Process Control in Investment Casting

Why is it Important?
What is a Process?

“What is a **Process**?

“Unique combination of machines, materials, methods, environment and people engaged in producing a measurable output.”

*Source: Wikipedia*
What is Process Control?

“Activities involved in ensuring a process is predictable, stable and consistently operating at the target level of performance with only normal variation.”

Source: Business Dictionary.com
What is a Process?

The **Output** of a process is a function of the **Inputs**

\[ Y = f(x) \]

- Independent
- Cause
- Control

- Dependent on Input
- Effect
- Monitor
- Inspection
What is a Process?

Example: Cut multiple pieces of lumber to a specific length

Wood
Saw backlash
Saw teeth sharpness
Saw blade runout
Person
Cutting speed
Tape measure
Work stop location
Table cleanliness

Input Variables

Process

Output Variables

Length
Cut quality
Angle
In Process Control, we direct most of our effort toward the important or **KEY** variables. “Vital few versus the trivial many.” How do we know which ones are Key?

**Outputs** that are important to **internal or external customers** are defined as Key Output Variables or KOV’s.

**Inputs** that have a **significant affect** on one or more KOV’s are defined as Key Input Variables or KIV’s.
Key Variables

Example: Cut multiple pieces of lumber to a specific length

- Wood
- Saw backlash
- Saw teeth sharpness
- Saw blade runout
- Person
- Cutting speed
- Tape measure
- Work stop location
- Table cleanliness

**Input Variables**

**Process**

**Output Variables**

- Length
- Cut quality
- Angle
The **Key Outputs** of a process are dependent on the **Key Input Variables**

If all of the **KIV’s** are identified and controlled within the proper range, the Key Outputs will be in control.
Summary

The Key Outputs of a process are controlled by the Key Input Variable (KIV’s).

If you control all of the Key Input Variables within the proper range, the Key Outputs will be in control.

This is a major tenant of Process Control.
Process Control Summary

If a Key Output Variable is out of control, then one or more of the following is true:

1. One or more of the KIV’s are not being controlled within the required range.
2. The required range of one or more KIV’s has not been optimized.
3. All of the KIV’s have not been identified (there are more KIV’s).
Monitoring Key Output Variables
Monitoring and Feedback

**Monitoring** the results of the Key Output Variables provides process control feedback. This data will provide a regular report on the stability and control of the process.

\[ X \rightarrow \text{Process} \rightarrow Y = f(x) \rightarrow Y \]

- **KIV’s**
  - Independent
  - Cause
  - Control

- **KOV’s**
  - Dependent on Input
  - Effect
  - Monitor
  - Inspection

An effective KOV based feedback system will have:
- Minimal time from processing to inspection.
- Clear reaction plan
Monitoring and Feedback

Example; Visual inspection of wax patterns

Key Input Variables

- Spray location
- Spray frequency
- Spray amount

Wax Injection

After each injection

Visual Inspection

Monitor KOV’s

Spray die with release agent

Reaction

Wax stuck in die

Timely and direct feedback. Pass / fail data
Monitoring and Feedback

Example; Dimensional inspection after wax injection

Key Input Variables
- Wax temp
- Hold time
- Wax pressure

Wax Injection

Wait for pattern to cool

Dimensional Inspection

Adjust injection conditions

Reaction

Excessive wax sink

Delayed and indirect feedback. Continuous data

Monitor KOV’s
Monitoring and Feedback

Example; Visual inspection of castings

Key Input Variables

- Metal temp
- Mold temp
- Preheat to pour time

Casting

Monitor KOV's

Many hours and operations later

Visual Inspection

Reaction

High percentage of castings with nonfill

What went wrong?
Maybe the wax patterns had nonfill.

Extremely delayed, indirect and possibly unclear feedback. Pass / fail data
Importance of Process Control

Why is Process Control so important in investment casting?

- There are many steps in the investment casting process.
- The result of each step is highly dependent on the quality from the preceding step. KOV’s from preceding step may be KIV’s in next step.
- Feedback from some operations can be significantly delayed and the reaction plan may be unclear.
- After the first shell layer is applied, you are not able to see the parts until knockout. Everything is hidden.
- To maintain high yields, minimize costs and achieve consistently fast deliveries, must have a system that prevents problems from occurring.
Types of Variation
Types of Variation

You need to control two types of variation.

- **Common Cause**; Normal variation inherent to a controlled process
- **Special Cause**; Non-random, out of the blue result
**Common Cause** variation results in a steady but random distribution around the average of the data. If there is a barrier or limit, may produce a skewed distribution.
Common Cause variation results in a steady but random distribution around the average of the data. If no barriers, will typically produce a bell-shaped or normal distribution.
**Special Cause** variation is created by a non-random event leading to an unexpected change in the process output.
**Example**
Investigation into the cause of the high nonfill percentage revealed the oven never reached temperature.
Special Cause variation is created by a non-random event leading to an unexpected change in the process output.
**Example**
Investigation into the cause of the small slot width revealed the operator never placed the pattern in a wax setter.

Special cause variation

Special cause result

Slot width
Normal Variation

**Example:** Variation in gate length after fixtured cutoff operation

- Variation between operators
  - Assembly operator, cutoff operator

- Variation caused by equipment
  - Cutoff saw table wear and spindle runout, fixture wear

- Variation caused by differences in methods
  - Adjustment of cutoff fixture, changing blade

- Variation caused by material
  - Differences between cutoff blade manufactures
Special Cause Variation

**Example**: Nonfill defects

- Normal nonfill amount
- Variation in **measurement**
- Variation caused by **methods**
- Variation caused by differences in **operator**
- Variation caused by **equipment**

*Special cause* result:

- Untrained inspector over-inspects, scraps good parts
- Wrong shell code selected resulting in 1 less layer being applied to the molds
- Untrained operator assembles patterns upside down.
- Preheat oven never reaches required temperature
Variation Reduction

What **Type** of Variation Are You Trying To Reduce?

- Improve overall capability – predictable results but need improvement (Common Cause)
- Eliminate bad, unpredictable results (Special Cause)

Different control tools are used for different types of variation.
The Process of Process Control
What is the process for process control improvement?

Process Control encompasses three main areas of activity:

1. Controlling known KIV’s within desired limits.
2. Uncovering hidden KIV’s.
3. KIV targeting and limits.
Controlling KIV’s
Controlling KIV’s

All processes have **variation**. We expect variation. But, we need to control it to a level that is does not negatively impact KOV’s. What are all of the sources of variation?

What is a **Process**?

“Unique combination of *machines, materials, methods, measurement, environment and people* engaged in *producing a measurable output.*”

Sounds like all of the fishbones in a Ishikawa diagram.
Sources of Variation

Environment  Equipment  Operator

Measurement  Methods  Material

An Ishikawa or Fishbone Diagram
These are some of the tools that can be used for each source of variation.
Sources of Variation

There is no one best method for controlling KIV’s. The control method is dependent on the type of variation:

1. **Operator** variation
2. **Methods** variation
3. **Equipment** variation
4. **Material** variation
5. **Measurement** variation
6. **Environment** variation

And, once you have established the controls, use auditing to prevent long term degradation.
Operator Variation

Differences between operators significantly affecting the output

- Assembly spacing, bond strength
- Dipping and draining technique
- Metal pouring speed and height
- Blending
- Weld repair
- Straightening

- Training
- MSA’s
- Instructions
- Guides, fixtures
Methods Variation

Differences in **method** significantly affecting the output

- Adjusting slurry viscosity
- Adjusting wax injection press settings to eliminate defects
- Adjusting cutoff fixture
- Adjusting for tooling wear on a machining center
- Equipment startup and shutdown

- Reaction Plans
- Checklists
- Standard Work
- Mistake proofing
Equipment Variation

Differences in equipment significantly affecting the output

- Mold temperature variation by oven
- Pattern quality by wax injection press
- Mold quality by shell robot line

Can be differences between machines or degradation over time

- Calibration
- Preventive maintenance
- Alarming
- SPC
Material Variation

- Differences in remelt quality
- Differences in as-mixed slurry viscosity
- Differences in stucco sizes
- Differences in mold strength and perm (flour size variation)
- Differences between cutting tool vendors

The material can be recycled internally or from an outside supplier

- Material specification
- Incoming inspection / SPC
- Vendor audit / SPC
Measurement Variation

Differences caused by **measurement** variation.

- Slurry viscosity measurement
- Wax pattern inspection
- Dewaxed mold inspection
- Casting inspection
- Dimensional inspection
- Straightening inspection
- Chemistry measurement
- pH measurement

- MSA
- Standards
- Instructions
- Training
- Visual Reference guides
Uncovering Hidden KIV’s
Uncovering Hidden KIV’s

We probably have not identified all of the KIV’s for every process.

What methods can be used to uncover hidden KIV’s?

1. Research
2. PFMEA’s
3. Root Cause Analysis
4. Families of Variation Analysis
5. Data Mining
Research

There are many sources of technical information. They may reveal hidden potential KIV’s.

- Experts and consultants
- Material vendors
- Equipment manufacturers
- Books and technical papers
- Atlas of Casting Defects
- Industry training
- Best Practices
PFMEA

Process Failure Mode Effects Analysis

“A PFMEA is a structured analytical tool used to identify and evaluate the potential failures of a process. PFMEA evaluates each process step and assigns a score on a scale of 1 to 10 for the following variables:

Occurrence - chance of failure happening
Detection - chance of the failure being detected
Severity – impact of failure mode
RPN – risk priority number; O x D x S

Root Cause Investigation

When you have an unexpected outcome from a process, figure out what happened and modify the controls to prevent a re-occurrence.

- Did we identify all of the KIV’s?
- Did we target the KIV’s properly?
- Are we controlling the KIV’s?
- Is our training system effective?

Perform a root cause investigation in order to find the failure mode.
A common method of analyzing data is to look at **Families of Variation**. In this approach we sort KOV results into different rational sub-groups (families) in order to reveal any hidden sources of variation.
Families of Variation

If a significant difference is revealed within a family, further investigation is required in that area to find the source of that variation.
Data mining is the process of examining large data sets to find new relationships between a response (KOV) and many predictors (inputs).

This can be done through regression analysis using statistical software.
“Significant” predictors discovered during data mining SHOULD NOT be treated as fact, only items that may warrant further investigation.

Predictors should only be considered significant after they have been verified through well-controlled experimentation.
Testing

These various methods will uncover a large number of **Potential Key Input Variables**. We need to determine the statistical significance between these factors and the Key Output Variables.

Using screening DOE’s we can quickly and efficiently separate the “trivial many from the vital few”. This is typically done using a 2-level factorial design.
KIV Targeting and Limits
Once a factor (KIV) is found to be significant, how do we determine where it should be targeted and the amount of variation that can be tolerated?

**Optimization Testing**
Optimization testing is a type of experimentation in which more than 2 levels are used on some or all of the continuous factors in order to determine the ideal settings. This can be done using either a 2-level factorial design with center points or with a General full factorial design.
Example – Determine the ideal wax injection parameters

- 3 factors; wax temperature, wax flow and injection time (KIV’s).
- 3 levels for each factor.
- Each pattern inspected for surface quality and dimensions (KOV’s).
- Results analyzed using statistical software. Response Optimizer and Composite Desirability function used to find the ideal conditions for both dimensions and surface quality.
Process Control Summary
Effective process control in investment casting is achieved by identifying and controlling the KIV’s.

Effective process control requires the use of many tools.
Process Control Tools

PFMEA  
Reaction plans

Calibration  
Control plans

Instructions  
Purchasing specifications

Control charts and SPC  
Research

Standard operating procedures

MSA’s  
Process flow diagrams

Design of Experiments

Standard work  
Guides

Families of Variation

Root cause analysis  
Reference standards

Data mining

Vendor Corrective Action  
Capability studies

Analysis of Variance

Training and verification  
Mistake-proofing

Audits

Preventative maintenance  
Alarming

Data logging

Vendor audits  
Checklists
Questions?