# PROCESS CONTROL:

## *POWER, VALUE, AND ADVANCEMENT FOR THE JEWELRY INDUSTRY*

### Abstract:

A collection of techniques is often an inadequate method to produce consistently high quality product to meet the needs of the jewelry industry. Systematizing techniques into a profile for a manufacturing process is essential to produce flawless product with minimum variation. The significance of characterizing an entire process is discussed along with an examination of quality control techniques to direct the quality of internal and external factors. The use of defect analysis and designed experiments is advanced as the best path to process optimization and continuous improvement. The casting of platinum, due to its inherent difficulties of manufacture, is used as a paradigm for this analysis.

### Key Words:

Characterizing, Defect Analysis, Environment, Equipment, Fishbone Diagram, Materials, Methods, People, Process Analysis, Process Map, Process Control, Quality Trilogy, Value

**Timothy L. Donohue and Dr. Helmut F. Frye, Ph.D.**

•**TechForm - *Advanced Casting Technology*, L.L.C.**

A process can be even more valuable than the product it creates. In 1805 William Wollaston, an English scientist, developed a scientific process to make platinum malleable and shape it into wires, crucibles, evaporating dishes, and sulfuric acid boilers. Since he never let anyone into his laboratory and never released the details of his process until after his death, he amassed a fortune by becoming the sole supplier of these products.[1]

In order for a process to be valuable and powerful, the process must produce acceptable products consistently and predictably. To accomplish this, the process needs to be in control at all stages. A controlled process may be defined as a directed and consistent application of: people, materials, equipment, methods and environment to produce a product.[2] A controlled process to manufacture castings is the only way to produce a high quality artistic jewelry design. Although the principles discussed can be applied to any alloy, it is the purpose of this article to explain the necessity for creating a controlled process in producing platinum castings since this metal provides the most challenging, and perhaps, rewarding end product. The most logical means of characterizing, controlling, and optimizing the casting process will be examined.

There are a variety of techniques used to make platinum castings for the jewelry industry. A wax design is assembled onto a sprue and invested with refractory materials. The wax is eliminated from the ceramic form which is then heated to improve the strength of the ceramic. Due to the high melting temperature of platinum (3223°F), a relatively high pressure oxygen-gas or hydrogen torch, or a high/low frequency induction melter is used for casting. Since the metal has a very narrow liquidus/solidus band, a centrifugal casting method is usually necessary to fill the mold with platinum before it freezes off. Then, the ceramic mold must be removed from the casting and the individual pieces cut off and finished. Different casting manufacturers will employ different techniques to assemble, invest, dewax, fire, melt, and cast the patterns. However, it is the control at each stage of the process that will predetermine the quality of the end product.

## The Value of a Controlled Process

There are many reasons that a controlled process is a valuable asset for platinum casters. A controlled process provides an index of capability for any level of production. It also boosts internal efficiencies and reduces scrap and rework. Additionally, it can help a company adapt to changing products and technologies. Finally, unlike product design, it is far more difficult for competitors to duplicate.

All controlled processes have an index of capability, i.e., a certain percentage of acceptable products can be predicted. For instance, if a caster can produce nineteen sound castings out of twenty put into the system, the process is capable of producing 95% quality products. This also predicts that 5% of the time the process will fail to make a salable casting. The capability index of a process is the most objective means to know how competently a company can produce products. Tracking the capability of a process will enable a company to ensure profitability when quoting new or existing customers. If the market cannot support the total cost of production, the company will need to focus its efforts where it is more capable.

A controlled process can increase efficiencies and reduce scrap and customer rework over time since it will indicate nonconforming trends that appear even within the limits of the process itself. When a process is not controlled, variation can become extreme. Variation always creates costs and inefficiencies; but, actions that reduce variability at the source will reduce subsequent costs while increasing product quality.[3] For example, phosphate based investment material is a very volatile material which can cause severe ceramic failure if it is too old. It is far cheaper to control the age of this material at the time it is received than to pay the costs involved with scrap castings. A fully controlled process plans the manpower, inventory, equipment, and sundry costs of each stage of production. This means there will be less waste and greater overall efficiency. Additionally, if variables of a controlled process display a trend toward either the upper or lower control limit, corrective action can take place before the process is shut down. The observation of these trends can also help improve the process capability by reducing the variability that drives the scrap rate. The process is made to be more efficient and, thus, cost effectiveness along with customer satisfaction will increase.

As one author exerts, "Well-honed processes can do more than boost internal efficiencies; when managed properly, they can be a competitive weapon."[4] A controlled process can be re-engineered to use new technologies as they develop. For instance, it is a fact that a crucible coated or made with silica will start to dissolve at a temperature 50°C less than the melting point of platinum. To resolve this problem the melt will have to be done very quickly or will have to be done in a ceramic material with a higher melting temperature (e.g., CaO or MgO). A controlled process experiment will permit a critical evaluation of the best course of action to fix this problem. Costs, designed experiments, and learning curves can all be considered before purchases are made if the entire process is in control. "A process under control can be continuously improved"[5] to reflect the leading edge of the industry. The impact of upgrading equipment, materials, or techniques in an uncontrolled process could never be properly determined; normally, the financial risk of the investment could not be justified. Since variables in a controlled process are under constant observation, the opportunity to input innovative ideas occurs on a daily basis and the return on investment can be calculated.

Moreover, when a process has been formalized with all the documentation in place, it becomes a proprietary asset to the company. While products and designs can be copied and made less expensively throughout the world market, a process is an entity that can only be performed with the people, materials, equipment, methods, and the controlled environment of the process owner. It would be possible, of course, for process users to reveal process details to other competing firms, but a contractual confidentiality agreement with employees can limit the effect of this potential. Of all the means of production that a company employs to produce its products, the controlled process is the most valuable asset in the arsenal. The following sections of this paper will examine the fundamental elements of a controlled process which include characterization, control and optimization.

## CHARACTERIZING A PROCESS

A truly powerful process is not one that defines quality in terms of rejects after all manufacturing operations have been completed. It is a process that creates a very high percentage of acceptable product and is monitored, analyzed, and documented at every stage. It is important to keep in mind that the most current models of production extend the process both "upstream" and "downstream" to include customer satisfaction (warranties) on the one end, and employee training and raw material control on the other. The key to habitually producing high quality castings lies in discovering the optimum operating parameters for each stage in the process and then performing the operations in precisely the same way every time. In other words, the people, materials, equipment, methods, and environment must be well defined and well controlled. The aim of a controlled process is not to compile charts and records, but to make a defective casting a process improbability.

The first step in controlling the process is to characterize all of the variables that can affect the output. Even a small casting facility can easily compile more than 100 individual variables in the entire process, meaning there are billions of simple interactions to consider. To succinctly characterize a process, it is best to look at each process stage (i.e., wax operations, investing, dewaxing, firing, casting, and finishing). To determine the process interactions, it is necessary to draw a "process map" (see Figure 1) to diagram the flow of products through the process. Once this is accomplished, the variables of control (people, materials, equipment, methods, and environment) must be determined for each stage.

Figure 1 - Process Map

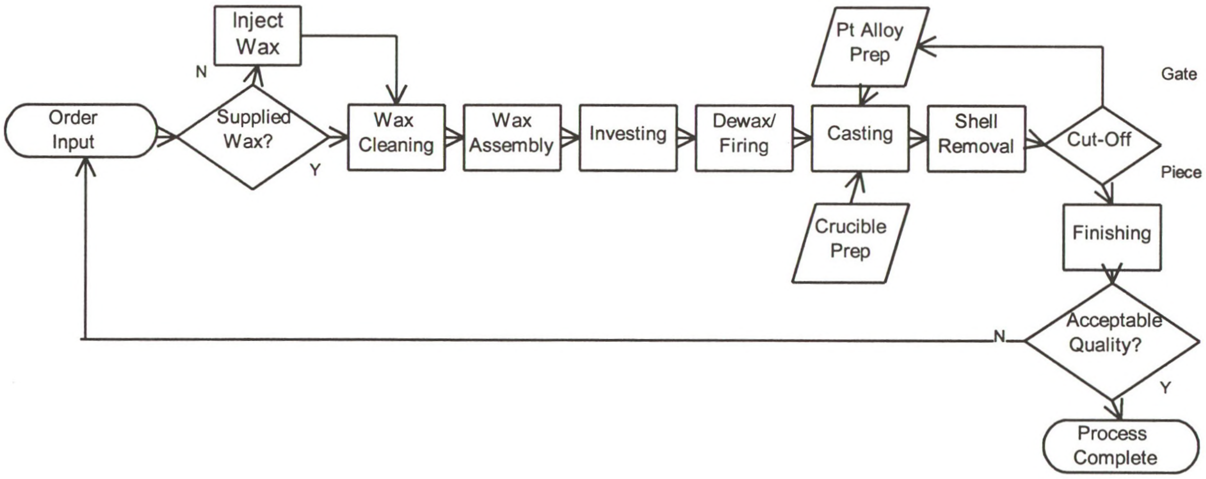
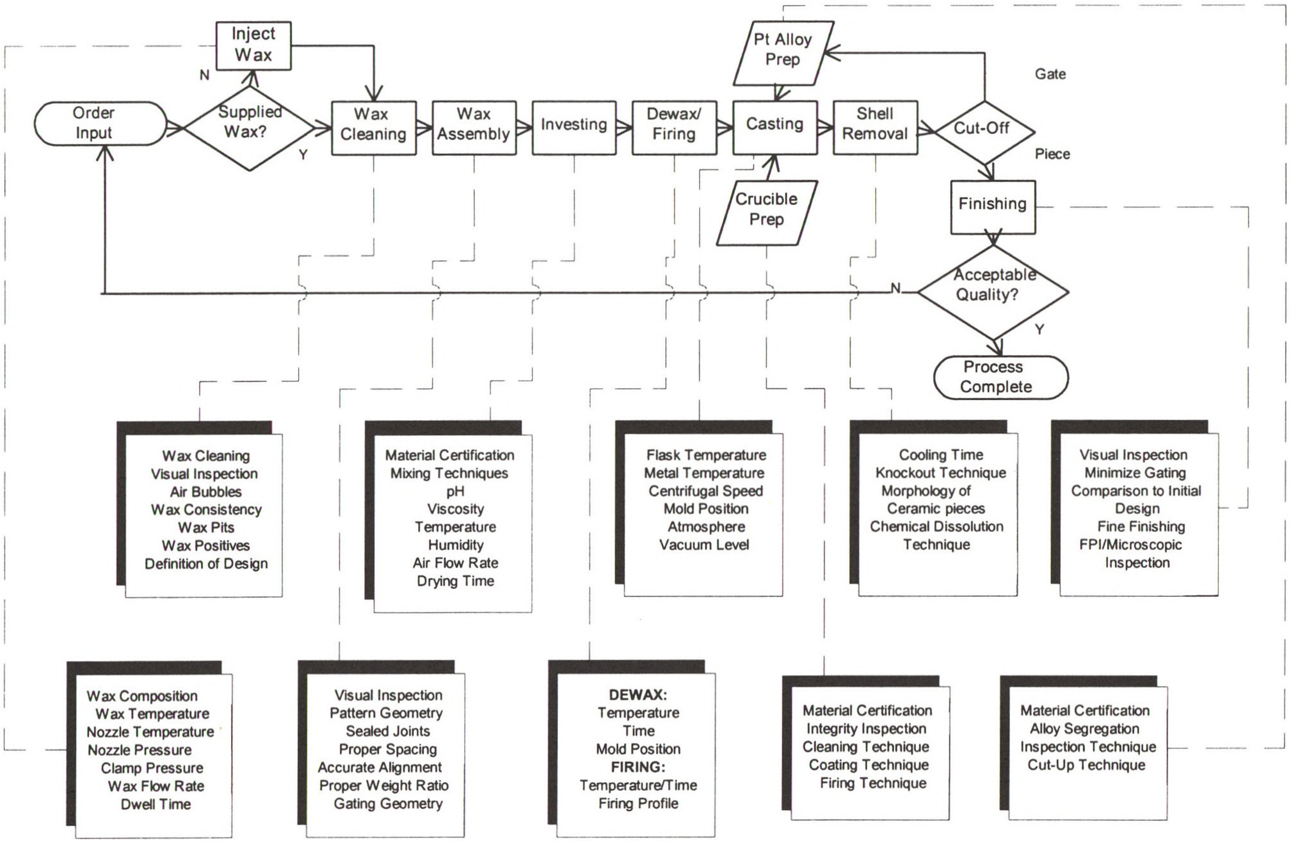


**Figure 2 - Process Analysis Chart (Adapted from Siff, 1984)**



In Figure 2 the process map has been taken a step further to provide a strategic plan for control of related variables.[6] The process variables can be outlined in their proper sequence and the actual techniques and conditions to be maintained are related to the individual stage of the process in the process analysis chart.

In the Process Analysis Chart, there are 59 variables listed for possible control. These variables represent a minimum control set, but there are many others to consider depending upon the specific process being characterized. It is important to remember that the measurement of each variable will need to be done with a controlled and calibrated instrument to insure that the recorded variable values reflect the item being measured and not the wear and tear of the measuring device. Consider the electronic scale as an example: As internal springs and contacts are constantly used, they can distort; the result can be inaccurate measurement which will result in an error every time the device is used. At whatever point this occurs, all of the downstream elements will be affected. An incorrect wax weight will result in an incorrect calculation of the metal weight needed for a casting and, thus, the risk of a short pour and scrap is very high.

What will follow next will be a brief examination of each process stage. This should help show the interaction of the operation and the control variables.

- **Wax Injection:** The chemical composition of the wax used in the process needs to be tightly controlled. A manufacturer's certification of analysis of the raw wax will usually fulfill this need. The manufacturer will also provide test information such as "softening point," melting temperature, and the ash content of the lot of wax being purchased: This is important information which will give an index for the consistency of the product. The parameters for injecting the wax into the mold also need to be consistent. It is readily apparent that severe variation of the wax temperature, nozzle temperature, pressure of the wax, the flow rate or dwell time under pressure, will affect the yield of acceptable wax patterns.

- **Wax Cleaning:** It is widely acknowledged that the earlier an inspection is placed in the process, the more benefit it provides to product quality. A poor quality wax cannot be improved with investment and casting. Defects repaired at this stage will save hours of time in defect analysis and eventual rework. Positives and negatives in the piece need to be identified and eliminated. The surface must be cleaned with a process proven technique that will allow an uncontaminated surface without diminishing the design features.

- **Wax Assembly:** Wax assembly techniques and inspections need to be documented and repeatable. Common controls for this stage include minimizing geometrical risks whenever possible. All joints must be properly sealed with no wax undercuts, the patterns must be properly spaced on the gating, and the patterns will need to be aligned on the sprue for optimum filling during casting. The geometry of the sprue and the pattern-to-gate weight ratio is of great importance at this process stage.

- **Investing:** This stage of the process requires the most critical evaluation of the people, materials, equipment, methods, and environment for control. This is the most proprietary stage of a valued process. If it works, the product will be acceptable (as long as the casting parameters are followed); if investing fails, all the process stages in front and behind it are wasted, and the customer may not be back for more business. The ambient air flow, temperature, and humidity are critical factors which must be controlled. The investment materials must be certified and viable at the time of use. Some testing of the materials may be necessary to insure that the more volatile binders are performing as designed. If the "life" of an investing material is determined, then control will require that the material will be discarded after a specific time from manufacture. The mixing and application techniques of the investment material must be documented and repeatable. Whether the mold is dipped into a ceramic slurry, or investment is poured around the pattern assembly, every motion and environmental condition must be duplicated from day to day and from mold to mold. The equipment used in this process stage must be monitored for variation due to wear and tear or other changes.

- **Dewaxing:** Removing the wax may lead to mold cracking by anomalous expansion of the wax during this stage of the process. Filled waxes will behave differently than unfilled ones. To guard against this type of cracking, the process must control the temperature, time, and mold position in the dewaxer. The mold position is important to eliminate wax residues which can translate into ash and, hence become negatives or pits in a casting. Depending upon the equipment used this can be done either with steam or in a dry environment; both systems have relative advantages. The main point is that once a system is proven to work, it is applied consistently.

- **Firing:** Time and temperature are extremely important in firing the ceramic before casting. The firing curve or profile must allow the evacuation of all water content before bringing the mold up to curing temperatures. Most investment ceramics contain a certain amount of silica; therefore, the mold must have a scheduled and prolonged period of exposure to a temperature above 870$^{O}$C to allow the ceramic to cure and provide the strength for centrifugal casting. The heating and cooling rate during the firing process stage must always present an established profile to insure process consistency, and it will need to be recorded on a permanent calibrated chart recorder.

- **Crucible Preparation:** Ideally, casting would take place without a crucible, i.e., levitation melting, or in a water-cooled copper vessel. This may be possible for some experimental applications, but, unfortunately, it is not currently practical for platinum production. A dirty or disintegrating crucible is an extreme hazard to a quality casting. The crucible must be clean, without any apparent "glassy-phase" present, and it should be coated with a relatively inert ceramic coating, yttria, for instance. Freshly applied ceramic coatings will require firing for bonding. The coating material must be certified, and the techniques for cleaning and coating need to be documented and consistent. The integrity of the crucible can be confirmed with a visual inspection for cracks as well as by listening to the tone made when it is lightly tapped. A cracked crucible will make a dull sound and should not be used.

- **Platinum Alloy Preparation:** All virgin material needs to have a certification of conformance from the supplier. This will allow traceability back to the metal chemistry if severe problems occur during casting or finishing. There are a variety of alloys used for platinum designs: Each alloy type needs to be kept discrete and segregated at all times! A technique to maintain the separation of the alloys should be documented and audited regularly. Usually, a predetermined amount of reused material from an alloy will be used in casting. This material needs to be marked, inspected, and properly segregated. In any case, the cleanliness of the metal used in casting is imperative. A cleaning and inspection technique (using microscopy) needs to be in place.

- **Casting:** Simple models of casting have determined that the most important variables affecting the filling of a mold are: atmosphere, ambient (flask) temperature, metal temperature, force of the pour (centrifugal speed and ramp rate), and mold geometry. All of these need to be measured, recorded, and standardized in a controlled process. It is also important to realize that the temperatures reached during the casting of any platinum alloy can start to dissolve the components of the crucible being used; the overall time it takes to cast is a significant factor which should be as short as possible.

- **Shell Removal:** Removing the ceramic from the casting requires a high degree of consistency. A prescribed period of time after casting must be applied, and this must be determined by experimentation. Molds can then be broken apart by quenching in a temperature controlled fluid or by knocking them out with a hammer; this technique requires an unvarying application. Operators should observe and record the morphology (shapes and sizes) of the broken ceramic to note significant differences if they occur. The type and potency of chemicals used to dissolve fine ceramic from the castings also needs to be consistent and recorded.

- **Finishing:** The piece and the gating must be separated in a manner that does not distort or damage the piece. The gating will need to be separated to guarantee the alloy integrity and then processed as revert material. The piece will need to have all gate stubs minimized in order that the customer does not pay excessive charges. The design should be checked against a photocopy of the initial pattern to insure that all details have been reproduced. A fine-finishing operation should insure that the surface quality is acceptable. Further inspection may include a fluorescent penetrant, microscopy, or other nondestructive examination of the pattern. All these finishing techniques need to be documented in the form of process instructions to ensure that the cast designs sent to the customer will be acceptable and fit for use with a minimum of rework.

It is important to note that characterizing the process will not inherently improve the process, however, it will permit a basis for correction when problems arise. Once the entire process has been characterized and analyzed for variables that require monitoring, standardizing, and documentation, the next step is to initiate control of these factors. It is only after the variables are controlled that the process can be optimized and improved.

## PROCESS CONTROL

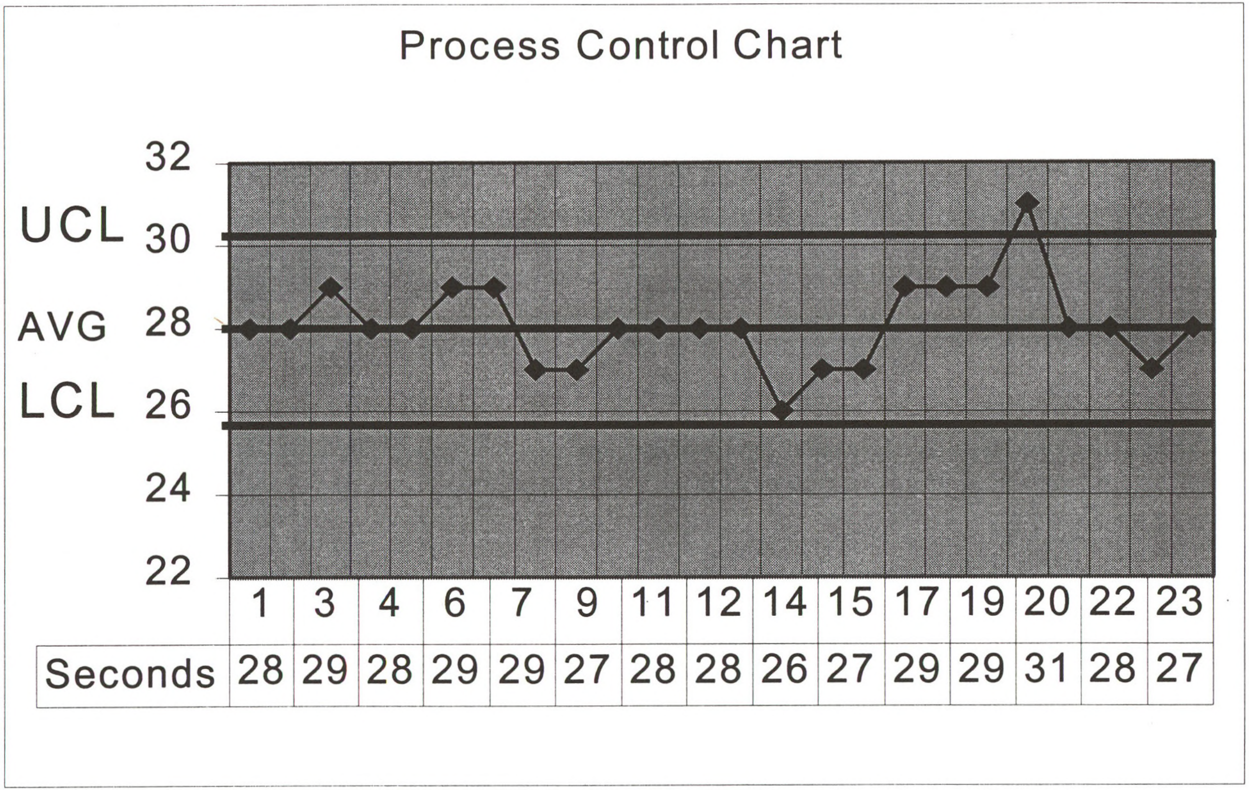
The tools of process control are the documented procedures, the attribute chart and the control chart. In order to control a process, it is necessary to direct and consistently apply all the process variables. In a classical sense, "this consists of observing actual performance, comparing this performance with some standard, and then taking action if the observed performance is significantly different from the standard."[7] The imposed standards must be representative of a highly capable process and be documented to clearly outline what the outcome must be. To establish the proper standard for each process variable, specific performance criteria must first be determined.

All process techniques which may affect the quality of the casting must be documented. Sometimes the performance criteria will be in the form of process instructions or, operational techniques. These techniques will need to be defined with clear and understandable directions to perform the operation. They need to be written in a "step-by-step" manner with all relevant instructions listed. This is generally not the place for theoretical considerations. Prescribed and proscribed activities with necessary precautions are the only details that should be included in a process instruction.

Sometimes the performance criteria will be measured data that represents a necessary condition (attribute). Historical information will establish the correct standard for this type of data. Attribute data is usually viewed as a "yes/no" or "go/no go" condition. It can be recorded and controlled on a simple checklist that confirms the required status of a variable. For instance, the pH of a caustic solution is ≥12 or it is not. The process continues if the pH of the solution is over 12; if not, new caustic will need to be made before it is used. It is important that the measurement be recorded, if only on a checklist. A simple checkmark (☑) with the date and operator's identification will verify that the controlled variable is in conformance.

Finally, sometimes the performance criteria will be measured data that can be of any value, e.g., the humidity level of the Investing Area. Variable data needs to be recorded on a Control Chart (see Figure 3). Historical data can be used to calculate the average value of a variable when the process is in control. There are a variety of resources (books or software) available to help with establishing the Upper and Lower control limits for individual variables. To control variable data, the measure must be taken and recorded on the Control Chart. If the value of the measurement is beyond either the upper or lower control limit, the process must be stopped until the condition is corrected and the variable can demonstrate a measure within normal variability. Once the control limits are in place, controlling variable data is as easy as controlling an attribute or following a clear instruction.

Figure 3 - Process Control Chart



The tools of process control need to be applied to all identified variables in each stage of the process. However, a variable may be measured in a variety of ways. For instance, the Investment Casting Institute outlines twelve different testing procedures that all determine shell strength.[8] For each item to control "there are numerous measurable and not-so-measurable characteristics."[9] Measurements may be tangible, but what they measure may be abstract and conceptual. To limit the number of tests and measurements that are used to control a specific portion of a process, it is necessary to define the key control characteristics which actually can affect the quality of the output. These will vary from process to process, but a realistic focus on the factors of the process (people, methods, materials, equipment, and environment) at each stage should help limit the quantity and type of the control variables.[10]

- **People:** Quality process guru, Philip Crosby has said, "All the results in a company are made by people."[11] Directly and indirectly this seems to be the case with most processes. The most important ways to control this significant process factor is to determine the knowledge, abilities, and skill levels required to perform the process operation. Once a person has been determined to have the prerequisite qualifications, they must be properly trained to do the job. This may appear to be a pure expense to the process; however, it has been confirmed through empirical research by Motorola that, "every $1 invested in training returns $30 in productivity within three years."[12] The general guideline for people performing a process is to 1) Insure an adequate skill level; 2) Provide them with unambiguous instructions for what they are supposed to do; 3) Give them feedback about their performance; and, 4) Arrange a means of regulating their performance with corrective action.

- **Methods:** Closely allied with people are the methods they employ to process manufacturing inputs. These include all the process instructions mentioned earlier as well as all the systems in place that guide the process. Methods to set up, run, and maintain equipment are also included in this consideration. Specifications for testing, inspection acceptance, and the way customer expectations are integrated into the final output are all methods of the manufacturing operation. Corrective action programs and continuous improvement strategies are all encompassed in the methods of a process.

- **Materials:** All raw materials in a stable process must be of a known and consistent quality. The suppliers of wax, investment, binders, and metals must certify the components and characteristics of the materials they supply. Such material certification and testing is widely available from most suppliers. A controlled process needs to record and track this data to guarantee the quality of the supplied raw materials. A casting manufacturer needs to have a trusting partnership with its suppliers; not one based strictly on the cost of materials. "It is very difficult to be better than you are supplied."[13]

- **Equipment:** All equipment used in a process must be appropriate for the task. While most equipment used to cast other jewelry metals can be used for platinum casting, we consider the use of a centrifugal induction melter with a pyrometer and vacuum capability as a bare minimum for a controlled process. The function of equipment must also be well maintained and consistent in operation. A wax injection machine must heat and inject consistently, a vacuum pump must evacuate gas to a certain level in a standard amount of time and have a controlled leak rate during operation, a centrifuge must accelerate and hold a certain rpm as prescribed. All these functions must be periodically checked and calibrated to attest that the equipment continually works to specifications.

- **Environment:** It is already broadly accepted that temperature and humidity need to be controlled during wax assembly and investing. Also, certain platinum alloys may require an inert environment during melting. It must be remembered that environment additionally includes things that do not directly envelope the castings. Items like safety, housekeeping, and empowerment of workers may be hard to measure; but, these can certainly impact the quality of the process output. It is the overall environment that will direct a controlled process to continuous optimization.

## Table 1 - Defect Analysis Chart

| DEFECT CATEGORY | SYMPTOMS | PROCESS STAGE INVOLVED |
|---|---|---|
| **1)Metallic Projections** | Finning, Crowning, Shell Failure, and Delamination | Wax Assembly, Investing, Dewaxing/Firing |
| **2) Cavities** | a) Pitting, negatives, Dirt<br>b) gas porosity, turbulence porosity, and dispersed shrink | a) Wax Cleaning, Investing, Dewax/Firing, Crucible/Metal Preparation, Casting.<br>b) Wax Assembly (gating), Casting |
| **3) Discontinuities** | Shrink, cracks, hot tears, cold laps | Wax Assembly (gating), Casting |
| **4) Defective Surfaces** | Orange-peel appearance, metal mold reaction | Wax Cleaning, Investing, Crucible/Metal Preparation, Firing, Casting |
| **5)Incomplete Castings** | a) No Fill<br>b) Leaker | a) Mold design, Incorrect metal weight, Casting parameters<br>b) Investing, Dewaxing/Firing, Casting |
| **6) Incorrect Shape** | a) Distortion<br>b) Incorrect dimensions | a) Wax Injection, Wax Cleaning, Sprue design, Investing, Casting, Finishing<br>b) Improper shrink allowance, Wax Injection, Wax Cleaning, Casting |
| **7) Inclusions or Structural Anomalies** | Subsurface pitting (usually uncovered during polishing) | Investing, Dewaxing/Firing, Crucible/Metal Preparation, Casting |

## PROCESS OPTIMIZATION

Process optimization means that corrective action is applied when non-standard variation or defects are detected, and that the process is improved by design. The quality of the output provides the requisite feedback about the effectiveness of the process. This feedback becomes a tool to correct problems as they arise and to improve the overall quality of the process itself. To obtain the greatest value from a controlled process, it is necessary to take advantage of the feedback provided from the products in the form of defect analysis and process improvement.

### Defect Analysis

Most platinum casters have experienced all types of problems despite the most stringent controls. As one platinum caster has reported, "There is approximately a 50-50 ratio of product to scrap in the industry."[15] In a controlled process this level of capability would be wholly unacceptable. Nevertheless, some defects can actually help a caster pinpoint problems in a process by identifying the root cause. This is the main focus of defect analysis where problems with the outcome are used to uncover greater than normal variation (special conditions) in the process. There are seven categories of casting defects,[14] which, when they occur, can direct the discovery of the process stage and possible variables responsible for the defect. Table 1 outlines the troubleshooting process using defect analysis.

After the defect has been categorized and the process stage which could have caused it has been identified, a careful examination of the variables in question must take place. A useful tool to accomplish this is the "fish-bone diagram" (see Figure 4). By relating individual conditions to each of the factors of the process stage, the defect analysis can be more complete, and thus, fruitful. This type of investigation will help sustain a capable process.

### Process Improvement

While defect analysis can sustain and fine-tune a capable process, process optimization provides more than mere sustenance. It requires deliberate action to reduce variability through process improvement. Improvement is the third "leg" of the Quality Triolgy[16] (see Figure 5) that is based on the

Figure 4 - Fishbone Diagram

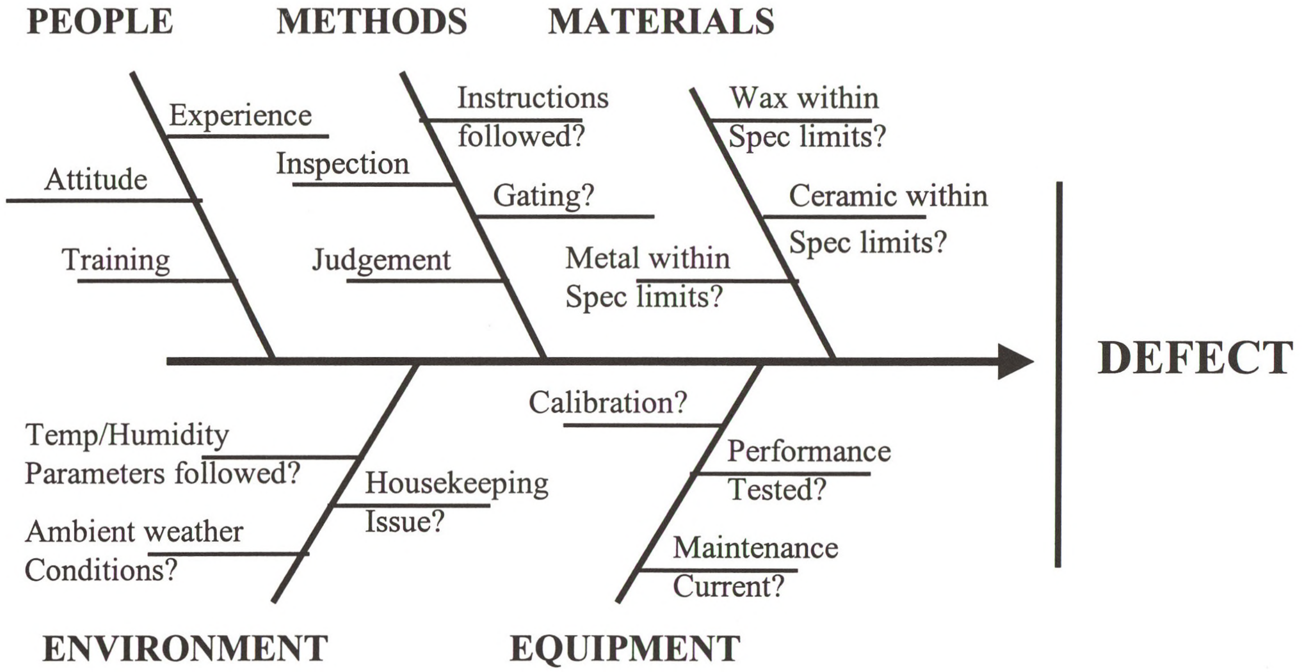
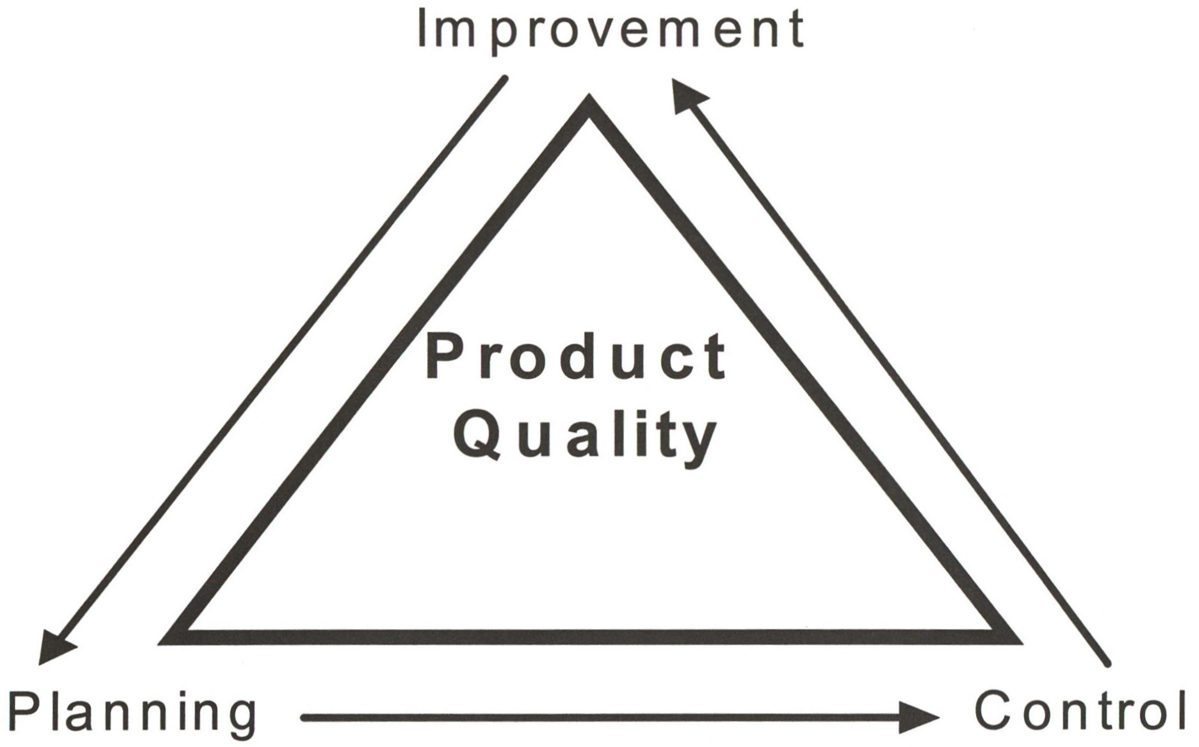


Figure 5 - Quality Trilogy



planning and control of the process for its stability. Through designing process improvement experiments, a company can "determine the optimum settings of the factors that control a process."[17]

While some companies attempt to improve processes based on hunches and intuition, these experiential schemes cannot be applied to a controlled process without the support of experiments to prove their value. New methods, new technology, new equipment, and other innovations can be tested within a process by designing an experiment to explore the behavior of all the other variables in a changed process. It is beyond the scope of this article to relate all the details of a designed experiment; but, there are many books and articles which can explain the Design of Experiment (DOE) process succinctly. Some of the software available at this time will allow those "with little or no formal training to successfully integrate the use of DOE into their experimental strategy."[18] It is with this type of experimentation that a process can move from a capability of 70% to 95%+. The method is relatively simple in principle.

- Use your knowledge of the process
- Decide on a critical improvement possibility
- Keep the experimental design and analysis as simple as possible
- Recognize the impact of the improvement on quality and costs
- Confirm the experiment[19]

It has been said that if you can make only one good part out of a thousand, then the process can be made capable of producing 100%. The hard part is to find the optimum conditions for the process to be fully capable. There needs to be a continual and regular deployment of designed experiments in the process in order to insure continuous improvement.

In conclusion, a controlled and powerful process pursues investment casting as a science, not an art. Casting platinum requires that all the scientific methods available will need to be deployed. Detailed characterization, control, and optimization of the investment casting process is the only way to create a process that will meet the needs of exacting customers. Like William Wollaston, it is possible to provide high-tech products to the market with the right process at the right time. The time is now right, since recently, "the use of platinum in jewelry has seen a meteoric rise, and it holds out the promise of interesting future developments."[20] The right process can be created, too with never-ending devotion to detail. It has been well established that, "the process of installing quality improvement is a journey that never ends."[21]

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