Use of Design of Experiments in Casting Platinum

Tino Volpe • TIFFANY & CO

Introduction

Casting platinum has always been tricky business in more ways than one might think. Not only is it a difficult metal to work with due to its high melting temperature, which requires special materials and equipment, it is very expensive to work with. Because of its value people are very reluctant to experiment with the material. Yet without experimenting to find the right parameters we run the risk of creating many bad parts at a hefty price.

So what to do? There is in fact a great tool that has been around in quality circles for many years called Design of Experiment or DOE. This fairly simple tool can be used to quickly determine important parameters for casting platinum while at the same time weeding out the trivial ones so we don't waste our time with them. This paper will show how we can use DOE, or more specifically factorial designs, to find out what is important when casting platinum.

Background

Designed Experiments, sometimes referred to as statistically designed experiments has been used in quality circles for many years. The classical view of experimentation is to change one factor at a time, run the experiment, observe the results, and move on to the next factor. This approach has several shortcomings.

1. This approach takes much longer and uses up more resources.
2. The optimum combination of all variables may never be revealed
3. The interaction between factors may never be revealed.

By using statistically designed experiments we can achieve the following benefits;

1. Many factors can be examined simultaneously
2. Some input factors which cannot be controlled, which are called noise factors, can influence the output, however other input factors can then be controlled to reduce the effect of this noise.
3. In depth statistical knowledge is not necessary to perform these tests and reap their benefits.
4. Relatively few experiments can look at a large number of factors and separate the trivial from the important.
5. Quality and reliability can be improved without increasing cost in most cases.

Experimental design was developed in England and the US many years ago however, it was aimed at statisticians and engineers were not exposed to it until a Japanese engineer by the name of Genichi Taguchi took the method and adapted it for use by Japan's engineering community. In the 1980's as Japan was fast becoming a world economic leader, American's noticed the Japanese using a powerful new tool. It was referred to as the Taguchi method. Taguchi published a book on the subject in 1987.

The celebrated case study showing the power of this method involved a tile manufacturer that purchased a new very expensive kiln to bake tiles. However the process was producing tiles with large dimensional variations. They measured the temperature in the kiln and discovered that there were large temperature variations in the kiln. The problem was that it would be too expensive to fix the temperature problem so they had to live with it. So they treated the temperature factor as noise and ran a designed experiment to find the proper levels of other factors that would make the temperature variation insignificant. They looked at seven factors and found after running the tests that by changing the level of limestone in the mix they could make the tile dimensions insensitive to the temperature variation in the oven. They also found at the same time that they could use less of a more expensive ingredient without affecting the quality of the tile, thus solving their problem and reducing their cost.

We can apply this same methodology to help us solve our casting problems and we can be confident in the data we collect.

Experimental Procedure.

I wanted to use this DOE not only to demonstrate the power of it but also to try and prove a hypothesis that I have, and to settle some bets. I've always wondered about whether position on a casting button affects the fill rate when casting by the centrifugal method. Common sense would dictate that parts located at the leading edge of the swinging arm would fill less since the metal wants to travel back in the opposite direction. Therefore parts on the trailing edge would fill better because the metal would enter with more force. It's like being on a roller coaster and at the first drop you feel yourself being pulled out of your seat as your body wants to go in the opposite direction of the coaster. If this was really true in centrifugal casting it would have large ramifications because it would mean that I should put all my parts on one side of the button and I would then need to orient my flasks as I placed then in the cradle to make sure all my parts were on the trailing edge of the arm swing.

I wanted to look at the four major factors in casting platinum by the centrifugal method; flask temperature, metal temperature, acceleration, and velocity.

The first thing I had to do was set up my factorial matrix. I will run what is called a 2 by 4 factorial which means I will be looking at 4 factors at two levels for each factor. The levels are denoted by a plus and a minus and you want to bracket your levels within reason of what you think will work or in some cases within the limits of the process. Once you set up the matrix it is going to look something like what we see in Chart 1.

Flask	Vel	Acc	Cast Temp (C)	Oven Temp (F)
1	–	–	–	–
2	+	–	–	–
3	–	+	–	–
4	+	+	–	–
5	–	–	+	–
6	+	–	+	–
7	–	+	+	–
8	+	+	+	–
9	–	–	–	+
10	+	–	–	+
11	–	+	–	+
12	+	+	–	+
13	–	–	+	+
14	+	–	+	+
15	–	+	+	+
16	+	+	+	+

Chart 1

As can be seen a 2x4 factorial requires 16 experiments to cover every factor at every level. This sounds like a lot of experiments but we will be looking at the effects of four factors and their interactions at once and a large amount of information will be garnered from this. Once we have our setup we can plug in our parameters for our levels as we did in Chart 2.

Flask	Vel	Acc	Cast Temp (C)	Oven Temp (F)
1	200	4	1825	1450
2	500	4	1825	1450
3	200	1	1825	1450
4	500	1	1825	1450
5	200	4	1975	1450
6	500	4	1975	1450
7	200	1	1975	1450
8	500	1	1975	1450
9	200	4	1825	1550
10	500	4	1825	1550
11	200	1	1825	1550
12	500	1	1825	1550
13	200	4	1975	1550
14	500	4	1975	1550
15	200	1	1975	1550
16	500	1	1975	1550

Chart 2

The two levels for velocity represent the maximum and minimum limits of the machine. The acceleration also represents the upper and lower limits of the machine. In the case of acceleration the higher number denotes the lower speed. The cast temperature was chosen a bit arbitrarily but I wanted to make sure and pick temperatures that will give me both fill and non-fill because if everything fills 100% then we won't have any good data to correlate. The oven temperatures represent the range of what I typically use in production.

The machine that we will be doing this casting on is a commercially available double broken arm induction casting machine. A single broken arm machine or a straight arm machine would probablt give me different results and if the machines were available they could have used as factors. Casting will be done in partial vacuum and casting temperature is measured and displayed via an optical pyrometer.

Our fill pattern is a classic grid used by many people to test for castability (Figure 1). The grid is divided into 100 squares which makes calculating fill very convenient as we can just count how many squares fill and we have our fill percentage. The criteria were that a square had to be filled completely to be counted. The grid had a gate along one edge with the main feeder located in the middle of that.

A grid was placed every 90° around the button, or at the 12, 3, 6, and 9 O'clock position. It was decided to place all the grids parallel to each other (Figure 2).

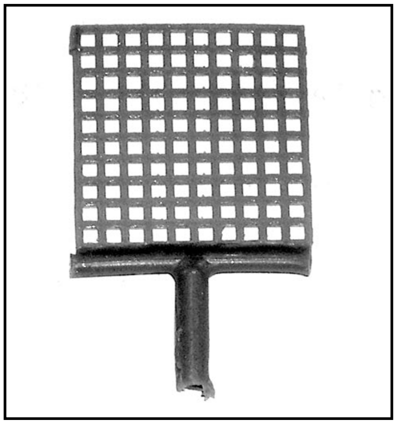

Figure 1: Grid

In order to be able to tell which grid is at the 12 O'clock position and which is at the 6 O'clock position, a very small bead of wax was placed at the top of the grid located at the 12 O'clock position (Figure 3). It was deemed that this small drop of wax would have no affect on the filling of the pattern.

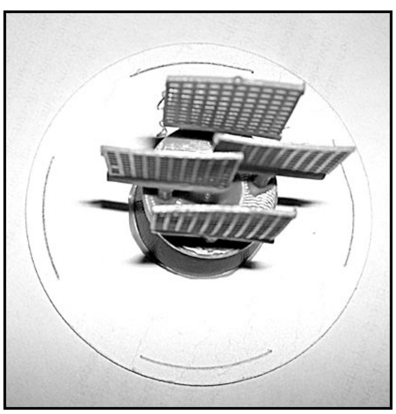

Figure 2: Grids showing location and identification. Note small bead at top grid.

Now once we have our waxes on the button and oriented, we have to find a way to make sure that orientation is held during the casting process. Once the flasks are invested, one cannot see the pattern to insure that the flask is oriented the same way in the machine. To accomplish this I welded a small bead of metal to the outside of the flask (Figure 3).

Figure 3: Flask showing welded bead

When the flask was mated to the based the bead of metal was lined up with the bead of wax on the grid (Figure 4).

Figure 4: Flask assembly showing bead line up.

Due to space restrictions on the button the waxes at the 3 and 9 O'clock positions had to be off set slightly to avoid them touching, a compromise that had to be made. The flasks were now ready to invest.

Investment occurred in a vacuum investment mixer utilizing the standard commercially available acid based platinum investment. Flasks were allowed to dry for 4 hours and then each flask marked with a sequential number 1 thru 16. Burnout was accomplished in a rotating electric burnout oven which gave a good degree of uniform heat. All the flasks were placed in the oven so that the metal bead faced outward. This would make it easy for the operator to grab the flask and place it in the cradle with the bead facing up in the 12 O'clock position and therefore the grids in the proper orientation.

Burnout was a 14 hour overnight cycle with the first 8 flasks cast at the 1450 degree temperature. Then the oven was raised to 1550, allowed to soak for 1 hour and the other 8 flasks were cast. Typically in a true

DOE one wants to perform the runs in a random order, however when dealing with flask temperature changes this can be very cumbersome so I chose to run the experiment in standard order. Metal used was Pt-5Ru. The flasks were quenched in water one at a time and the flask number immediately engraved on the button to preserve the integrity of the order. The trees were then cleaned by boiling in caustic soda solution. Without removing the grids from the buttons the number of squares that filled on each grid was counted for each position on the button. Once all the data was collected, it was ready to be analyzed (Figure 5).

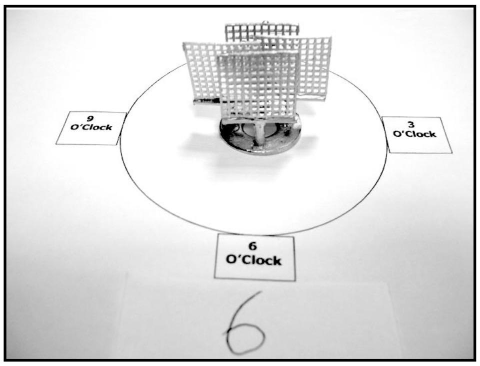

Figure 5: Example of complete fills

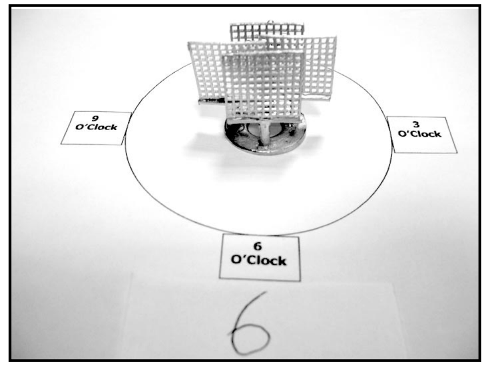

Figure 6: Example of incomplete fill

Results

There are several ways we can look at this data. Just looking at the raw results, we can see that the higher temperature seemed to give us complete fill regardless of position (Chart 3).

					Position on tree			
Flask	**Vel**	**Acc**	**Cast Temp (C)**	**Oven Temp (F)**	**12**	**3**	**6**	**9**
1	**200**	**4**	**1825**	**1450**	76	27	58	60
2	**500**	**4**	**1825**	**1450**	86	86	39	86
3	**200**	**1**	**1825**	**1450**	28	74	75	56
4	**500**	**1**	**1825**	**1450**	97	82	97	100
5	**200**	**4**	**1975**	**1450**	100	100	100	100
6	**500**	**4**	**1975**	**1450**	100	100	100	100
7	**200**	**1**	**1975**	**1450**	100	100	100	100
8	**500**	**1**	**1975**	**1450**	100	100	100	100
9	**200**	**4**	**1825**	**1550**	71	63	72	82
10	**500**	**4**	**1825**	**1550**	64	76	57	98
11	**200**	**1**	**1825**	**1550**	59	48	100	91
12	**500**	**1**	**1825**	**1550**	88	83	68	100
13	**200**	**4**	**1975**	**1550**	100	100	100	100
14	**500**	**4**	**1975**	**1550**	100	98	100	100
15	**200**	**1**	**1975**	**1550**	100	100	100	100
16	**500**	**1**	**1975**	**1550**	100	100	100	100

Chart 3

It also seems at first glance that temperature was the only influence. However, our calculations will confirm that.

Now that we have our data we would like to see which factors influenced fill at each position and whether that position played a role in the amount of fill. The way to find out the influence of the factor is to take the results from all the low level runs of that factor, sum them together and subtract that number from the sum of the results from all the high level runs of that factor. Then take that result and divide it by the number of runs at the high level, in this case, 8.

Taking the influence of the velocity factor at the 12 O'clock position for example, our calculation will look something like this:

$$\frac{(86+97+100+100+64+88+100+100)-(76+28+100+100+71+59+100+100)}{8} = 12.625$$

What this tells us is that running the experiment at the higher velocity level (500 RPM) will increase our fill rate by 12%. It seems like a decent influence.

We can run these formulas for all the factors at all the positions. Doing so will give us the results seen in Chart 4.

Looking at the data we can confirm our earlier feeling that the greatest influence seems to come from the metal temperature, where going from 1825 to 1975 will increase our fill between 15 and 32% depending on the position of the piece on the button. The least amount of influence comes from the flask temperature as well as the metal x flask interaction. This means that changing the flask temperature at a given metal temperature will not really affect our results. This would be true for that range of flask temperature. If we were to pick a range of let's say room temperature vs. 1800°F our results may be very different. To create the formula for the interaction of two factors, one needs to multiply our pluses and minuses for each factor at each run. Remembering that two minuses make a plus and so forth, we come up with our column of pluses and minuses in which to calculate our formula.

These influences can also be graphed which sometimes makes them easier to visualize. While the formulas for this exists, there is also great software out there today that will not only do these calculations but they will also set up the experiment, graph the results and show all the interactions as well as calculate the possible error margins. All you have to do is type in your factors and levels. Figures 7 and 8 show these influences in charted form for the 12 O'clock position.

Factor	12 o'clock Position	6 o'clock Position	3 o'clock Position	9 o'clock Position
Vel influence	12.625	-5.5	14.13	11.875
Acc Influence	-3.125	14.25	4.625	2.625
Metal Temp. Influence	28.875	29.25	32.375	15.875
Flask Temp. Influence	-0.625	3.5	-0.125	8.625
Vel x Acc Interaction	11.875	3	-3.375	1.375
Flask x Metal Interaction	0.625	-3.5	-0.375	-8.625

Chart 4

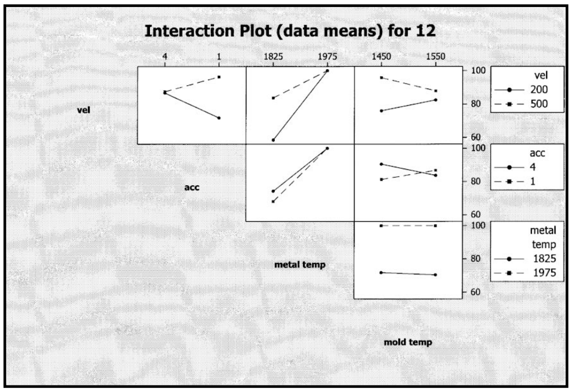

Figure 7

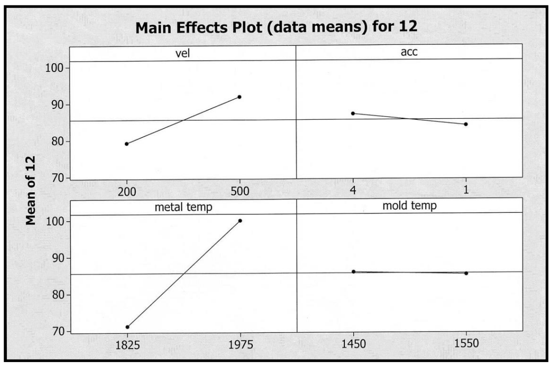

Figure 8

In Figure 8 the effects are plotted against the percent yield we achieved. A horizontal line, such as what we have for mold temperature indicates that there is no increase in fill going from 1450 to 1550, therefore, no influence. Metal temperature however, shows a sharp increase in fill going from 1825 to 1975. Interestingly enough we see that there is a slight decrease in fill going from a slow to a fast acceleration. Does this mean that increasing the acceleration causes more turbulence, thus reducing the ability to fill?

Figure 7 plots the interactions. Parallel or nearly parallel lines demonstrate little interaction as we can see in the bottom most chart of mold vs. metal. What this demonstrates is that at a given metal temperature, increasing the mold temperature has no effect on amount of fill. Criss crossing lines mean a strong interaction such as can be seen in acceleration vs. mold temperature, where at the higher acceleration fill goes up with mold temperature but at the lower acceleration fill actually goes down with mold temperature going up. This seems unusual and one would want to repeat the experiment to see if this holds out. In fact the DOE software allows for replication so that it can calculate the residual errors that the data might show. This allows one to greatly increase the confidence level of the results.

Going back to our chart of the results, we can also see that if we look at the metal temperature influence, there seems to be a difference to whether the pieces is on the forward side of the swing or the back side. The influence at the 3 O'clock position is twice of that at the 9 O'clock position while the 12 and 6 O'clock positions show the same influence. This seems to show that there is indeed a difference in whether the parts are on the forward end of the swing or the back end.

Does this mean that we have to put all our parts on one side of the button and orient our flasks? Not necessarily. We can go back to the case study of the ceramic kiln and follow the same path. We can treat the position of the piece on the button as a noise factor and work with our other factors to eliminate the influence of the position. We seem to have done that already because looking at the data we see that all the flasks cast at 1975°C had all the grids filled regardless of mold temperature, acceleration, or velocity.

Conclusions

In running DOE's it is important that one understands the factors at work and also the effect of other variables. This experiment just presented showed what factors could influence fill in a casting. Based on the data all we would have to do is crank the melting temperature up and we would not have to worry about fill any longer. However, a factor that this experiment doesn't address is porosity in a casting and whether raising the casting temperature would influence porosity. We would have to run another DOE looking at the amount of porosity as a result if we could quantify the number. So it is important to understand how other variables and factors might affect your results.

- DOE's allow us to reduce trail and error experiments by looking at many factors at once instead of one at a time.
- DOE's allow us to separate the important from the trivial
- DOE's can show us previously unknown interaction between two factors
- To get the most out of the power of DOE's it is important to plan out the experiment and understand all variables that may come into play.
- Modern day software allows us to setup large DOE's and run only a fraction of the tests (fractional factorials) that still show the influences and interactions of factors.
- Even in its most basic form DOE's are powerful tools for collecting information from a relatively small number of tests.
- In order to run a successful Experimental design, it is important to be able to quantify your results.

Acknowledgements

1. Taguchi, G. (1987) System of Experimental Design, 2 Volumes, Dearborn MI: Unipub/Kraus/American Supplier Institute
2. The Quality Engineer Primer © by Bill Wortman, Quality Council of Indiana 6th edition August 1999
3. ©MINITAB release 14. Minitab Inc. 2003