Chapter 5

Experimentation Details

5.1 Design of Experiment

The design of experiments (DOE) was needed to analyze our data. Our aim is to find the optimized values of our 3 variables namely,

1. Melting temperature (tm)
2. Shell preheat temperature (tpst)
3. Pour height (hp)

and their combined effect on following responses.

1. % inclusions rejections
2. % cold shut rejections
3. Hardness
4. Surface finish
5. Tensile strength

Based on our process system aim as explained above, factorial design is used. Details in brief for the same are given below.

**Factorial Design:** In statistics, a full factorial experiment is used for a data which consists of two or more factors (or variables), each with discrete possible values or "levels" (generally low and high). These factors take on all possible combinations of these levels across all such factors. Such an experiment allows the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. In our case there are 3 variables and 5 responses and we can determine correlation of every response with all variable individually and with interaction of variables. As we have 3 variables, it was decided to use $2^3$ factorial design and details are given as below.
5.2 Selection of Variable Parameters and Ranges

Since pour process for investment casting method is chosen for the experimentation, variables involved in the processes are to be selected carefully. The variables which affect directly towards the cost of quality or to the reduces rejection rate due to defects are

1. Composition of alloy
2. Pour time in seconds (more the better)
3. Flow control of metal pored in kg/sec (should be continuous and consistent)
4. Effect of turbulence caused by flow rate inside the shell cavity (Height of pour nozzle from pour cup)
5. Shell temperature consistency in °C
6. Melt/pour temperature consistency in °C
7. Weather (control of temperature in the melt area) in °C
8. Time consistency for every operation involved in the pour process above as applicable.

Based on above parameters following variables were selected

As our observation of current process and defects data, for production pieces CD-50, it is clear that major defects were found to be cold shut and inclusions. Ceramic inclusions though related to shell area, slurry, slag and inclusions from melting and return scrap also contribute to overall inclusion defects. Cold shuts are due to molten metal temperature, Shell temperature. Also pour height consistency during pouring influence flow velocity and pour control. Based on these variables, Melt Temperature (tm), Preheated shell Temperature (tpst) and pour height (hp) were chosen as major variables. As our aim is to see effect and study of these variables with defects, it is also important to check other properties of casting like hardness, tensile strength and surface finish. This will also give better understanding of chosen pour variables on the overall quality of castings. Three variables are explained as below

1. **Melt Temperature (tm)**: Melt temperature is the basic parameter which controls the metallurgical properties of metal when poured in the investment shell. Variables within pour temperature will give inconsistent results with fluidity of metal inside the mold, uniform filling of the mold etc. for SS 304 melting point is between 1400-1500 °C. But the actual liquidus phase can be roughly as high as 1650 °C from the phase diagram. The foundry in experimentation uses generally 1595-1620 °C based on their experience for melting. Therefore it is decided to cover this range and then come with high and low ranges accordingly.
2. **Preheated shell temperature (tpst):** Preheated shell temperature is also an important variable in the pour process for investment casting process. Most of the time shells are kept in the firing oven but not uniformly heated based on the efficiency of the oven and location of shells in the oven. Variability in shell temperature will cause heat transfer properties of the shell causing changes or inconsistency of solidification of metal. It is very much related to melt temperature also as a co-factor. The actual maximum temperature achieved inside the oven in the experimental foundry is $1080^\circ C$ When checked with laser gun, shells inside the oven seem to vary every time by considerable range many times. The oven temperature was set anywhere in between $1980$ to $1040^\circ C$ based on shell types on an assumption without any scientific background. So it was decide to keep the oven at $1000^\circ C$ and $1060^\circ C$ and ranges of the shell temperature were set according at respective temperature.

3. **Pour height (hp):** Pour height plays an important role in pour systems and methods. In general an optimal pour height to be optimized. Too low pour height may cause less turbulence and not give enough head pressure to fill the investment shell properly. In the other hand too big of the pour height might give more turbulence but might lose more heat while in pour process. To exactly know the effect of pour height on quality of castings pour height ranges were chosen according based on average pour height achieved by current hand pour method (2" and 5").

### 5.3 Experiment Details

Based on our data collection method for variables and output parameters it was decided to use $2^3$ factorial design. It was used to obtain the correlation between all outputs and variables individually. Later on this correlation is further optimized for variables ad parameters using Genetic Algorithm method. Variables.

1. Pour Height: a) Lower range (1-3" from pour cup) b)Higher range (4-6" from pour cup).

2. Pour temperature: a) Lower range (1590-1610 $^\circ C$ -) b)Higher range (1615-1635 $^\circ C$+).

3. Preheated shell temperature: a) Lower range (830-870$^\circ C$-) b)Higher range (880-910$^\circ C$+).

Responses based on the Design of Experiment and analysis were chosen as

1. Percentage rate of castings due to inclusions (Slurry).

2. Percentage rate of castings due to cold Shuts.

3. Surface hardness (BHN).

4. Surface finish effect of bottom pour (RA).
5. Tensile Strength (MPa).

Table 5.1: Details of design of experiment

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Melt Temperature</th>
<th>Shell Temperature</th>
<th>Pour Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As observed from the data collected at the foundry where experiments were conducted, inclusions and cold shuts were found to be the main reason for scrap and for cost of quality. So it was essential to take these tow defects as the responses to chosen variables. Surface finish is related to interface reactions of molten metal and preheated shell and is very important for quality of castings, especially in investment castings where surface finish does matter as a parameter of quality. Hardness and tensile strength are mechanical properties of SS 304 and was chosen to see any effective relation was found between combinations of chosen variables.

5.4 Details of Automation and Changes to the Current Process for Experimentation

5.4.1 Gantry Crane Set up with X, Y, Z Movements

For handling the bottom pour ladle and pouring, Gantry train was set as shown in the Picture.

Details:

- X = Transverse travel = 50 ft.
- Y = Across Travel = 20 ft.
- Z = Up & down movement = 4 ft.
Figure 5.1: Crane structure view from front

Figure 5.2: Crane structure view from front
5.4.2 Details of New Bottom Pour Ladle Construction

5.4.2.1 Phases for Construction of Ladle

1. Design ladle per requirements
2. Fabrication of pour ladle per phase 1
3. Assembly of pour nozzle & stopper rod
4. Ceramic coating of SUPERHEAT-A
5. Firing of ceramic coating for setting up ceramic core in phase 4

Separate ladle was manufactured to hold maximum of 400 kg molten metal. Basic material was Mild Steel plate (15 mm) fabricated into 400 mm Dia x 600 mm Height open cylinder with single hook overarm with crane hanging hook (Fig. 5.5).

Then was layered with a special ceramic coat 3.5” all around with special coat as given in table 5.3 (SUPERHEAT SUPREME A - Vibration Cast).

Fig. 5.7 shows the application of ceramic coat along with ceramic fabrication layer at the bottom of the ladle.
5.4.2.2 Design of ladle

Calculations for 400 kg ladle (Total volume of SS304)

Total mass = 400 kg.
Density of SS 304 - 7800 kg/m³
Total Volume needed \((\frac{400}{7800})\) m³ = 0.051m³ = 51000000 mm³ = \(V_1\) \(\ldots\) Eqn 1

Maximum Dimension were take 600mm (Height-h) x 400mm(Bottom Dia-r)x450mm (Upper Dia-R)
(Based on physical measurements to see the operation of ladle in current situation)

Using Formula for frustum of a cone

\[ V = \frac{\pi h}{3} (R^2 + Rr + r^2). \] \(\ldots\) Eqn 2

It was decided to put 30 mm coat of SUPERHEAT SUPREME Material with practical/affordable cost for the price of the material.

That gives 570mm inner height, 420mm Upper Dia, 370 mm Lower Dia and volume with same formula as in Eqn 2 we get, inside volume to hold the metal of 64626695 mm³ = \(V_2\) > \(V_1\) = 51000000 mm³ (Eqn 1) Giving factor of safety of 1.26 for over spill of alloy.

This gave volume of with a formula below of \(-85172500\) mm³ = \(V_3\)

So it gave \((V_3) - (V_1) = 341725000\) mm³ extra volume for ceramic coat thickness.

So final dimensions of height = 600 mm, Upper Dia = 450mm and lower Dia = 400mm
with 15 mm standard thickness MS plate fabrication was decided.

Figure 5.5: First Phase MS Fabrication

Figure 5.6: Coating details of Ladle
The coat was cured by 12 hours of wooden heating to be ready for use as shown in Fig. 5.8.
A special shaped lead nozzle was used for smooth contact area of bottom ceramic cup and the nozzle as shows in fig. 5.10 & 5.9. That helps slow freezing of metal at the contact surface for longer pour.
Stopper rod assembly consists of Lead stopper nozzle (Fig. 5.11), 2 ceramic hollow cylinders (For protecting stopper MS rod from high heat of molten SS 304)

Fig. 5.12 Shows eccentric stopper rod assembly to facilitate pouring from furnace to this small ladle compared to large ladles used in conventional bottom pour systems. Also
it helps for pressure variation from large area of eccentric side to create more force at pour opening compared to centrally located stopper rod system.

### 5.4.3 Special Coating Used in Ladle

Increasing of refractory strength to sustain heat effectively – More effective refractory metals with right thickness and strength to be used and right cross section area of the chosen refractory are to be used. In this case, SUPERHEAT SUPREME A (Vibration Cast) is used with following composition and properties given in Table 5.2.

Composition: Al₂O₃ 77.6%; SiO₂ 13.5%; CaO 4.4%; TiO₂ 2.3%; Fe₂O₃ 1.4%; Other - 0.8%

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Temperature °F</th>
<th>Density gm/cm³</th>
<th>Linear Expansion %</th>
<th>MOR MPa</th>
<th>Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>230</td>
<td>2.45</td>
<td>1.53</td>
<td>7.6</td>
<td>21.7</td>
</tr>
<tr>
<td>1315</td>
<td>2400</td>
<td>2.4</td>
<td>1.5</td>
<td>9.3</td>
<td>29.2</td>
</tr>
<tr>
<td>1400</td>
<td>2550</td>
<td>2.65</td>
<td>1.67</td>
<td>18.0</td>
<td>19.4</td>
</tr>
<tr>
<td>1480</td>
<td>2700</td>
<td>2.8</td>
<td>1.78</td>
<td>26.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>

As discussed before a ceramic coat was used with lowest thermal conductivity using higher percentage of Al₂O₃ and subsequent higher percentage of SiO₂. This is a newly developed coating system and can be used also for a crucible layering for lining and it has more longer cycle life than conventional ceramic brick lining.

### 5.4.4 Details of Spring Introduced for Easy Control and Back Up Force for Pour Handle

After few trials with the ladle, it was realized that due to metal flow under the bottom nozzle, it was hazardous to stop the flow after pour into each shell and lots of force was needed by the operator. So it was decided to add a compressive spring to assist the operator to close the flow automatically when lever was pulled down to open the flow. The design of spring was done as followed:

**Calculations for Spring:**

- Buoyancy force of 300 kg of 304S = 300 x 9.8 N = 2940 N.

**Buoyancy Force Calculations:**

- \( V_s \times D \times g = F_b \) (Force of Buoyancy as shown in fig. 5.13)

\( F_b = 328.7 \) as Max work load so for Spring design

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Figure 5.13: Buoyancy force & pressure acting on spring

Where,

- $V_s$ - Volume of Specific of object immersed in fluid (Metal) = 0.0043 m$^3$
- $D$ - Density of metal (SS 304) = 7800 kg/m$^3$
- $g$ - Gravitational acceleration = 9.8 m/s$^2$

Figure 5.14: Spring details

Where,

- $D$ - Mean Diameter
- $d$ - Wire Diameter
- $\alpha$ - Helix Angle
- $n_t$ - Total no. of turns
- $P$ - Torsional Shear Stress
CHAPTER 5. EXPERIMENTATION DETAILS

Input data:

- Maximum working load (Fmax) = 328.70 N
- Minimum working load (Fmin) = 150 N (weight of stopper rod mechanism)
- Length of spring at maximum load (Lmax) = 112 mm
- Length of spring at minimum load (Lmin) = 121 mm
- Shear modulus of material (G) = 77500 MPa
- Permissible torsional shear stress (Tmax) = 2065 MPa (SS 302)
- Selected SS 304 spring (Bhakhand Industries, Pune) with 36 mm mean diameter (D) and spring of 3 mm Dia (d).

With the given max Buoyancy force for and spring dimensions, required torsional shear stress (Tmax) was calculated as

\[ T_{\text{max}} = \frac{8 \times D \times F}{\Pi D^3} = 1116.60 \text{ N/mm}^3 \text{(Less than } T_{\text{max}} \text{ of SS 304 = 2065)... Eq. 1} \]

So the spring was used for the given purpose of automatic push back of stopper rod nozzle after pour for each shell was over without manual closing.

Figure 5.15: Spring as bought - 279 mm free length
5.4.5 Pour Height Control as a Variable

To control the pour height of ladle, vertical Y direction support beam was calibrated using Radium Scale of Standard 30 cm (1') scale. Standard CD-50 Shell as shown in fig. 5.17 was used for the calibration. The procedure was as followed:

1. Put CD-50 Shell on the sand tray (Sand level to be maintained at +/- 1 in).
2. Attach bottom pour ladle to the crane hook.
3. Adjust the pour nozzle and pour cup distance to 2” by lowering or increasing ladle vertical movement using crane control.
4. Once the height is as adjusted as in step 3, a radium scale was attached at the joint of the sliding part of the vertical channel with exactly 2’ mark will touch there.
5. Now taking step 4 as shown in fig. 5.18 a reference a crane height from pour cup of the CD-50 shell as required.
5.4.6 Gas Nozzle to Preheat The Ladle

To reduce $\Delta T$ between molten metal (about $1600^\circ$C on average) and inner surface of ladle, a special commercial nozzle that can be used on home/commercial LP gas was chosen which can produce a flame of $1200^\circ$C is chosen as shown in fig. 5.19 & 5.20. Details of the same are given in Table 5.3 below.
This gas nozzle was bought from Poona Gas Company. Its maximum flame at almost 84,000 kCal/hr produces flame of almost 1130°C (Checked by Laser Gun). This allows preheating volume of the ladle in one hour compared to oil heat of 4 hours. Also Oil heating only gives temperature only to 700°C after preheat of almost 4 hours. Also the preheat temperature achieved by this gas gun is about 1050°C and works very well to reduce T to almost 550°C giving more time for fast cooling alloy like SS 304.

Table 5.3: Properties of S-80 burner [17]

<table>
<thead>
<tr>
<th>Model</th>
<th>Length</th>
<th>Head D</th>
<th>Working Pressure</th>
<th>Consumption/Hr</th>
<th>Rated Heat output</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-80</td>
<td>383 mm</td>
<td>50 mm</td>
<td>0.14 Kg/cm²</td>
<td>2.70 kg</td>
<td>65,000 kcal/hr</td>
</tr>
<tr>
<td></td>
<td>15.01 in</td>
<td>2 in</td>
<td>2.0 psig</td>
<td>6 lbs</td>
<td>120,000 btu/hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.40 Kg/cm²</td>
<td>7.61 kg</td>
<td>84,670 kcal/hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20.0 psig</td>
<td>16.9 lbs</td>
<td>3,36,000 btu/hr</td>
</tr>
</tbody>
</table>
CHAPTER 5. EXPERIMENTATION DETAILS

5.4.7 Non-Contact Temperature Measurement Laser Gun

As one of the variable in the experiment was the preheat temperature of the shell, we had to make sure that there was an exact temperature with at most accuracy and with safe handling. The laser gun was used to take these measurements. It is made by EUROLAB and its Specifications are given as below in Table 5.4.

The laser gun was useful and handy to reconfirm some the temperatures quickly other than only checking preheated temperature of shell.

Table 5.4: Specifications for Non-contact and Contact IR laser gun

<table>
<thead>
<tr>
<th></th>
<th>(EUROLAB IR 1850) Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR1850 Range</td>
<td>-50°C to 1850°C (-58°F to 2462°F)</td>
</tr>
<tr>
<td>Optical Resolution D:S</td>
<td>50:1</td>
</tr>
<tr>
<td>Type K Temperature Range</td>
<td>-50°C to 1370°C / -58°F to 3362°F</td>
</tr>
<tr>
<td>Type K Temperature Range</td>
<td>0.1 degree upto 1000 degree, 1 degree over 1000 degree</td>
</tr>
<tr>
<td>Resolution Time</td>
<td>less than 150ms</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 °C / °F</td>
</tr>
<tr>
<td>Basic Accuracy</td>
<td>±2% for reading, ±3.6 °F (+2°C)</td>
</tr>
<tr>
<td>Spectral response</td>
<td>8~14μm</td>
</tr>
<tr>
<td>Emissivity adjustable</td>
<td>0.1 to 1.0</td>
</tr>
<tr>
<td>Operating temp</td>
<td>32-122 °C ( 0 to 50 °C )</td>
</tr>
<tr>
<td>Storage temp</td>
<td>-4 °F to 140 °F ( -20 TO 60°C )</td>
</tr>
</tbody>
</table>

![EUROLAB Laser Gun](image)

Figure 5.21: EUROLAB laser gun

Fig. 5.21 shows an actual picture of EUROLAB IR 1850 non-contact laser gun. It has been used for getting accurate temperature of preheated shells.
After above modifications, new equipments set-up, experimentation procedure was decided as per flow chart in fig. 5.22. Also Experimental procedure is shown in detail in Chapter 5.

Time study of modified bottom pour cycle

1. Crucible to ladle pour - 10 sec
2. Ladle to sand bed - 20 sec
3. Time to pour two shells - 25 sec
4. Total cycle time - 55 sec (10 sec + 20 sec + 25 sec)
5.5 Experimental Procedure for experiment

1. Keep the metal composition as required by SS 304 specifications. Melt the heat to the temperature specifically to the temperature range as per the design of experiment table given in Table of Design of Experiment. This is done by pyrometer checks as shown fig. 5.23 and digital output of the same. Metal was poured in the ladle as shown.

![Pyrometer metal temperature check](image1)

Figure 5.23: Pyrometer metal temperature check

2. At the same time ladle is preheated using gas nozzle S-80 as shown fig. 5.24 as described before for minimum of one hour so that inside temperature of ladle ceramic coat (SUPERHEAT SUPREME GRADE A) is in the range of 900-1000 °C.

![Ladle preheat by S-80 gas nozzle](image2)

Figure 5.24: Ladle preheat by S-80 gas nozzle
3. De-waxed shells are put in the oven along with test bar molds (Used for mechanical properties) and oven range is set to 1000-1060 °C depending on temperature range required as per the experiment. Then they are put in the sand bed when ladle is moving from crucible to sand bed as shown fig. 5.25.

![Preheated shells kept on the sand bed](image)

Figure 5.25: Preheated shells kept on the sand bed

4. Ladle was taken to the furnace as shown in fig. 5.26 and an approximate amount of SS 304 was poured in the ladle to fill at least two molds of CD-50.

![Metal transfer from crucible to bottom pour ladle](image)

Figure 5.26: Metal transfer from crucible to bottom pour ladle

5. Ladle was moved to pour area/sand bed where preheated shells are put. Shell temperature was measured with laser gun EUROLAB 1850 to confirm the temperature of shells is according to experiment requirements.
6. Confirm that ladle opening was aligned with pour cup of 1st mold as shown in fig. 5.27. Mold is poured by using lever connected to stopper rod assembly.

![Figure 5.27: Bottom pour of the shell using stopper rod lever](image)

7. After it the ladle was immediately moved to the next mold in line of pour. Second mold pour temperature was measured again by laser gun EUROLAB 1850.

![Figure 5.28: BHN hardness machine at Siddhalaxmi Engg. Pvt. Ltd](image)
CHAPTER 5. EXPERIMENTATION DETAILS

Specifications:
- Mode: AI B 3000 H
- Sr. No.: 146/2007/08
- Load: 3000 kgs.
- Indent ball dia: 10 mm

Fig. 5.28 shows the BHN hardness tester used for hardness data collection.

Feedback/comfort observed from workers:
- Preheating of ladle is easy as compares to oil finned heating current crucible process
- Movement of ladle is easier with X-Y-Z movement
- Pour by mechanical lever is easy & faster
- Need some practice to get adapted to new practices

Table 5.5 shows the cost savings and time savings per annum with modified melt and pour processes compared to conventional process only for CD -50.

Table 5.5: Costing for the changes made to current process

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Description of Bought out and installed items</th>
<th>Cost (INR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EUROLAB – 1850 (Non-Contact Laser Gun)</td>
<td>22,800/-</td>
</tr>
<tr>
<td>2</td>
<td>Bottom Pour Ladle Manufacturing Cost (With Ceramic Coat)</td>
<td>42,000/-</td>
</tr>
<tr>
<td>3</td>
<td>Gantry Crane System with Maximum Payload of 3000T</td>
<td>1,85,000/-</td>
</tr>
<tr>
<td>4</td>
<td>Preheating gas Nozzle – S 80</td>
<td>6,200/-</td>
</tr>
</tbody>
</table>

Based on the changes made to the current process next chapter defines the design of estimated. We can also see the effect of the same on scrap percentage compared to current process. (Using approx. 5.06% rejection contributed by cold struts & inclusions only)

Overall 8 experiments were performers with combination as per 2³ Design of experiment as shown in wo shells were poured for each experiment. Defects were analysed for each shell. Hardness and surface finish was checked on 1 piece each from every shell. Their data was averaged. Tensile strength was taken from 1 test bar for each experimental metal heat was checked. Table 5.6 shows the final data collected. Details of this data individually as provided later in the chapter as

Defect data: Table 6.22 and Annexure B
Hardness Data: Annexure B
Tensile Strength Data: Annexure C
Surface Finish Data: Annexure D
Table 5.6: Final data sheet for analysis

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Melt Temp (tm)</th>
<th>Shell Temp (tpst)</th>
<th>Pour Temp (hp)</th>
<th>Inclusion %</th>
<th>Cold Shut %</th>
<th>Hardness BHN</th>
<th>Surface Finish RA</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1621</td>
<td>894</td>
<td>5</td>
<td>1.71</td>
<td>0.00</td>
<td>132.5</td>
<td>2.55</td>
<td>592.49</td>
</tr>
<tr>
<td>2</td>
<td>1619</td>
<td>844</td>
<td>5</td>
<td>1.68</td>
<td>0.84</td>
<td>138.5</td>
<td>1.90</td>
<td>597.88</td>
</tr>
<tr>
<td>3</td>
<td>1598</td>
<td>834</td>
<td>5</td>
<td>1.67</td>
<td>4.17</td>
<td>132.5</td>
<td>2.76</td>
<td>593.49</td>
</tr>
<tr>
<td>4</td>
<td>1604</td>
<td>892</td>
<td>5</td>
<td>0.84</td>
<td>3.36</td>
<td>134.0</td>
<td>2.04</td>
<td>596.48</td>
</tr>
<tr>
<td>5</td>
<td>1621</td>
<td>885</td>
<td>2</td>
<td>1.71</td>
<td>0.85</td>
<td>137.0</td>
<td>2.76</td>
<td>580.71</td>
</tr>
<tr>
<td>6</td>
<td>1627</td>
<td>845</td>
<td>2</td>
<td>2.52</td>
<td>1.68</td>
<td>140.0</td>
<td>2.32</td>
<td>595.59</td>
</tr>
<tr>
<td>7</td>
<td>1602</td>
<td>886</td>
<td>2</td>
<td>0.00</td>
<td>2.61</td>
<td>138.5</td>
<td>2.39</td>
<td>569.73</td>
</tr>
<tr>
<td>8</td>
<td>1599</td>
<td>847</td>
<td>2</td>
<td>1.69</td>
<td>3.39</td>
<td>137.0</td>
<td>1.82</td>
<td>565.47</td>
</tr>
</tbody>
</table>

Specifications for the spectrometer (fig. 5.28) are given above. All the hardness data is checked in-house on this spectrometer.

Based on the above data in the table 5.6, nonlinear regression analysis was performed as per factorial design using MS-Excel software tool. That gives the correlation of all three variable with each output independently. Details are given in the next chapter of Data analysis.