600 \sec} = 69.54 hrs / year \quad (6)$$

$$\frac{\$}{Yr} = \frac{83{,}444 disks}{Yr} * \frac{\$0.07}{disk} + \frac{69.54 hrs}{Yr} * \frac{\$22}{hr} = \$7{,}370.96 / year \quad (7)$$

The results are that with a Yield of 81% the company will have a cost saving of $2,227.10 per year. This is an average value, thus it is important to keep in perspective that the Yield varies with each order, for which these savings will be higher at the end of the year. Also it is important to take into consideration that the utility cost wasn't taken into concern in this analysis.

Conclusion And Recommendations

After many attempts to improve the Yield for the replication line for both technologies DVD9/DV5, a significant improvement was made. Below a summary of the mayor contributors:

- Orders below 2000 units were the more impacted
  - Average Yield of 74% was increased to an average of 81%
  - Target Yield is 90% or higher, but the Yield was improved by a 7%
  - The process still having some external variables that affect the runs, such as stamper problems, that impacted negatively the Yield
- Orders greater than 2000 units achieved a Yield of 90% or greater, with the new cycle time
- Scrap cost was reduced by $2,227 per year, these saving will depend on the amount of units processed, and the impact could be greater.
- A recommendation would be to maintain the temperature more balanced in the downstream area plus the Yield could be even higher if the company adds a device in the downstream area that can balance the temperature between room temperature and machine temperature.

References

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[2] Montgomery, D. C. (2001). Introduction to linear regression analysis. (3rd ed., pp. 131-199). New York: John Wiley.