ABSTRACT

Six Sigma method have been applied to manufacturing process of a rotary Stirling cooler: RM2. Name of the project is NoVa as main goal of the Six Sigma approach is to reduce variability (No Variability). Project has been based on the DMAIC guideline following five stages: Define, Measure, Analyse, Improve, Control. Objective has been set on the rate of coolers succeeding performance at first attempt with a goal value of 95%. A team has been gathered involving people and skills acting on the RM2 manufacturing line. Measurement System Analysis (MSA) has been applied to test bench and results after R&R gage show that measurement is one of the root cause for variability in RM2 process. Two more root causes have been identified by the team after process mapping analysis: regenerator filling factor and cleaning procedure. Causes for measurement variability have been identified and eradicated as shown by new results from R&R gage. Experimental results show that regenerator filling factor impacts process variability and affects yield. Improved process have been set after new calibration process for test bench, new filling procedure for regenerator and an additional cleaning stage have been implemented. The objective for 95% coolers succeeding performance test at first attempt has been reached and kept for a significant period. RM2 manufacturing process is now managed according to Statistical Process Control based on control charts. Improvement in process capability have enabled introduction of sample testing procedure before delivery.

KEYWORDS
Six Sigma, Cryogenics, Coolers, Stirling, Assembly line, Control chart, R&R gauge.

INTRODUCTION

Thales Cryogenics
Thales cryogenics is the brand name for Thales group activity in the field of cryogenics. Product development is mainly oriented to provide cryogenic cooling solutions for IR detection and imaging systems. Commercial offer involves product lines as: Linear and Rotary Stirling coolers, Pulse tube coolers, Joule Thomson coolers and associated High Pressure Vessel and compression devices. Activity is split on two sites: Eindhoven, the Netherlands and Blagnac, France.

RM2 cooler
RM2 is a lightweight, rotary, integral, ICDA type, ¼", Stirling cooler designed for providing heat pumping capacity of 400 mW @ 77K. RM2 is a mature industrial product as up to twenty thousands of these coolers have been produced in the last fifteen years.
Six Sigma method

Six Sigma has been developed by Motorola Company in the 1980’s to improve customer satisfaction. This method has then been consolidated and used by many other major industrial companies and can be considered today as a widespread practice. This business management strategy uses statistical analysis. Main concern is to reduce variability of product characteristics to lower manufacturing defect rate\(^{(1),(2),(3)}\).

A Six Sigma project has been undertaken by Thales Cryogenics applying to manufacturing process of the RM2 cooler. Implementation and results are reported thereafter.

DMAIC PHASE

The project has been scheduled according to DMAIC approach, a five step sequence commonly used in Six Sigma, namely: Define, Measure, Analyse, Improve, Control.

Phase 1, define: in this first phase the objective of the project has to be clearly defined. An output data (Y) is identified to measure current quality level. Project schedule is built. The dedicated team is set up. Process mapping is done and analysed to identify input parameters (X) critical to variability.

Phase 2, measure: values (X, Y) representing the initial situation are recorded and analysed to determine which input parameters (X) are the most critical to process variability (Y), measurement process is checked in terms of repeatability and reproducibility.

Phase 3, analyse: data are analysed, cause and effect relationship is studied. Solutions are proposed to strike a positive impact on variability. These solutions may arise from teamwork creativity workshop and must prove to be efficient in an experimental validation phase. Risk due to evolution is to be analysed.

Phase 4, improve: new improved process is set up integrating solutions. Results on output parameter (Y) are checked.

Phase 5, control: improved process is monitored to prove durability. Deviations are identified and corrected before leading to defects. Process is under control.

DEFINE

According to current manufacturing process, RM2 coolers undergo performance test after assembly. Testing is conducted at room temperature and 100% coolers are run to achieve 77K cold temperature. Parameters recorded during the test sequence are: cool down time (CDT), Maximum power consumption (Pmax) during cool down phase, and, power consumption in a stabilised 77K regulated mode (Preg). The rate of products achieving successfully the test sequence at first attempt is 80%. Coolers rejected after the test sequence are reworked and final yield is 95%.

The output data (Y) chosen to monitor improvement is the rate of coolers compliant after performance test at first attempt (CFA). Goal value for CFA parameter is 95%.

The effects awaited are: cost reduction due to elimination of reworking procedures and yield improvement, lead time reduction.

The operation leader for the project is Jean Marc Ventre, process engineer. He is the “Black Belt” according to Six Sigma terminology, combining knowledge both on cooler technical aspect and Six Sigma procedures. He has been specifically trained in preliminary phases and is supported by an external expert (Master Black Belt).

The project Champion is Jacques de Lallée, commercial and program manager. His main role in the project is to ensure that the required level of resources is allocated.

The team is also made up of different members whose profiles represent the different skills associated to cooler manufacturing: workshop operators and manager, logistics, test operators, part incoming inspection.

The name of the project is NoVa as a short cut for “No Variability”.

A process mapping has been conducted by the team, using the SIPOC method. Elements describing the manufacturing procedure are listed in columns: Supplier, Input, Process, Output, Customer and organised to give a complete image of the process. Analysis and discussion of this mapping were conducted by the whole team during specific workshops and enabled to identify several possible causes for variability. Among these causes and after analysis two parameters are chosen because of their critical influence on variability: filling factor of the regenerator and cleaning phase after running in.

MEASURE

Test equipment: among the main causes for variability, first thing to check is the influence of measurement means themselves. According to repeatability and reproducibility concern, test benches may induce a certain level of variability in the expression of the output data “Y”. Specific measurement system analysis (MSA) procedures are available for this purpose.
Gage repeatability and reproducibility (Gage R&R) is a statistical tooling used to evaluate variability induced by the measuring procedure, including contributions from measuring device, operator or environment. Repeatability is the variation between several measured values made by the same operator on the same equipment for the same item. Reproducibility is the variation occurring when measurement is conducted by different operators or on different measurement means.

%R&R is the ratio of measurement variation to total variation. %P/T is the ratio of measurement variation to tolerance and is called “precision to tolerance ratio”. It is important to note that this ratio depends strongly on specified acceptance values for the different parameters. Nominal value for these factors is below 10%. Results between 10 and 30% are marginal but acceptable. Performance test equipment for RM2 coolers is an eight track automated bench. Capability gage procedure was conducted using eight different coolers. Each sample was measured three times on each of the eight channels. Total number of test is 192 (8 samples, 3 runs, 8 channels). For each test, three different parameters are recorded:

- Cool down time, 20°C to 77K, (CDT)
- Maximum Power consumption during cool down (Pmax)
- Power consumption in a stabilised regulated mode at 77K (Preg)

After data statistical treatment the %R&R and %P/T ratio are calculated for each of the three measured parameters and are reported in table 1.

<table>
<thead>
<tr>
<th>CDT</th>
<th>Pmax</th>
<th>Preg</th>
</tr>
</thead>
<tbody>
<tr>
<td>%R&amp;R</td>
<td>10</td>
<td>38</td>
</tr>
<tr>
<td>%P/T</td>
<td>12</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 1

Results are quite satisfying for cool down time but power consumption measurement show R&R and P/T ratio way up above the assumed value of 30%. It is then obvious that measurement itself induces a high level of variability into the manufacturing process of the RM2 cooler and that this has to be corrected. Variability chart for Preg criteria is reported in fig2.

Figure 2: Variability chart

Results from Gage R&R have been analysed and show that variability on testing results is due more to reproducibility than to repeatability. Further enquiries have shown that, for each channel, behaviour may be impacted by global load of the bench. For two runs on the same channel, testing the same cooler, results may differ depending whether the seven other channels are operating or not. Power consumption measurement may be slightly overestimated on some occasion depending on bench load. This behaviour clearly impacts success rate and variability as periodic calibration of the bench is conducted separately, for each of the eight channels, while the seven other channels are free of load. It has been decided to change calibration procedure of the bench and to operate in full load conditions. Calibration and testing mode is then similar. Loading rules for the test bench have been set to make sure results will not be impacted any more by channel interference.

A new Gage R&R process has been conducted on the bench after calibration according to new rules. Test parameters were the same as previously (8 samples, 3 runs, 8 channels).
Results for %R&R and %P/T are presented in table 4. As a reminder previous results %R&R-1 and %P/T-1 are also presented for comparison.

<table>
<thead>
<tr>
<th></th>
<th>CDT</th>
<th>(P_{\text{max}})</th>
<th>(P_{\text{reg}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>%R&amp;R</td>
<td>7</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>%R&amp;R-1</td>
<td>10</td>
<td>38</td>
<td>66</td>
</tr>
<tr>
<td>%P/T</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>%P/T-1</td>
<td>12</td>
<td>66</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 2

Variability chart for Preg criteria is reported in fig2.

![Variability chart](image)

Figure 3: Variability chart

The results are now quite satisfactory. One cause for variability in the manufacturing process of the RM2 cooler has been eradicated.

**Regenerator filling factor:** Regenerator is an important part of a Stirling cooler. It is a thermal exchanger joining cold and hot side of the cooler. Gas inside the cooler is alternatively flowing from one side to the other through the regenerator exchanging heat with its porous matrix. Filling of the regenerator is done by metallic gauze stacking. A certain level of variability is happening due to filling procedure and can be observed after measuring gas flow rate in regenerators prior to assembly in the cooler. This measurement has been done for series of regenerator, using the same procedure: same gas and same inlet pressure. Those values have been analysed and compared to performance test results related to coolers on which the regenerators have been assembled. Table 2 gives flow rate distribution and plot for a population of more than one thousand regenerators. Flow rate values are expressed in arbitrary units (u.a.)

<table>
<thead>
<tr>
<th>Flow Rate Range (u.a.)</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (%)</td>
<td>5</td>
<td>8</td>
<td>21</td>
<td>19</td>
<td>29</td>
<td>18</td>
</tr>
</tbody>
</table>
There is variability in regenerator filling factor and this may be a cause for variability in the manufacturing process. Table 3 gives the relationship between regenerator filling factor and cooler performance test result. Test result appears as the compliance rate at first attempt (CFA) versus range of regenerator flow rate.

<table>
<thead>
<tr>
<th>Flow Rate Range (u.a.)</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFA (%)</td>
<td>73</td>
<td>73</td>
<td>83</td>
<td>88</td>
<td>88</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 4

Results confirm regenerator filling factor as a root cause for variability in performance test results. Success rate is lower for coolers showing high filling factors (low gas flow rate).

Cleaning procedure: it has been stated by the team during process mapping analysis that coolers failing performance test at first attempt may turn successful after they undergo a specific cleaning phase.

ANALYSE

Three root causes impacting variability in the manufacturing process of the RM2 cooler are now identified: measurement bench reproducibility, regenerator filling factor, cleaning process. Each of these three subjects have been studied and process changes can be proposed.

Regenerator filling factor: it has been decided that regenerator filling procedure should be adapted to avoid the use of regenerators showing gas flow rate under 135 u.a..
No risk is awaited as new regenerator specification is a restriction of the current population.

Cleaning procedure: decision is made to add a cleaning stage in the cooler manufacturing process after running in.
New process being an extension of operations commonly experimented for years in the reworking procedure, there is no risk arising from this process change.

Test equipment: a new calibration process is proposed for the test bench. Channel behaviour is now recorded under full load condition. Bench loading rules are added to the test process. Process change leads to elimination of random measurement error, no risk is identified in this change.

IMPROVE

RM2 manufacturing process has been improved according to NoVa project prescriptions. Figure 4 shows recording for monthly rate of coolers compliant at first attempt (CFA). These results show clearly that the objective of CFA > 95 % has been reached and kept after process improvements induced by the NoVa project.
Statistical Production Control (SPC) has been applied to RM2 cooler assembly line. Control charts have been set up for cool down time (CDT), maximum power consumption (Pmax) and power consumption in regulated mode (Preg). The control charts are built up using a specific software (STATGRAPHICS). In a first phase, calibration of the process is done to determine process capability and set limit values. Two types of control charts are issued for each parameter: the X-bar chart based on parameter mean values for a batch and the S chart based on parameter deviation in the batch.

Once calibration of the process is done, requiring recordings for thirty batches, the software is able to declare if new batches are satisfying capability criteria or not. Control charts limit being more restrictive than specification values, process regulation is done without affecting manufacturing yield.

Examples of X-bar and S control charts for Preg are given in figure 5 and 6.
ASSEMBLY LINE SETTING

In a second phase, improvement brought by NoVa project and Statistical Production Control have been used to enable to lower test level on the manufacturing line of the RM2 cooler. New process has been set based on sampling. For each batch of coolers two samples are taken and tested on the bench. Control charts are created for CDT, Pmax and Preg and permit batch acceptance without necessity for a 100% testing procedure.

FEEDBACK FROM CUSTOMER

For one specific application, RM2 coolers are now delivered to customer with an acceptance procedure based on sample testing. After delivery, testing is conducted on a 100% rate at customer’s premises after dewar integration. Test results are fed back to Thales and are integrated in secondary control charts to improve process control. This approach is in place for more than one year and proves to be very efficient as a very low rate of coolers have been returned for failing post integration test. Reject rate for coolers after 100% post integration performance test at customer’s premises is 0.5% for delivered and tested cooler quantities over 800.

CONCLUSION

Six Sigma approach proved to be very successful when applied to RM2 cooler manufacturing process. The initial objective to rise the percentage of coolers succeeding performance test at their first attempt over 95% has been reached and permit to reduce reworking procedures. Process control brought by these improvements has been capitalized to propose test procedure reduction. Statistical production control proved to be very effective to keep an excellent quality level.

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REFERENCES