

COMPARISON OF SIEVING EFFICIENCY BETWEEN X-LINE MULTI-FREQUENCY AND FINEX VIBROSONIC MACHINARY



[1]



[2]

Paul Davies | B Eng. (Hons) Material
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Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Abstract

Two different types of sieving machinery that are used in 'Organization X's' sizing of atomized powder operation, have been compared to find out their process efficiency because of the occurrence of rework. When different batches are blended together to create a larger batch for customer demand, it is found that some fail customer specification because of there being too much oversize in the product or Malvern D₁₀, D₅₀ and D₉₀ values are out of specification. Particle size is important to a customer for their manufacturing purpose.

Literature has been reviewed of the sieve machines used in 'Organization X' and other types. Standards such as sampling methods have been reviewed and other literature reviewed relevant to the study.

DMAIC Methodology was used for the study and found problems and the root causes in processes with both sieve machinery. Changes must be made to improve the current situation, post blending machinery could help to do that.

Declarations and Statements

In this dissertation I declare that all work has been done by myself. Information and material from sources included have been fully acknowledge and identified.

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1. Introduction

'Organization X' is a company based in the United Kingdom that manufactures gas atomized metal powder with either nitrogen or argon inert gas, alloys produced can range from low-alloy steels, stainless steels and special alloys like copper, nickel, or cobalt. Atomized powder feedstock has numerous applications to many fields of industry when bought as a raw material by customers worldwide who use it for many different manufacturing purposes. Applications for manufacturing purposes could be Metal Injection Molding (MIM), Hot Isostatic Pressing (HIP), Metal 3.D. Printing also known as Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM) [3], and for Additive Manufacturing (AM) purposes or uses. Some of the alloys produced in a powdered form are 17-4 PH and 18Ni300, compositions of these alloys are furnace melted and gas atomized. 17-4PH is usually used in MIM applications [4], 18Ni300 is for DMLS or other AM purposes. [5]

Atomization of molten metal is the breakup of liquid into a fine spray that then freezes into powder. [6] The desired micron size distribution for customer specifications and yield is achieved from suction and pressure in the chamber from the atomizer block and the metal flow rate control from the jet stream of liquid metal entering the chamber when it is being atomized by inert gas. Usually a faster flow rate creates coarse powder particles and a slower flow rate create fine powder particles, the diameter size of a nozzle fixed underneath a tundish that protrudes into the opening of the atomizer also helps to control the flow rate. [6] Particle sizes are desired to achieve customer specification and yield, powder made needs to be within a certain size range to suit the manufacturing purpose and to make sure there is minimal yield loss during further processing.

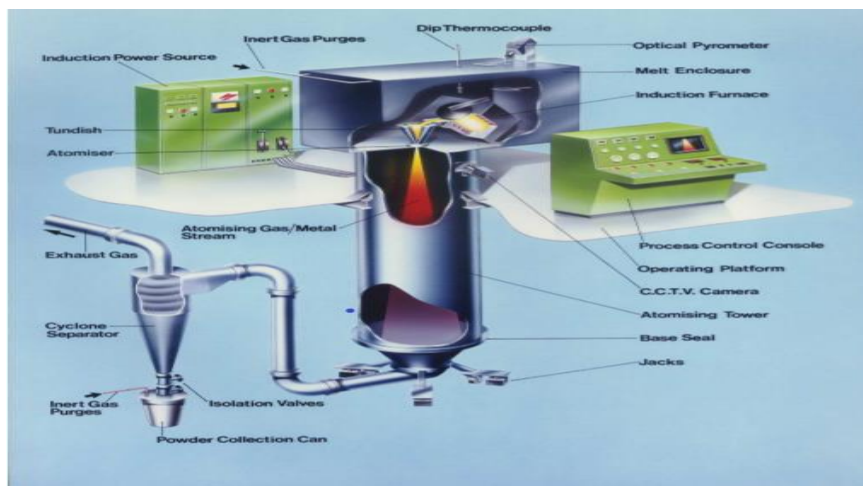


Fig.1. Schematic diagram of inert gas powder production plant. [7]

During the atomization process powder is collected into a hopper then transferred after completion of atomization to the sizing area for further processing to remove (cut out) the unwanted grain size, sizing operations are carried out on either sieving or classifying machinery, with the aim of removing the unwanted particle size distribution in the powder to better achieve customer specification. Powder made by atomization will contain a wide range of particle sizes and depending on the intended application, coarse or fine particles will need to be removed to achieve the desired micron size distribution for end customer use.

There are two types of sieves available that have no particular use because they are both used for all the same sizing operations depending on availability, which are X-Line Multi-frequency that use high speed vibration to pass powder through the mesh and Finex Vibrosonic sieves that pass powder through the mesh, with the aid of electronic pulses and vibration. A screw feed determines the speed that the powder falls on to the mesh kg/per/hour for both of sieve types.

'Organization X's' capability includes supplying metal powder in small lots for prototype development and high-volume batches for large scale production. However, it has been found that batches added together to create a larger batch sometimes fail the result of customer specification and then must be reworked again on sizing operations. It is believed that major factors contributing to this failure is the sampling method carried out and the process capability of machinery for achieving specification.

When a need to re-work many negative outcomes to business functions occur such as added non-profitable costs of having to re-process on machinery, added labor, delays to a customer and delays with other jobs waiting for processing after atomization. The problem has been more realized by the organization from recent data retrieved from a three-month log of the re-work that was needed after blend failures which accumulated to a quantity of 52,756kg worth of material that had to be reworked, which has given motivation for the study.

18Ni 300 with a size range of -53+15 microns and 17-4PH with a size range 80%-22 microns will be compared using the two types of sieve machinery available, Vibrosonic and X-Line sieve machines. 18Ni 300 has been found to fail because of too much oversize in the product after a blend, other alloys have been found to fail Malvern analysis.

There have been numerous reports stated by operatives that X-Line sieves let in too much oversize particles into the product, even though correct procedures have been followed and no damages are present. 'Organization X's' standard working practice (SWP-044) for sieving is supposed to be followed as a procedure to prevent re-work with the objective of getting the product right first time and represent a true reflection of the micron sized distribution of the product for customer requirements from measurement analysis activities carried out in a process.

In this study the DMAIC methodology will be used to verifying the current sampling methods stated in SWP-044 and to compare the process efficiency of the two types of machinery from data collected. The input of data collected will be interpreted in to graphs to show better understanding when being analyzed. The goal is to reduce rework, hope fully this study will help improve the sizing process by highlighting the problems occurring in the current process.

Literature will be reviewed of the different type sieve machinery already used in 'Organization X' and other types available. Standard methods that include sampling methods, mesh size and certain operations applicable are reviewed. Machinery that is /or could be applicable to this type of metal powder industry is reviewed for benefits, or for better understanding.

The particle size and particle size distribution of these alloys are very important for the understanding of physical and chemical properties of the material because they affect key colloid properties such as rheology, surface area, packing density and film gloss. [8] [9] [10] [11] The specifications of product are a quality assurance tool to the manufacturer for their industrial purpose. [11] [8] Before the literature review a brief introduction will be given of both the MIM and DMLS feedstock towards a manufacturing process to show why it is critical to the manufacturing purpose, and why micron size is important to achieve success when used as a feedstock in a manufacturing process.

1.1. The Importance of Metal Powder Feedstock for MIM

Metal Injection Molding (MIM) is a segment of a technology called powder Injection molding (PIM) developed in the 1970's that uses the shaping advantage of Injection Molding but is applicable to metals and ceramics. [12] Engineering properties are more superior than polymers, they have higher strength, stiffness ratios and can operate at higher temperatures. Some materials also exhibit electrical, magnetic and thermal properties that are not possible with polymers. [12] The two main processes to produce fine metal alloy powders used in MIM which are inert gas and water atomizing, gas atomized powder is generally preferred because it offers the benefits of low oxygen and highly spherical powder which contributes to good flow ability. [6]

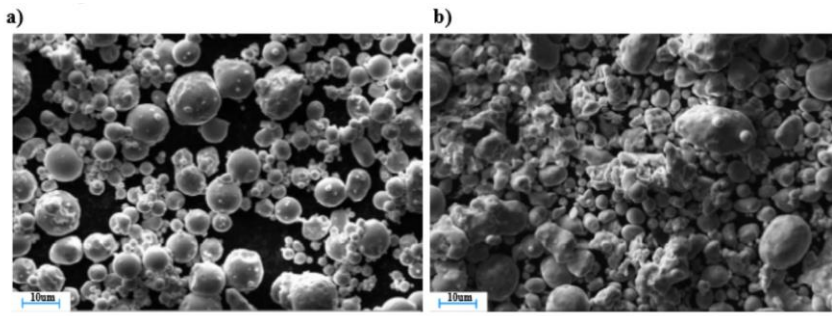


Fig.2. Images shown; a) Gas atomization showing spherical particle shape, b) Water atomization showing rigid particle shape. [13]

17-4PH alloy produced by 'Organization X' used for MIM applications, is a precipitation hardening stainless steel widely used for many industrial applications such as medical, food processing, aerospace and chemical because it exhibits high strength, hardness, corrosion resistance and heat treatment ability. [4] Parts are typically small net shaped and can be complexed in their design, but can still be relatively cost effective towards manufacturing purposes for certain applications, [12] [14]



Fig.3. Images of MIM parts. [14]



Fig.4. Image of stainless-steel medical device. [15]

The stages of the MIM process includes blending powder with plastics or waxes, injection molding the oversized part, removing the binder (de-binding) and then sintering the part to achieve full density. [6] Special fixturing and design features can help support the part during sintering and straightening afterwards by preventing sagging or deformation during shrinkage, but ideally it should support itself and not deform in the sintering furnace. [16]

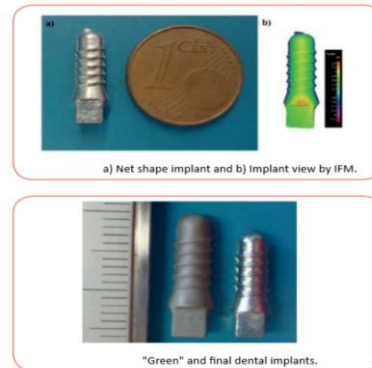
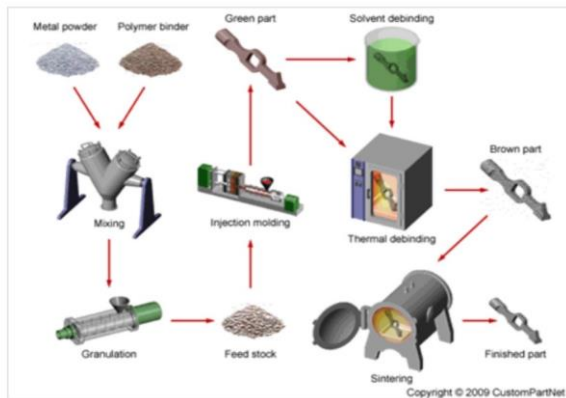


Fig.5. The Metal Injection Molding (MIM) Process. [17] Fig.6. Scale Shown of part and analyzed. [18]

The understanding of material is highly needed for when in the sintering process, small particle size provides high sintering density, excellent strength and surface texture in the final part. [19] [20]

1.2. The Importance of Metal Powder Feedstock for DMLS

18Ni300 which is an Iron- Nickel Alloy 'Osprey' produce for DMLS is a marginal Steel widely used in military and aerospace applications because of its excellent hardness and strength. [21] The powder feedstock is important because there is a need to understand sintering kinetics of the material to achieve full density and a need for good flowability. [22]The process relies on thin layers being spread to form the bed of the 3D component being made [23] [24] and like MIM, gas atomized powder would be the preferred choice. [6]

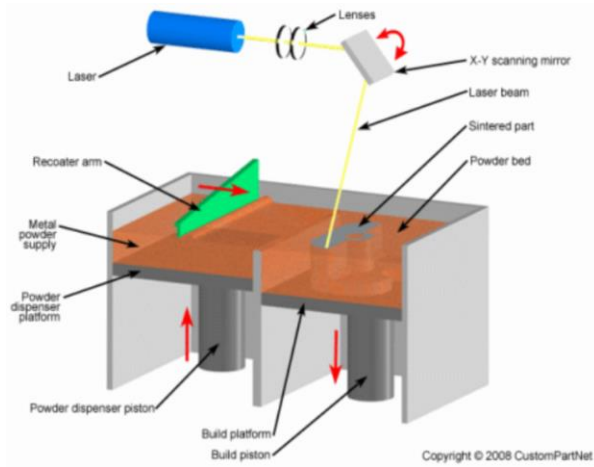


Fig.7. Schematic diagram of DMLS process. [24]

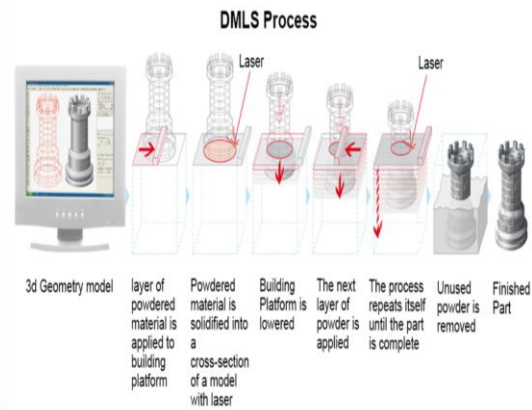


Fig.8. 3D Geometry of DMLS process [25]

Direct Metal Laser Sintering (DMLS) also known as Selective Laser Melting (SLM) is a rapid prototyping 3D printing additive manufacturing (AM) technique designed to use a high power-density laser to melt and fuse metallic powders together. [3] [24]



Fig.9. Parts made from direct metals sintering (DMLS). [26]

With the metal powder used in the process, a high volume of solid fully functional rapid metal prototypes or production parts can be built 'Three-Dimensional' quicker than other processes that make similar components. [27] [25]



Fig.10. Part made by DMLS showing complexity in design. [27]

2. Literature Review

Literature will be reviewed on sieve machinery that 'Organization X' use and other types that are available for better understandings on how they operate differently to achieve particle size distribution (PSD) for customer specification, and if there could be solutions to improve the current sieve sizing operation.

Because of there being too much oversize found in the product, ISO-9044 standard tolerance of mesh size and 'Organization X's' standard working practice (SWP-044) for carrying out sampling methods of moving powder will be reviewed, to try and see if there are discrepancies which could be improve the current process from reviewing the literature.

Other machinery will be reviewed that is relevant to this study relating to Malvern machines that are used to sign a job off after a process, and blending machines to see if there are other options available where blending can be made easier and offer a more accurate result when a process has finished, instead of being blended to create a larger batch.

2.1. Vibrosonic Sieving

Russell Finex offer a range of sieving equipment designed to offer solutions that suits the exact requirements for certain applications [28], such as the grading sieves 'Organization X' use for removing fines or oversize to achieve customer specification of powder made after atomization. They say that their sieves are designed and built to the highest standard because of understanding the importance of consistency and reliability needed for industries, in addition they only use the best quality mesh to ensure increased efficiency that also provides longer mesh life. [28]

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The machine 'Organization X' has purchased from 'Russel' on eleven occasions is the Finex Separator. The machine is designed for accurate grading, scalping or sizing of wet and dry materials up to five fractions in one operation by adding additional sieve decks and mesh screens. [29] It has a standard non-vibratory motor driving a vibrator assembly mounted on a rubber suspension for quiet operations and optimum transmission of vibration to the mesh screens. [29]



Fig.11. Finex Separator Machine [29]



Fig.12. Finex Separator Motor. [29]

The Vibrosonic Deblending System (VDS) is often used with this type of machinery. The system consists of a generator and a probe and applies an ultrasonic frequency directly to the mesh screen, effectively making the mesh wires friction free and eliminating blinding and blocking of the mesh apertures. [30] The ultrasonic screens prevent blinding and blocking of mesh for when screening difficult powders, allowing to sieve on finer meshes. The patented Spiro-screen is a mesh screen especially designed to be used with Vibrosonic equipment [31]

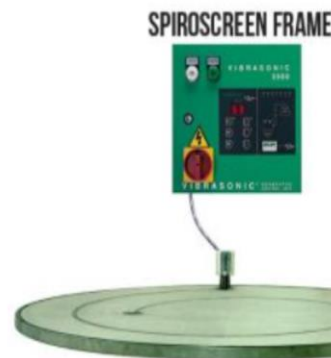


Fig.13. VDS used with separator machine. [30] Fig.14. Spiro screen connected to VDS. [31]

The mesh screen on any sieve is the most critical component, ensuring reliability on sieving solution safeguards the quality of final product [31], it is said ultrasonic can improve sieving capacities up to ten times because powder is enabled to pass through the mesh screen faster, screen overload and a lower frequency of mesh cleaning reduces production downtime. Quality of product is improved in the final product when sieving finer meshes as low as 20 microns, running cost are reduced because the mechanical deblending system reduces mesh damage and the need to repair and replace. [31]

2.1.1. Success Shown in Other Industries Using ‘Russel’s’ Ultrasonic Equipment

Treibacher Industries AG. an international producer of materials for the chemistry and metallurgy industry and Reading Alloys which is a titanium and alloy powders supplier for the medical industry both needed a system to sieve metal powders to remove contaminants and reduce particle sizes through sieving, they turned to Russell Finex for the ultrasonic de-blinding equipment and both found it very successful to achieve this. [32]

Treibacher noticed that sieving at fine mesh sizes posed a challenge to supplying high volumes at repeatable qualities because finer particles sizes can often clog the mesh that reduces sieving efficiency and can damage the equipment. [32] In 1989 they turned to ultrasonic de-blinding technology on its sieving machines and was one of the first companies to do so. This technology since then by upgrading it, has proved indispensable

in allowing Treibacher to manufacture its specialized metal powder resulting in consistent high throughputs enabling for finer and more precise sieving than other de-blinding methods currently available. [32]

Different coating process equipment and process routes require, exceptionally narrow PSD for fine powder to correctly bond with the implant surface. Medical coating manufacturers often choose five or more PSD specifications depending on the medical device treated. To satisfy the customer's needs, Reading Alloys sought to ramp up its capacity to produce titanium and alloy powders, [32] but the company noticed its existing vibratory screeners were experiencing problems attaining the necessary particle size distributions, throughput, and material recoverability. In search of a solution, Reading Alloys decided to install an ultrasonic screening de-blinding system that has helped eliminate blinding at the fine mesh sizes/narrow particle size distributions required by the medical market. Material throughput was enhanced to the point where specified requirements were met in single screening passes and still showed improvements on material recoverability. [32]

2.1.2. Russel's Compact Sieve

There are several challenges when metal powders are reclaimed and reused again in production just like in 'Organization X's' sizing operations, frequent stoppages for cleaning and maintenance means continuous monitoring by operators. [33] The Russell Compact Sieve is designed to achieve high throughput rates while minimal contact parts and tool free assembly keep downtime to the minimum. [33]



Fig.15. The Russell Compact Sieve. [33]

'Organization X' has not purchased this type of sieve from Russell but instead purchased a similar type sieve machine on two occasions which is the X-Line multi-frequency sieve made by Virto-Cuccolini.

2.2. X-Line Multi-Frequency Sieving

Virto-Cuccolini's provide industrial screening equipment's that includes vibrating, tumbling and multi-frequency sieving technologies, that offers efficient and large capacity equipment for wet, dry and slurry based applications needing particle separation. [34] Their patented technology called X-Line is said to deliver a multi-frequency screening solution and is recognized worldwide as a benchmark for screening metal powder. [35] [36]

The machine consists of two-sided electric vibrating motors operating at 1500 RPM that causes multifrequency vibration [37] and the technology is based on accelerating the working mesh up to 500G which is a 10,000% increase of acceleration on the mesh achieved with standard sieving equipment. [38]



Fig.16. X-Line Multi-frequency Sieve. [37]

It is stated that the equipment has had success with fine particle separation at high and low volumes of metal powders to a size of less than 10 μm with an efficiency of 99%. [39] The sieving machine is said to achieves far greater capacities for fine and difficult materials because of their patented multi-frequency vibration technology. [39]

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This could be debatable because powder cut when there is a need to cut anything below 32 microns is usually further processed on classifier machinery.

The Table below shows the sieving capacity of a 650 mm diameter machine for different fine and ultrafine metal powders. [39]

Material	Mesh (micron)	Capacity (kg/hr)
Aluminium	6	42
Iron	20	67
Tungsten	25	355
Gold	7	20
Titanium	15	70
Stainless steel	22	106
Copper	40	49

Fig.17. Sieving capacity of a 650 mm diameter machine. [39]

'Organization X' found that when operating at 106kg per hour there was too much powder being obtained on the mesh that caused ripping of the mesh and too much coarse powder was staying on the mesh so the operation was run the same as vibro-sonics 45kg per hour.

Another purpose for this sieve is to offer a quick response to downtime for screen cleaning. It is said that X-line offers the best technology around for screen cleaning and is more efficient with energy savings when being compared with traditional sieve screen cleaning methods, it is also more environmentally friendly because of less energy consumptions. [40]

Operators in 'Origination X' might disagree with this because the machine has been implemented in to the sieve line structure that was built for Vibrosonic sieving and find that it is difficult to strip the machine down for cleaning, also they find difficulty in building a new mesh screen themselves and building the machine back up ready for use.

2.2.1. Information in the Manual for Building X-Line Meshes

The manual states to never activate the X-line machine if the mesh is not well tensioned. [41]. The appropriate way to fit a working mesh to an intermediate mesh appropriate is shown below in (Fig.18.).

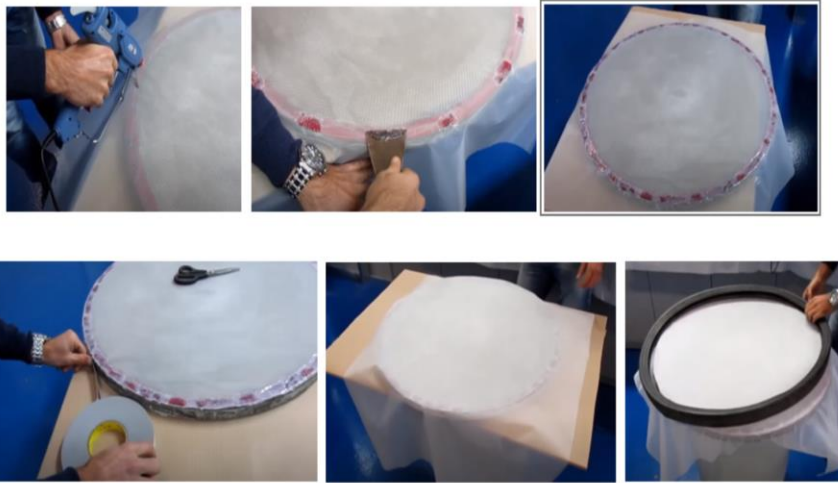


Fig 18. Best way to change the intermediate and the working mesh cloth. [42]

The working mesh should be pulled and tightened around the intermediate mesh, glued, and fixed in to place by using double sided tape to achieve light tension. [41]

This is not being fully adhered in 'Organisation X's' sieving operations because the meshes are not being fully tightened around the intermediate mesh by gluing the working mesh to it and by using double sided tape to support the fixed mesh in to position.

For installation in a structure the dynamic loads must be considered to avoid non-reasonability, calculations of allowable force values are given to support the structure and it is possible forces can act on the supporting structure. [41] The installation of these machines might not have been fully adhered when 'Organisation X' implemented them into the sieve line.

2.3. ISO-9044 Mesh Standard size for 53micron size mesh

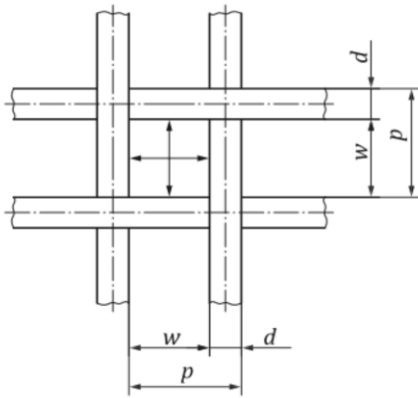


Fig 19. Aperture width, wire diameter and pitch. [43]

Wire diameter= d (diameter of the wire in the screen).

Pitch= p (distance between the midpoint of two adjacent wires).

Warp= w (all wires running length us

Weft= w

Number of apertures per unit length= n (number of measurements taken).

Open screen area= A_0 (percentage of the surface of all the apertures in the total screening surface). [43]

Formula for calculating open screening area; -

$$A_0 = \frac{w^2}{(w + d)^2} \cdot 100\%$$

Fig.20. Open screening area formula. [43]

The ratio of the nominal aperture width, w , and the square of the nominal pitch, $p = w + d$, ratio of the value is rounded to a full percentage. [43]

Formula for calculating maximum standard deviation; -

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (w_i - \bar{w})^2}$$

with

$$\bar{w} = \frac{1}{n} \sum_{i=1}^n w_i$$

Fig.21. Separate maximum standard deviation (s) aperture width calculations. [43]

The maximum standard deviation (s) of aperture widths measured in both weft and warp directions should not exceed values stated for allowable tolerances of mesh size.

Industrial woven stainless-steel mesh has acceptable limits and for all micron sized woven mesh. [43] [44] For example, 53micron mesh tolerances should consider 3 points; -

1. Essentially it is acceptable for a 53micron sized mesh to have 6% of its apertures up to approximately 50% greater than its nominal size. [43] [44]
2. The average aperture size for a 53micron mesh should lay between 48-58 microns, i.e. it is perfectly acceptable for a 53micron mesh to sieve an average of 58 microns. It cannot be assumed that a 53micron mesh will remove everything over 53 microns, theoretically it may not remove anything between 53 and 58 microns. [43] [44]
3. No apertures should be greater than approximately 100 microns if this happens then this is deemed a 'major blemish' and only 10 major blemishes are acceptable within a 10m² panel of mesh of this nominal aperture size. [43] [44]

2.4. Other Sieve Type Machinery

Other machines are available for sizing metal powders, Farley Green's Ultrasonic de-binding machine is like a hybrid of both Russell Finex's Vibrosonic and Virto-Cuccolini's X-Line equipment, Tumbler machines produced by Minox operate at a much lower frequency that is supposed to simulate how a Rotap machine operates for analyzing PSD, These machines will also be reviewed.

2.4.1 Farley Green's Ultrasonic de-binding System

Another manufacturer based in the UK who has been designing and manufacturing sieve machinery is "Farley Green". They consider themselves as expertise to the field and offer a week trial free of charge to check beforehand if their machine can be required for the job. [45] Although they tend to supply more for food and drink, pharma, and chemical applications they can also supply to the metal powders industries for grading such as when purchasing the 'Sieve Master Multiscreen' with the ultrasonic sieve deblending system. [46]



Fig.22. Farley Green's' Sieve Master Multiscreen' machinery. [46]

It is stated that the sieve can separate grade, and sort nearly all types of materials through multiple screens, using the multiscreen vibratory sieve and the weight eight configuration technology controls the amount of time product is sat on mesh screens, and the deblending system eliminates clogging for a consistent throughput and mesh longevity. [46] Band clamps can be easily removed without tools, and the decks and meshes can be easily removed for cleaning. The ultrasonic de-binding system is designed to improve throughputs by 300%. [46]



Fig.23. Farley Green's ultrasonic de-binding system. [46]

2.4.1.1. Success with Farley Green Technology

A case study is shown on their website to check sieving capability of a heavy metal fine powder for the machine tool manufacturing industry. The product came direct from the

raw material process via vibratory feeder and was discharged into collection bins. [47] A machine with ultrasonic and high frequency variation to a single screen format was used that was specially designed discharge outlet to eject oversize product after each batch. [47] The product was introduced to the machine via the open top from a vibratory tray feeder and the sieve unit was timed to sieve the product, once complete the machine stopped and reversed the direction of the motor and the pneumatic shuttered outlet opened and oversize material was ejected. Once the oversize material was clear the machine stopped and reversed the motor back to sieving mode for the next batch. [47]

The machine was floor mounted on an extended height mobile base to suit the feed height of the vibratory feeder. The result was that it provided an ideal solution to sieve a difficult product as previous throughputs were not as good without the use of the ultrasonic de-blinding system. [47]

2.4.2. Minox Tumbler Screening Machines

Minox state that their high-tech tumbler screeners are a solution for conventional fine and difficult screening problems for all industrial applications such as metallurgically when powders and granular materials are in the fine, ultrafine range and especially for when there is difficulty with a certain material. [48]

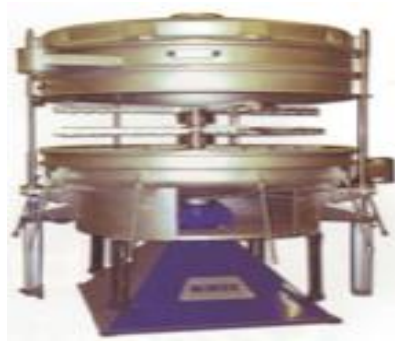


Fig.24. Minox Tumbler Machine. [48]

The tumbler screening machine is mechanically simulated by the simplest screening method, which is hand screening by eye. This basic motion is gyratory with the horizontal motion being like a plane sifter, the slow speed V-belt drive allows speed from 170 to 280 rpms and the residence time of each product can be adjusted by the patented Minox assembly in a radial and tangential angle, towards the drive axis.

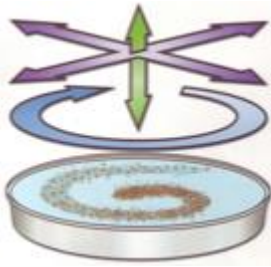


Fig.25. Image shows gyratory motion of power being sieved on a mesh. [49]

A three-dimensional tumbling motion of a mixture of plane and throw is created. The screening material is uniformly distributed over the entire surface from the center to the periphery it travels in a spiral transport direction, finer particles will pass through the mesh holes in the center. [49]

2.5. Rotap Testing Machine

A Rotap testing sieve shaker accurately reproduces the circular and tapping motion given to testing sieves in hand sieving. A uniform, mechanical action assures dependable, comparable sizing tests when a precision separation is required, a sample can be tested on a series of six sieves and a bottom pan. [50]

To determine the size distribution of particles, the sieve analysis test procedure is an effective method to test samples from sizing operations. In sieve analysis particle size distribution is defined using the mass or volume. Sieve analysis is laboratory test procedure in which particles will move vertically or horizontally through sieve mesh. [51]
[50]



Fig.26. Image of Rotap machine used for measuring particle size in a sample. [50]

2.6. Classification Sizing Methods for Metal Powders

With air classification of metal powders, due to particle size distribution some processed products do not meet application requirements because of fine or oversize fractions of particles can interfere with further processing and make the final product not usable for the intended customer application. Some sieve processes require additional processing to meet the desired particle size distribution necessary to improve the product's characteristics [52], like for instance 18ni300 -52+15 micron size powder, these machines provide the necessary need of cutting powder below 15 microns.

Particle size range of >100 microns can be classified without difficulty using a screening machine, however, air classifiers are essential for finer particle size distributions that require a more controlled separation. [52] Typical applications for fine classifiers are for the separation of undesired coarse grains and the distinct reduction of fines (de-dusting). Different machine designs are available, depending on the desired cut points or application and machine sizes are available for nearly all ranges of capacity. [52]

An advanced classification system is said to offer high product yields of ultra -sharp size cuts from 500 microns down to 7 microns and is also said to offer precise product oversize removal. [53] A twin discharged classification system offers fine particle size cuts from 250 microns down to 3, it allows higher RPM for a given feed rate requirement for certain specification, twin discharge allows a smaller diameter rotor that leads in to increase efficiency and top size cut. [53] 'Organisation X' use the twin classification system in their process.

2.7. Malvern Low Angle Laser Light Scattering (LALLS-Laser Diffraction) PSD Analysis Testing Machine

Malvern offers leading instrumentation for all types of particle size analysis and characterization from sub-nanometre to millimetres in particle size. [54] The machine that 'Organisation X' use in their process is the Malvern 2000.

The method in which the machine operates includes a laser beam passing through a sample of particles in a suspension of liquid and the data collected from light intensity at different angles. A low concentration of a sample is applied to minimise multiple scattering because that would make it difficult to produce an accurate reading of particle size distribution based on scattering angles. [55] [56]

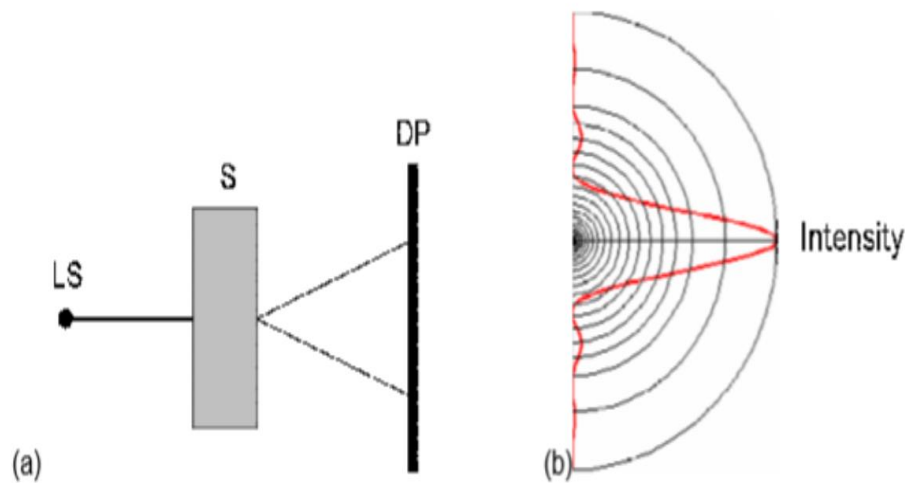


Fig.27. Schematic of LALLS technique. [55]

A schematic representation of LALLS technique is shown in Fig 27. (a) The experimental set up (LS: laser source; S: particle suspension; DP: diffraction pattern.). (b) Measurement of scattered light intensity by circular light at the detection plane. [55]

An advantage is that data collection is simple and fast, that offers a broad dynamic range of analysis testing of particle size from 0.1 microns up to a millimetre in size. A disadvantage is mixtures of particles with different optical properties cannot be normally measured, if strong absorbing particles are present then problems occur because they may not produce usable scattering signals. Accuracy depends on the optical parameters as well as information about the particle shape. [55] [56]

2.7.1. ASTM-BS22 Standard allowable tolerance for Mastersizer Machines

'Organisation X' have two Malvern Machines, Master Size machines are shown to have allowable tolerances which could mean that each machine could give slightly different results. [57]

Mastersizer 2000

The specifications for the Mastersizer 2000 dispersion units are set at $\pm 3\%$ for the $Dv50$ and $\pm 5\%$ for the $Dv10$ and $Dv90$.

	$Dv10 / \mu m$	$Dv50 / \mu m$	$Dv90 / \mu m$
Lower Limit	34.735	58.779	83.944
Target Value	36.563	60.597	88.362
Upper Limit	38.391	62.415	92.780

Mastersizer 3000

The specifications for the Mastersizer 3000 dispersion units are set at $\pm 2.5\%$ for the $Dv50$, $\pm 3\%$ for the $Dv10$ and $\pm 4\%$ $Dv90$.

	$Dv10 / \mu m$	$Dv50 / \mu m$	$Dv90 / \mu m$
Lower Limit	35.597	60.054	85.928
Target Value	36.698	61.594	89.508
Upper Limit	37.799	63.134	93.088

Fig.28. Mastersizer 2000 and 3000 allowable tolerances for D number values. [57]

Mastersizer 3000 machines offer more accuracy but 'Organisation X' use Mastersizer 2000 machinery in their operation.

2.8. 'Organization X's' Standard Working Practice for Vibrosonic Sieving SWP-o44

Operation

(a). Check the Vibrosonic system is working prior to starting sieving.

(b). As the sieve runs; -

1. Monitor feed to the sieve and record finding.
2. Carry a hand sieve test analysis on powder every hour.
3. Visually check powder build up on the mesh. High levels more than 25mm of powder is unacceptable.

(c). In-process testing; -

1. Take a test sample of approximately 200g at least every hour or at an interval specified from the product powder container (hopper).
2. Run through a hand sieve of the same aperture size.

3. The sample taken should be visually checked as it is laid on the hand sieve to check for any anomalies in the powder.
4. Most of the powder should flow easily through the hand sieve. The powder should be swirled through and maybe lightly tapped or brushed to encourage movement through the mesh.
5. Any large particles not going through the hand sieve indicates either damage to the Vibrosonic or the presence of slag in the powder. Report to shift leader and do not proceed with operation.
6. Provided that there are no large particles in the sample taken, place approximately 20g in a sample bag. For example, at the end of a bath of 100kg as atomized powder, then there should be 450g obtained.
7. The 450g sample of product is to be tested by a Malvern analyzer. Provided that the Malvern results are in spec, the 450g should be emptied back into the product container.

(d). Each pass analysis; -

1. Take a 200g representative sample of material from the revert bin and carry out a hand sieve test.
2. Weigh the undersize of the 200g sample.
3. To calculate the percentage of weight of product retained, divide the undersize weight by 200g and multiply by 100.
4. Weigh the revert bin material recovered from the first pass.
5. To calculate the weight of product retained in revert (4), multiply the weight of the material recovered in the revert bin by the retained product percentage as in (3).
6. To calculate the overall yield percentage, add the weight of product retained to first time pass weight and divide by the as atomized powder weight.
7. As a rule, if the retained product percentage is less than 10% then stop processing, otherwise re-process.
8. If the overall yield is greater or less than 5% of the target yield, then it should be reported to the team leader.

[58]

This will be followed further in the study for when comparing process efficiency of Vibrosonic and X-Line Machinery.

2.9. ASTM-B215 Sampling Method Standard

Composite samples must be blended to achieve the entire gross sample the increment of the quantity of powder obtained is by a sampling device at one time from a larger quantity of powder. The gross sample is determined from the total quantity of powder adequate for

the intended purpose, consisting of all the increments combined. Test samples for the quantity of powder (generally taken from the composite sample) on which the test is performed. [59]

Specifications and test methods for metal powders and metal powder products require the sampling, testing, and performance evaluation of small samples taken from large quantities of powder. The sampling procedure is equally as important as the testing and evaluation and the sampling methods used must include every precaution to ensure that the samples obtained will show the true nature and condition of the large powder quantity that they represent. [59]

The primary objective of any sampling procedure is to obtain a small quantity of material that is truly representative of the larger amount from which it is taken, a condition that is readily comprehended but difficult to define, quantify, and prove. The criteria desirable to meet these conditions are as follows; 1. Every sampling increment should have a non-zero probability of being selected; 2. All increments should have an equal probability of being selected; 3. The sampling procedure should not alter the material (for example, by changing the particle size or chemical composition). [59]

Sampling a moving powder is more asserted to these criteria shown in Practice 1A and should be used whenever possible to obtain the composite sample.

2.9.1. Sampling a Moving Powder

Practice 1A—Sampling a Moving Powder

1. The preferred method for sampling powders is always when the powder is in motion i.e., when being transferred from a blender or falling from a conveyor, or in a moving process stream.
2. The Equal amount of powder increments should be taken at random intervals over the life of the flow.
3. The number of increments that make up the gross sample should be agreed upon between the parties concerned.
4. Pass the rectangular receptacle at a constant speed completely through the stream of flowing powder, starting immediately upon flow. Repeat at random intervals until the agreed-upon number of increments is obtained, taking the last increment near the end of the flow.
5. Alternatively, use a commercial sampling device to collect the agreed-upon number of increments, starting immediately upon flow, and taking the last increment near the end of the flow.

6. The total amount from all increments shall be adequate for the tests or evaluations to be performed.
7. Blend the gross sample in a small blender to form the composite sample.

[59]

2.9.2. Sampling Stationary Powder

Practice 1B—Sampling a Stationary Powder

Although sampling a moving powder is always preferred but is not always possible. Stationary powders must be sampled using either a tube (slot) sampler or a simple. [59]

For sampling stationary powder, a tube sampler can be used which is a hollow tubular multi-level slot sampler for removing powder from several depths of the container is the recommended way to sample packaged powder. Alternatively, a single-level tube sampler may be used repeatedly to remove powder from several depths of the container. Equal powder increments should be taken at each depth and the number of increments that make up the gross sample and the number of increments taken from each container should be agreed upon between the parties concerned. [59]

2.9.2.1. QAQC Lab Variable Volume Multilevel Powder Sampler

The multilevel powder sampler is ideal taking powder samples from containers that have collected free flowing or granular material. The sample volume of each cell amount can be adjusted from 5ml up to 60ml in 1ml increments using interchangeable pugs, reversing the plugs also offers a use for single point sampling method across a certain cross section. [60]

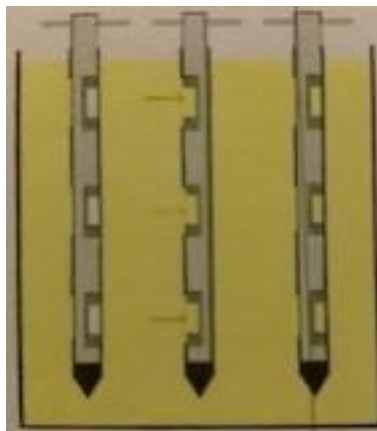


Fig.29. Image of multi leveler powder sampler. [60] Fig.30. Directions to retrieve samples. [60]

Operation Steps

1. Select correct volume inserts and place in inner rod.
2. Slide assembled inner rod into outer sleeve and lowest sample level.
3. Insert sample in product, turn handle to expose sample cells.
4. Turn handle again so no inserts are exposed and remove sample from product.
5. Remove inner rod from outer sleeve to obtain sample.

[60]

2.10. Post Hopper Blending Machinery

The Ideal situation would be to blend product retrieved after sizing operations straight away after completion, but this is not possible because blending machines are in constant use and would cause delays in the process. However, it has been found that hopper post blending machinery is available developed by company called SaintyCo. [61] This equipment could be suitable to 'Organization X's' manufacturing purpose because they would be able to blend straight away after a sieving process and then be able to test a more accurate sample.

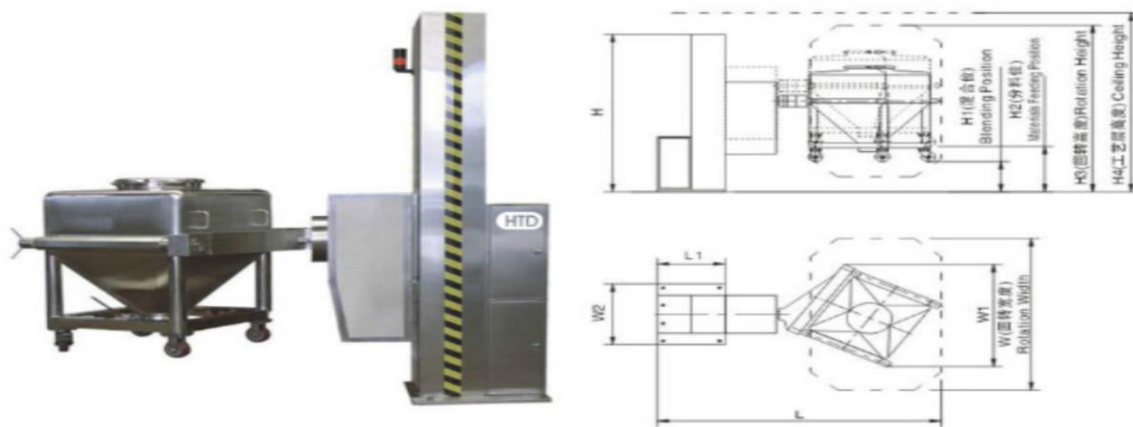


Fig.31. Saint Co post blending machine. [61]

Technical Data	HTD400	HTD500	HTD600	HTD800	HTD1000	HTD1200	HTD1500	HTD2500
W	2100	2300	2400	2500	2700	2800	2800	3600
W1	1445	1530	1583	1730	1898	1888	1800	2650
W2	800	800	800	800	900	900	900	850
L	2555	2595	2663	2800	3020	3150	3200	4051
L1	800	800	800	800	820	980	1500	2350
H	2400	2500	2500	2500	2900	4250	2800	4000
H1	350	350	350	350	400	450	450	500
H2	750	750	750	750	900	1700	1700	2400
H3	2250	2400	2500	2600	2800	3100	3100	3800
Blending speed(rpm)	3-20	3-15	3-15	3-15	3-10	3-8	3-10	3-8
Max bin volume(L)	400	500	600	800	1000	1200	1500	2500
Loading volume(L)	320	400	480	640	800	960	1200	2000
Loading weight(Kg)	200	250	300	400	500	550	750	1250
Total power(kW)	5.2	5.2	5.2	7	7	7	6.2	9.7
Total weight(kg)	1000	1200	1300	1600	2000	2200	2000	5000

Fig.32.SaintyCo post blending machine range. [61]

Machines are available that could cope with the weight after a sieving operation. Hopper containing product is usually under 750kg and the size goes up a maximum loading weight for machine availability is 1250kg.

3. Methodology

The Main purpose of this study is to try and reduce re-work that occurs in 'Organization X's' manufacturing operation. A three-month log of data was retrieved in 2019 that indicated a large amount of product that failed customer specification after batches had been blended for customer requirements.

It has also been noticed on numerous occasions that some operatives have complained that X-Line multi-frequency sieving has allowed too much oversize through the mesh, but the mesh has shown not to be damaged and will pass through a mesh slightly higher in aperture size.

The two types of sieves available are X-Line multi frequency and Finex Vibrionic. The project will include the efficiency of these two machines being compared to each other and, the SWP for operating these machines will also be followed to try and root out a cause that could be causing failure to the final blending process. DMAIC Six Sigma Methodology will be used in this project because of it being highly applicable to this kind of task when used as a metric to measure the efficiency of a process. [62] [63] [64]

3.1. A Brief Introduction to DMAIC Methodology

The DMAIC module is a data driven improvement cycle that is structured so it can be applied for businesses to detect inefficiencies or flaws that cause output defects in a certain process. [65] From this, solutions of how to overcome problems can be better understood with a goal set out to optimize, improve or stabilize the current process [65]. This approach is used as a gated process and must have closure in each phase before moving on to the next, the abbreviation of DMAIC means Define, Measure, Analyze, Improve and Control. [63] [62].

Motorola take credit for the development of the DMAIC methodology, but they expanded on improvement technique systems first developed by the Japanese car manufacturer Toyota. [65] Motorola manufactured television sets in the United States during the 1970's and were consistently beaten on the market by other competitors due to quality issues of their product, when taken over by a Japanese firm it prompted drastic change and they started producing TV sets with less defects. [62].

DMAIC is commonly used in Six Sigma because of the availability of certain tools and techniques imbedded in this process tool that is highly applicable to Six Sigma project systems. [63] It is a universally scaled system which offers opportunities for different areas of business processes to be compared with as long as established limits are kept. Objects or fields that are dissimilar can be compared when considering measurements such as weight, length, temperature, and other desired measurement factors. [66].

When used as a metric, set measurement scales for quality improvement targets can be used for any business process, quality can be defined from describing people, describing product and for describing a process. [67] [66]. Results achieved from Six Sigma can enhance profitability by reducing cost when improving productivity, efficiency and quality, when emphasizing on reducing variations by focusing on doing thing right first time, core process improvements and customer knowledge would then lead to improving a company's growth of revenue and sales. [62] [63]

4. Define Stage

Define stage is used to show why a project is necessary, requirements are captured that specify deliverability of quality, estimations of resource and the time scale needed for when activities are carried out. [65] A plan should be developed and implemented firstly in a project to shows a business case that justifies the need for a company to agree towards investing time and money towards a project to have a successful outcome, this is included

in a project charter. [63] [62] Other tools and techniques are used in DMAIC projects to define further necessities of a project. [65] [63] [62] [66].

4.1. Project Charter

The problem statement shown at the start of the project charter shows where the problem is hurting the most and states the reason in to why there is a need for a project to be undertaken. [65] If deemed acceptable by company hierarchy, then the project can go ahead providing there is an end goal that would benefit business needs from improvements found. [65] The scope, methodology plan, timeline for completion and team members of the project are also included in the problem charter.

Below is the project charter for the study 'Comparing the Process of Sieving Efficiency between X-Line and Vibrosonic Machinery'.

Project Charter

Project Name: Comparison of Sieving Efficiency between X-Line Multi-Frequency and Finex Vibrosonic Machinery

Problem Statement:

In a 3-month period (2019), a study was carried out to find the accumulated kg quantity of batches that failed customer specification from sizing operations after blending and had to be reworked again on sizing machines because of too much oversize in the product. The quantity accumulated to 52,756kg worth of failed product that failed customer specification after blending in in that 3-month period, the failed blended batches had to be reworked (over-processed) to obtain customer specification.

Although not solely to blame, but it was found that 18Ni300 alloy with a size range of -53+15 microns subjected most blend failure. A high percentage of +53 oversize particles was found when carrying out final testing after blending of batches, such as when applying a Rotap test and other alloys failed when collecting a Malvern result from a final blended sample.

- The average selling price of metal powder is £8per/kg, it takes 22.2 hours to sieve 1000kg of product because the feed of powder put on to the mesh is at a rate of 45kgper/hour.
- It would take 1172.35 hours to sieve 52,756 kg which means £422,048 worth amount of product was not being processed in sieving operations in that 3month period, if that were to happen over 12 months it could accumulate to £1,688,192 worth of material that is not being processed.

Goals:

To find the root cause of why blended batches fail customer specification by looking at the sieve sizing process to verify the SWP for sampling methods carried out by operators in the process and to compare the efficiency of the two different type machinery available which are Russel Finex Vibrosonic and Virto Cuccolini X-Line Sieves . The aim is to see if the operation carried out is fit for purpose and to find a solution that would improve the current situation by eliminating or reducing rework.

Scope:

Scope is to compare performance of sieving operations on Vibrosonic sieves and x-line sieves Using a finer grade alloy 17-4ph sieved at -32 microns and a coarser grade powder sieved at -53 microns before being further processed on classifying machines.

- % of oversize particles in product = quality issue, time loss.
- % of undersize particles in revert = yield loss, time loss
- Sieving stations included in the study.
 - Vibrosonic: number 7, 10 and 11.
 - X-Line: number 5 and 13.
- Compare particle size distribution of composite and blend samples.
 - 18Ni 300 Alloy with a size range of -53+15 microns.
 - 17-4PH Alloy with a size range of 80%-22 microns.
- Product in-process testing described in SWP-044.

Paul Davies (P151993)

- Collect 200 g sample from the product powder container every hour.
- Hand test the 200 g sample through a sieve of the same aperture.
- If no large particles found, place ~20 g in the sample bag (composite sample).

- Revert testing described in SWP-044.

- Collect 200 g sample from the revert powder container.
- Hand test the 200 g sample through a sieve of the same aperture.
- Weigh the undersize extracted from the 200 g sample and calculate yield.
- If % of product in revert < 10 % then stop re-processing.
- If yield +/- 5 % of target yield, then report to SPL

- Data collection form to be developed to follow as a measurement system, which includes added procedures for the study and the SWP standard being adhered.

Business Benefits:

If solutions from the study are found it could benefit the business by improving the quality of the product and customer satisfaction because lead times are met, eliminating rework would enable moving on to the next customer and free up space from jobs in waiting for processing. Production is enhanced which would increase profitability.

Preliminary Plan and Timeline:

DMAIC methodology to be followed. Deadline for completion is to be done by the end of the first quarter of the business year 31/03/20.

Team Members:

- Production Manager
- Process Manager
- Technician (Author)

The author of this study will be carrying out all the activities, data from testing activities will be discussed with the process manager and then presented to the production manager, who then implements the testing process in to the production plan and provides a timescale of when a process should be completed.

4.2. Internal CTQ

CTQ's are internal parameters that are critical to quality that show a connection to the needs of a customer. [68] [69] A simple but power full tool to help define the criteria needed for success, that shows the scope and deliverables meet the requirements. [68]

'Organization X's' Internal CTQ for Success

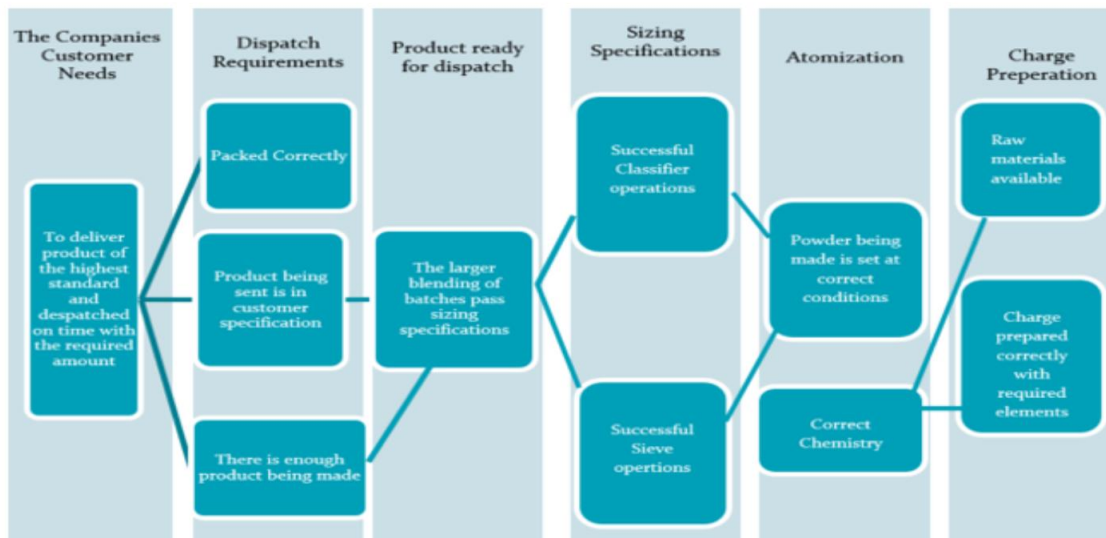


Fig.33. Internal CTQ. [70]

If sizing processes do not achieve specification but are still blended, then the goal does not reach the customers' needs for quality.

4.3. SIPOC Diagram of a Sieving Process

SIPOC diagrams help understand how a process works by visually looking at it [71] and help identify a process improvement before a project has started. [72] It can be used as a tool to help a manage the project [73] and find if the right process has been identified. [74].

SIPOC Diagram of the Sieve Sizing Process

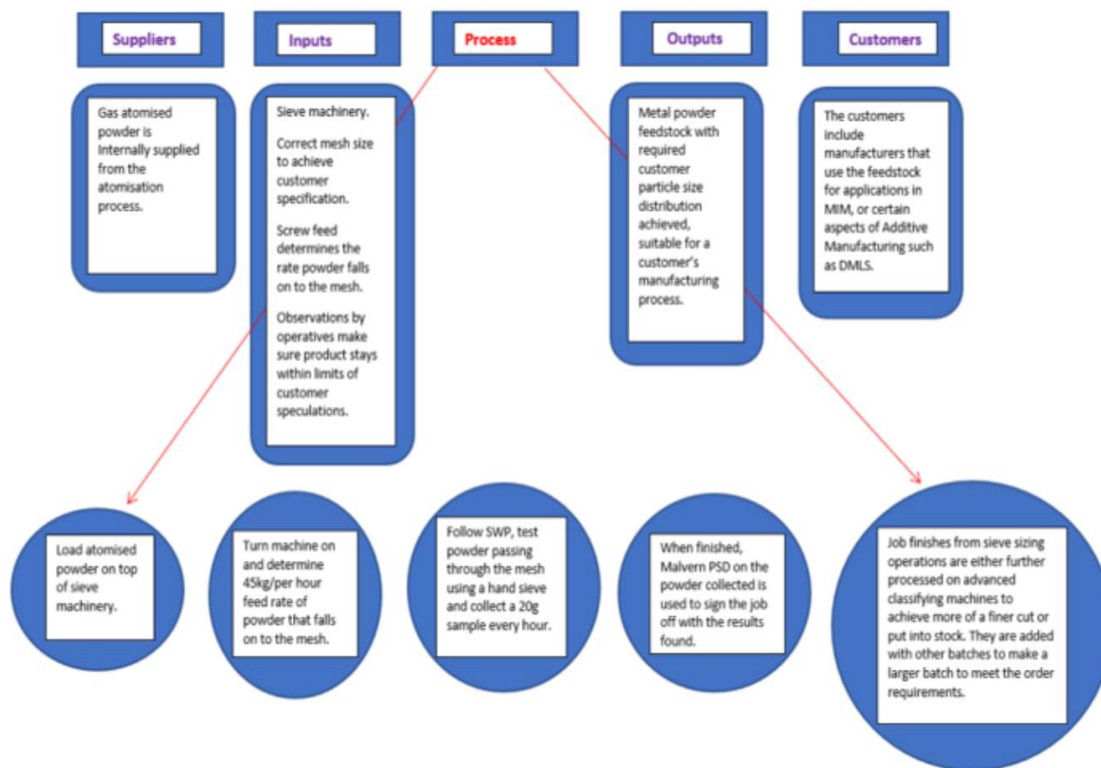


Fig.34. Sieve sizing process SIPOC. [70]

The diagram basically describes that atomized powder is supplied on to the sieve machinery and is then sieved correctly following standard procedures of operation. If successful, then a quality powder feedstock is made for customers who require the product to use for their manufacturing purpose.

It also shows a lot more for when wanting to understand a project. The process shows how the procedure of the project should be followed and why it is important that it done correctly, to produce a quality material for the customers end use. If followed correctly using the process steps and failure has been found, then alarm bells are raised that the process is not at the correct standard and should be investigated to improve the current situation.

4.4. Cost of Quality

Cost of quality determines the extent resources are used in activities to prevent poor quality and what extent results of poor quality would result to in an organization. [75] The cost of quality is incurred to prevent loss of quality when not conforming to specification [67], cost of poor quality is occurred when there is a need to refurbish and overhaul a product to meet requirements. [67] Cost of quality can be used as a method to define ore measure resources used to prevent failure and the cost from failures. [76]

'Organization X's' Cost of Quality

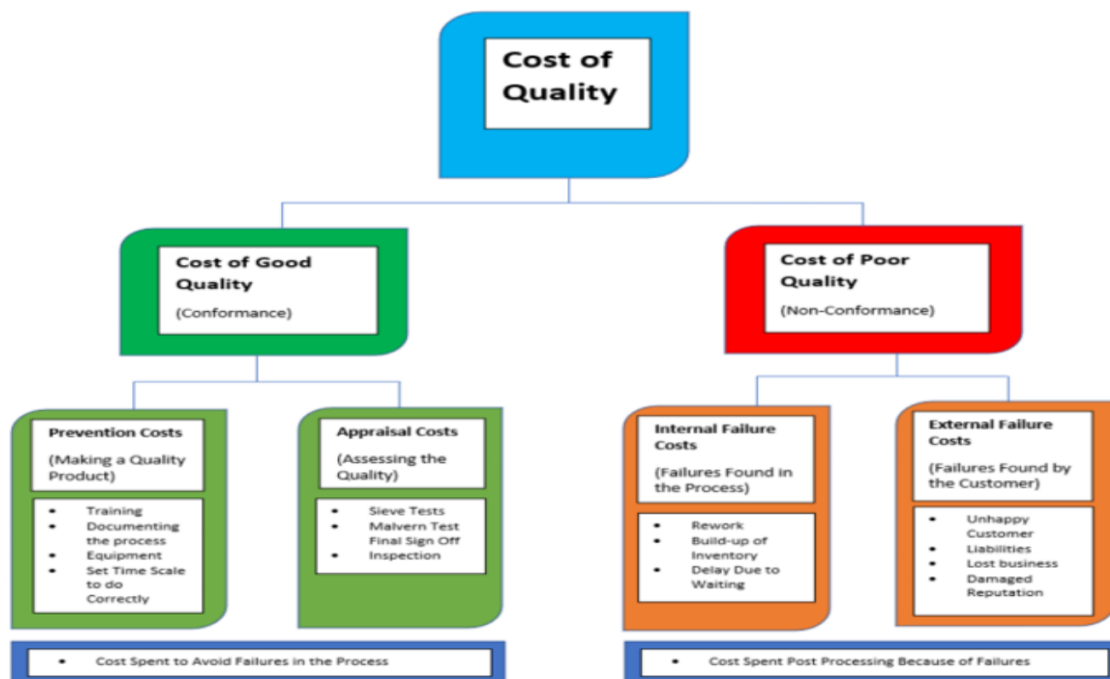


Fig.35. Cost of quality diagram. [70]

The project entails adhering to the cost of good quality when following the SWP in the project steps for comparing the efficiency of the two sieve types and will be measured. Poor quality is described here and will be better understood if failures are found in the current process from the study.

5. Measure

The Measure phase is where metrics and measurement systems for the inputs and outputs of the project are formed [77] and where the validation systems of measurement occur, the capability to quantify data and criteria for success must also be determined. [67] For graphical methods establishing a correct metric from the tools available is crucial so it would address the problem successfully. [67] Inaccurate data would cause wrong conclusions further into the project. [77]

Who, where and when the data will be collected and what will be done with the data after being collected? are importing questions to consider regarding the method of data collection. [78]

An overview of the measuring phase is to measure the current process or performance, identify the sources of making the data available for example units of measurement/measurement scale, develop a data collection plan and then describe the problem on the basis of data collected with the involvement of graphical tools. [78]

5.1. The Data Collection Sheet and Method

A data sheet was developed to use for logging down results for when carrying out activities in the testing process. Firstly information is captured of what the product type is i.e. 17-4PH or 18Ni300, the size range of the powder before being processed on the sieve which would be -500 microns because it is 'As Atomized' powder, the batch number, date of when the activity is being carried out, temperature of powder beforehand because it is not acceptable to process if the powder temperature is above 60 degrees, the size of the sieve mesh, the sieve station number and the sieving angle which should be set at 110 degrees for Vibrosonic machines but does not apply to X-Line Machines. This part of sheet could be describe as being like a check list before starting.

The values on the data sheet follows the SWP for sampling and the sieving process, but other steps have been added for the study. Testing required in the SWP states the feed the

powder should fall on to a mesh should be a rate of 45kg per hour [58], there is an allowable tolerance of +3 or -3, sieve tests of product contained in the hopper and a 20g sample collected should be carried out every hour. Time has been used to make sure testing is carried out every hour and the feed rate setting logged down which is not required in the SWP.

Results from the hourly sieve test of product to check the oversize value, and if it passed or failed is logged down on the data collection sheet. The allowable limit of oversize is 2%, anything over would indicate a problem and the process should stop because it indicates mesh damage or the feed rate is too fast. However, on X-Line it has been reported that the mesh is not damaged, or the feed rate is not too fast, and no rough particles are found in the powder when carrying out a sieve test. It passes through a mesh the next size up so when carrying out testing in this study results will just be recorded, and the process allowed to continue. The Malvern test will be done on the collected composite samples at the end like stated on the SWP-044. [58]

A Malvern test is only required at the end of a process, in this study a Malvern test would be carried out every hour and logged down to see if there are any changes to particles size thorough out the process, it could also reveal relationships between other factors of data being measured.

A test is only required on revert powder when a process has finished and if product obtained is greater than 10% then a 2nd pass is required. [58] This study will include a sieve test carried out every hour and the results logged down and a composite sample collected.

Before process testing is carried out the machine must be cleaned down thoroughly, a new mesh used (or clean and in good condition if not possible) and all components of the machine must be working correctly.

Product: _____, size: _____ μm , batch number: _____, date: _____, powder temperature: _____, sieve mesh size: _____ μm , sieve station number: _____, sieving weight angle _____ ($^{\circ}$)

Time	Feed Rate (kg/h)	Feed Rate Setting (from control panel)	Product Sieve Test Sample (200 g)	Product Sieve Test: grams oversize in 200 g sample	Product Sample (20 g)	Product Malvern Test: % -22 μm (17-4 PH) or -15 μm (18Ni300)	Revert Sample Size (20 g)	Revert Sieve Test: grams undersize in 200 g sample
7:45 am	48	12	Fail/Pass	2.05	Yes/No	75 %	Yes/No	1.25

Fig.36. Data Collection Sheet. [70]

5.1.1. Further Steps Required after a Process has Finished

- With the product composite collected, blend and carry out x3 Malvern tests on Machine B.
- With sieved product collected in the hopper, blend for 30mins and carry out x3 Malvern Test on Machine B.
- Graph Developments of +32 or +53 in product and -32 or +53 in revert.

Fig.37. Steps when the process has finished. [70]

On the bottom of the data collection sheet information describes a plan of what to do after data has been collected. The product composite sample containing all the samples collected throughout the process will be blended and 3 Malvern tests will be carried out the same Malvern machine (B). Then the product in the hopper retrieved from the process will be blended in the blending machine and 3 Malvern tests will be carried out on the same Malvern machine as the composite blend. From this it would verify if the current process following the SWP is a suitable method or if it is not suitable, ideally results from both blends should be more or less the same, any large inaccuracies indicate there is a problem in the current method.

Customer specification for oversize for processes requires oversize to be under 2%, if the product is over 2% then it would not be suitable for them to use for their manufacturing purpose. Data from the oversize of a 200g sample when carrying out a sieve test on the product will be used to develop a cumulative chart, also a chart will be developed from the undersize data retrieved from when carrying out a 200g sample from the revert to look at the yield being loosed in a process.

5.1.2. Tools needed to Carry out Measurement Activities

Data Collection During a Sieving Process:

- Machine availability i.e. X-line or Vibrosonic Sieves
- Available mesh size.
- Stopwatch to time the feed rate of powder that falls on to the mesh.
- Sample thief to collect powder from the feed and to collect composite samples for testing.
- Weighing scale to measure the federate of powder i.e. if the sample thief was put under the screw feed for 10 seconds and the weight of the powder collected was 126g then it would be ideal and the settings would not need to be adjusted ($126 \times 6 \times 60 = 45.360\text{kg}$). A weighing scale is also needed to weigh the oversize from a 200g sample of product and the undersize from a revert sample.
- Malvern machine B available to carry out testing requirements stated.

The Blending of the Product Collected in the Hopper:

- Machine availability i.e. 3000kg blender if over 500kg of product collected, if under then 500kg blender would be needed.
- Sample thief to collect sample when blending operation has finished.
- Malvern machine B available to carry out testing requirements stated.

Development of Graphs from Input of Data Collected:

- Microsoft XL used to input data and develop output data in form of CUSUM charts.

5.1.3. Cumulative Sum Chart

A cumulative sum chart (CUSUM) is designed to identify slight changes in a process, it is used to monitor small shift in the mean of a process. [79] It can be a type of control chart

that uses the cumulative sum of deviation from a target and the chart plots the cumulative sum of deviation for individual measurement means from the target. [79] When Designing a chart, the average run length, and the shift to be detected needs to be considered.

CUSUM can be modified and used in a process to quickly detect if limits are out of control from the start up. [79]

Standard deviation is a measure of how values widely dispersed from the mean value. [80] The formula of standard deviation is shown below in fig and is used as a function on Excel for chart development from data inputs retrieved.

$$\sqrt{\frac{\sum (x - \bar{x})^2}{(n - 1)}}$$

Fig.38. Excel SDVT function formula. [80]

x is the sample mean average of all values, and n is the sample size. [80] CUSUM requires a reference value (k) specified in sigma units (Σ) which often is set to half the shift to be detected in sigma units, and the decision limit (h) is specified in sigma units. [79]

Charts have been developed with all to analyze the oversize particles in a product over time and the cumulative of oversize in product, the yield loss of undersized in revert overtime and the yield loss cumulative in revert is also shown.

Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Product Sample Weight (g)	Product Sieve +32 µm Residue (g)	+32 wt. % in Product	Oversize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD	Product Malvern Test -32 µm (yield)	Revert Sieve Test -32 µm Residue (g)	-32 wt. % in Revert	Undersize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD
1	46	46	200	0.86	0.43%	0.43%	1.08%	0.42%	-0.24%	72.91	2.56	1.28%	1.28%	3.23%	1.66%	0.10%
2	48	94	200	1.20	0.60%	0.52%	1.08%	0.42%	-0.24%	71.88	2.37	1.19%	1.23%	3.23%	1.66%	0.10%
3	48	142	200	2.01	1.01%	0.68%	1.08%	0.42%	-0.24%	69.88	1.53	0.77%	1.08%	3.23%	1.66%	0.10%
4	48	190	200	1.52	0.76%	0.70%	1.08%	0.42%	-0.24%	72.33	1.85	0.93%	1.04%	3.23%	1.66%	0.10%
5	49	239	200	1.54	0.77%	0.71%	1.08%	0.42%	-0.24%	72.49	2.85	1.43%	1.12%	3.23%	1.66%	0.10%
6	48	287	200	0.86	0.43%	0.67%	1.08%	0.42%	-0.24%	74.00	3.20	1.60%	1.20%	3.23%	1.66%	0.10%
7	48	335	200	0.90	0.45%	0.64%	1.08%	0.42%	-0.24%	72.21	3.00	1.50%	1.24%	3.23%	1.66%	0.10%
8	48	383	200	0.44	0.22%	0.58%	1.08%	0.42%	-0.24%	72.81	3.10	1.55%	1.28%	3.23%	1.66%	0.10%
9	45	428	200	0.40	0.20%	0.54%	1.08%	0.42%	-0.24%	71.39	3.20	1.60%	1.31%	3.23%	1.66%	0.10%
10	45	473	200	0.29	0.15%	0.50%	1.08%	0.42%	-0.24%	74.41	3.40	1.70%	1.35%	3.23%	1.66%	0.10%
11	46	519	200	0.40	0.20%	0.47%	1.08%	0.42%	-0.24%	73.91	3.60	1.80%	1.39%	3.23%	1.66%	0.10%
12	46	565	200	0.30	0.15%	0.45%	1.08%	0.42%	-0.24%	74.69	4.20	2.10%	1.45%	3.23%	1.66%	0.10%
13	46	611	200	0.40	0.20%	0.43%	1.08%	0.42%	-0.24%	73.76	4.18	2.09%	1.50%	3.23%	1.66%	0.10%
14	46	657	200	1.00	0.50%	0.43%	1.08%	0.42%	-0.24%	74.16	2.91	1.46%	1.50%	3.23%	1.66%	0.10%
15	46	703	200	0.90	0.45%	0.43%	1.08%	0.42%	-0.24%	74.96	2.93	1.47%	1.50%	3.23%	1.66%	0.10%
16	47	750	200	0.80	0.40%	0.43%	1.08%	0.42%	-0.24%	76.77	2.90	1.45%	1.49%	3.23%	1.66%	0.10%
17	48	798	200	0.80	0.40%	0.43%	1.08%	0.42%	-0.24%	74.59	2.50	1.25%	1.48%	3.23%	1.66%	0.10%
18	48	846	200	0.82	0.41%	0.43%	1.08%	0.42%	-0.24%	71.66	2.55	1.28%	1.47%	3.23%	1.66%	0.10%
19	46	892	200	0.82	0.41%	0.43%	1.08%	0.42%	-0.24%	75.44	4.86	2.43%	1.52%	3.23%	1.66%	0.10%
20	45	937	200	1.30	0.65%	0.44%	1.08%	0.42%	-0.24%	76.46	3.90	1.95%	1.54%	3.23%	1.66%	0.10%
21	45	982	200	0.80	0.40%	0.44%	1.08%	0.42%	-0.24%	77.19	3.89	1.95%	1.56%	3.23%	1.66%	0.10%
22	47	1029	200	0.47	0.24%	0.43%	1.08%	0.42%	-0.24%	77.08	5.20	2.60%	1.61%	3.23%	1.66%	0.10%
23	47	1076	200	0.48	0.24%	0.42%	1.08%	0.42%	-0.24%	76.42	5.90	2.95%	1.66%	3.23%	1.66%	0.10%

Fig.39.Excel data example used to produce graphs. [70]

(Fig.39.) Shows the inputs of data implemented into Microsoft XL from the first Vibrosonic trial of 17-4PH -32 microns, that was used to develop the charts.

The cumulative weight of feed rate, oversize and undersize in each section is worked out by adding all values of feed rate percentage towards the target and then the amount is divided to give the value.

Percentage of oversize +32 is worked out by dividing the amount of oversize to the sample size (200g) and then multiplying by 100. This would be the same for finding the percentage of -32 in revert.

The upper control limit (UCL: Average + 3SD) and lower control limit (LCL: Average – 3SD) are worked from the mean average of + in product or – in revert and the standard deviation with the sigma value of 6. The same method will be used for all the tests.

5.2. Measurement Results

Ten tests have been carried out with two different type alloys with different customer micron size specification (17-4PH 80%-22 microns processed on -32 micron mesh and 18Ni300 -53+15 microns processed firstly on a -53 micron mesh and further processed on classifier machinery to achieve -15 specifications) , on two different types of machinery to compare their process efficiency (X-Line and Vibrosonic Sieves).

17-4PH alloy has been tested four times, twice on X-Line and twice on Vibrosonic. 18Ni300 alloy has been tested six times, three times on X-Line and three times on Vibrosonic.

5.2.1. 17-4PH Results

The trials have been carried out by the same operator who turned the machine off after an 8-hour shift and started the machine back up again at the start of the shift the next day. 1000kg of As Atomized powder is used to process on the sieve machinery, it would take 22.2 hours to sieve at a rate of 45kg, 23 samples have been taken every hour because atomized weight in approx. 1035kg.

Paul Davies (P151993)

Trials were carried out when agreed machines were available and scheduled into the work planning system a week before.

Data is shown in Appendix A.

Results; -32 Micron, Vibrosonic 1.

Product: 17-4PH, Size: 500 µm, Batch Number: 1980729, Date: 07/11/19, Powder Temperature: 30.4°C Sieve Mesh: 32, Sieve Station Number: 11, Sieve Weight Angle: 110(°)

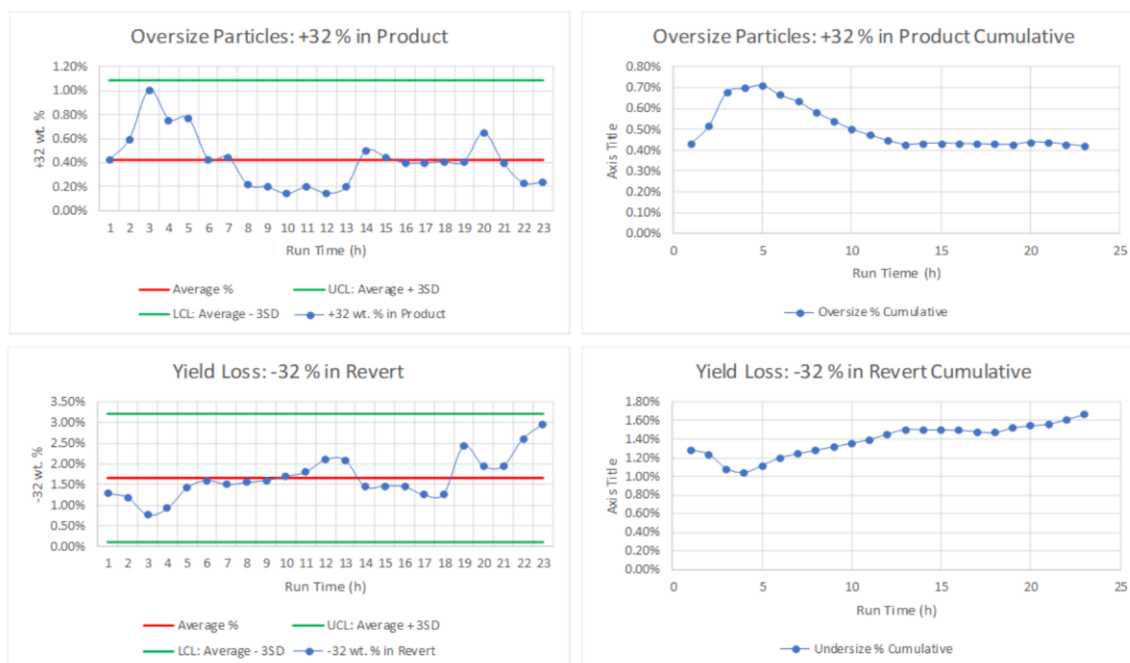


Fig.40. Excel: 32 Micron, Vibrosonic 1. [70]

The process seems to be stable, +32% oversize particles in product stay below 2% and -32% in revert stays below 10%. Cumulative oversize particles decrease in product, yield loss increases with -32% in revert over time.

Results; -32 Micron, Vibrosonic 2.

Product: 17-4PH, Size: 500 µm, Batch Number: 2080114, Date: 25/02/20, Powder Temperature: 18°C Sieve Mesh: 32µm, Sieve Station Number: 11, Sieve Weight Angle: 110(°)

Paul Davies (P151993)

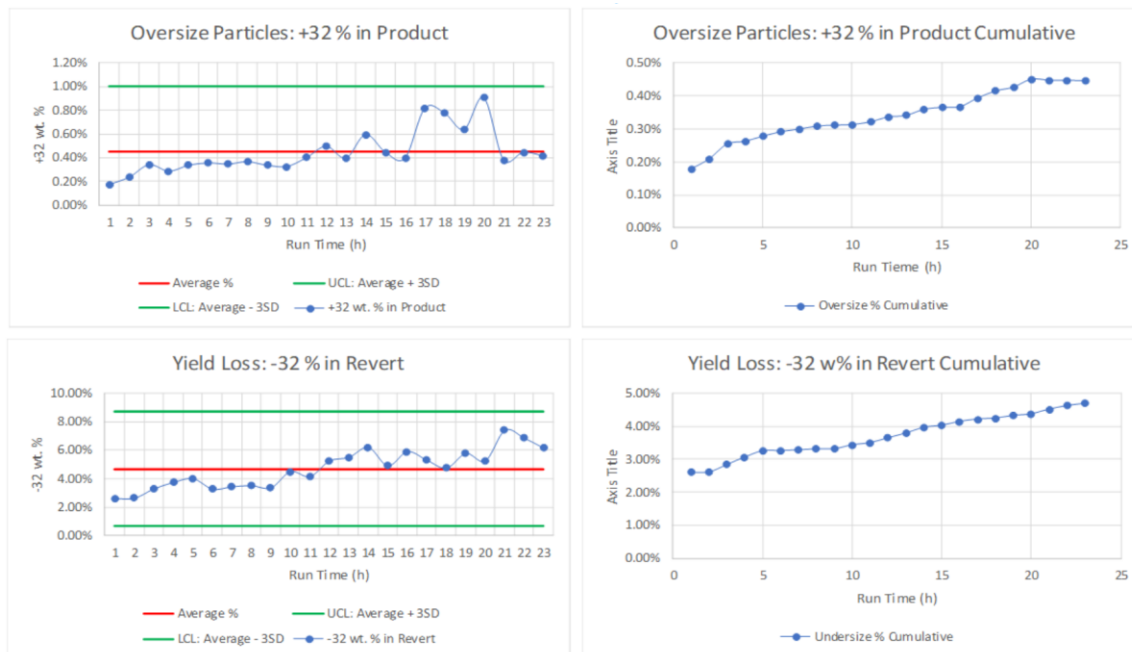


Fig.41. Excel: 32 Micron, Vibrosonic 2. [70]

The process seems to be stable, +32% oversize particles in product stay below 2% and -32% in revert stays below 10%. Cumulative oversize particles increase in product, yield loss also increases with -32% in revert over time.

Results; -32 Micron, X-Line 1.

Product: 17-4PH, Size: -500 μm, Batch Number: 2080095, Date: 11/02/20, Powder Temperature: 54°C Sieve Mesh: -32 μm, Sieve Station Number: 13(X-Line), Sieve Weight Angle: N.A(°)

Paul Davies (P151993)

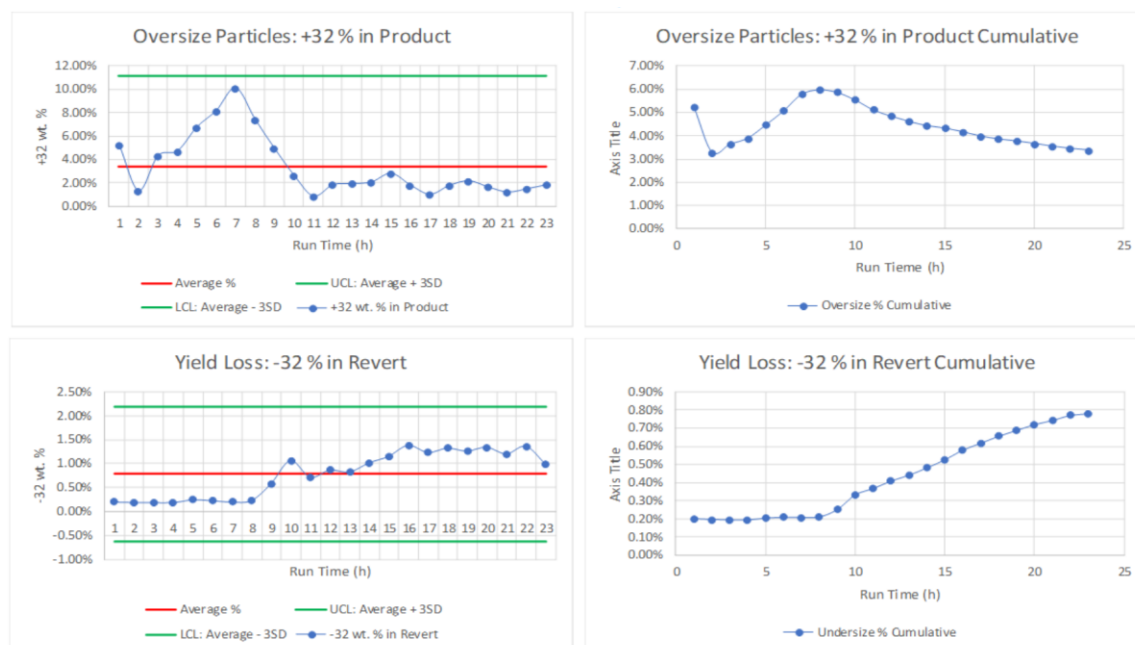


Fig.42. Excel: 32 Micron, X-Line 1. [70]

The process starts off unstable and then becomes stable after 10 hours. - 32% below 1% for 9 hours and then increases above 1% but stays below 1.5%. As oversize particles decrease in product, yield loss increases with -32% in revert over time.

Results; -32 Micron, X-Line 2.

Product: 17-4PH, Size: -500 μm, Batch Number: 2080097, Date: 12/02/20, Powder Temperature: 42°C
 Sieve Mesh: -32 μm, Sieve Station Number: 13(X-Line), Sieve Weight Angle: N.A. (°)

Paul Davies (P151993)

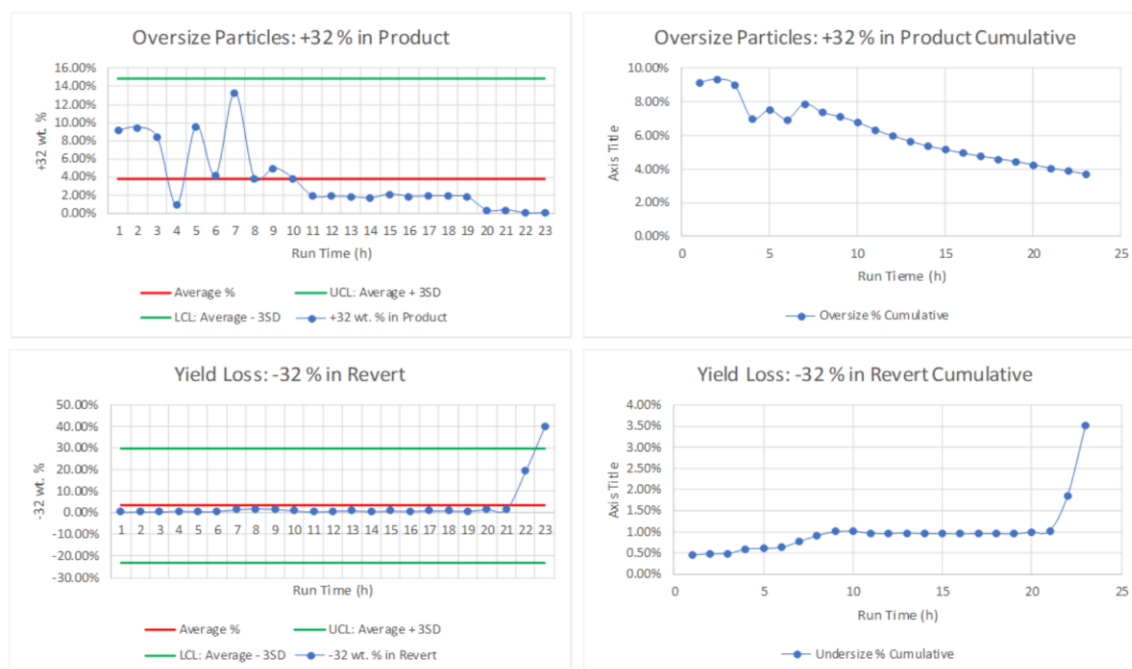


Fig.43. Excel: 32 Micron, X-Line 2. [70]

Process starts off unstable and then becomes stable after 11 hours. – 32% in revert stays below 1% throughout but increases to 20% in 22 hours and then 40% in 23 hours. Cumulative oversize particles the +32% decrease over time, large increase of -32% shown after 21 hours.

5.2.2. 18Ni300 Results

A batch of two from Atomization was split in half but not blended thoroughly. The two halves are compared by sieving them both using two different types of sieve machinery siezing -53 microns, one half by Vibrosonic and the other by X-Line sieving. The total weight of the batch was 720kg so when split in half 360kg would be processed on each sieve and 8 samples would be taken. (Results; -53 Micron, Vibrosonic 1. Results; -53 Micron, X-Line 1.)

Two batches of two were both split in half and blended thoroughly. The two halves of each batch of two are compared by sieving them both using two different types of sieve machinery siezing -53 microns. One half by Vibrosonic and the other by X-Line sieving. The weight of the two batches of two were both approx. 630kg so when split in half 615kg would be processed on each sieve and 7 samples would be taken. (Results; -53 Micron, Vibrosonic 2. Results; -53 Micron, X-Line 2. / Results; -53 Micron, Vibrosonic 3. Results; -53 Micron, X-Line 3.)

Data is shown in Appendix B.

Paul Davies (P151993)

Results; -53 Micron, Vibrosonic 1.

Product: 18Ni300, Size: -500 μ m, Batch Number: 2050064-0065, Date: 24/02/20, Powder Temperature: 18°C Sieve Mesh: -53 μ m, Sieve Station Number: 10, Sieve Weight Angle: 110(°)

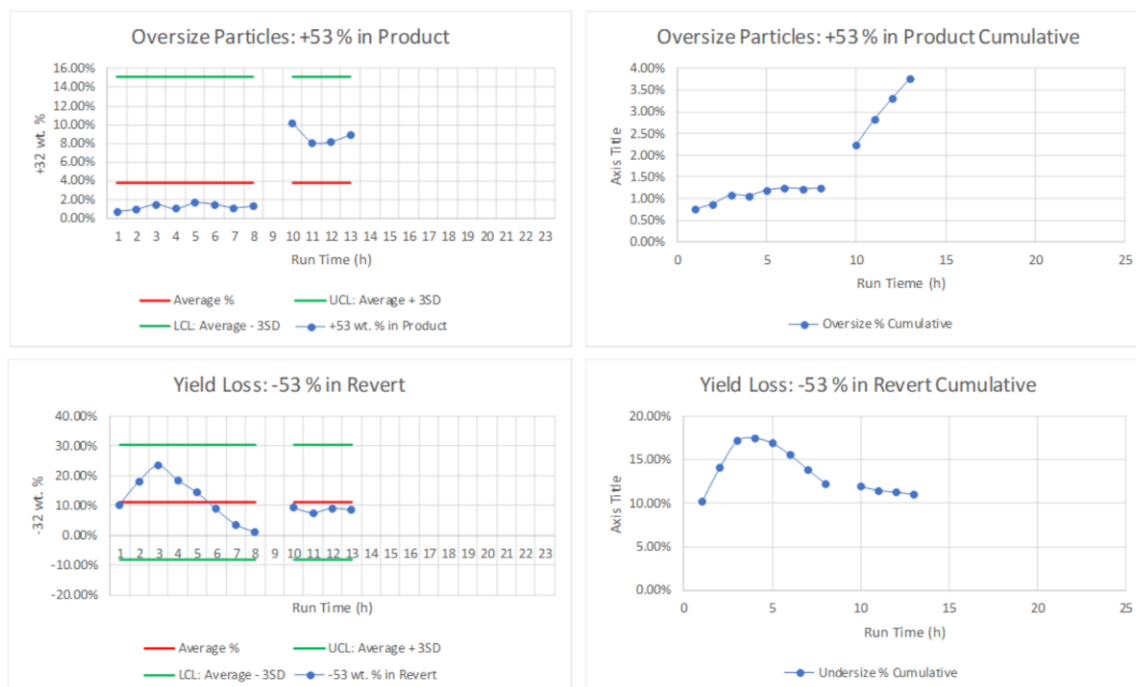


Fig.44. Excel: -53 Micron, Vibrosonic 1. [70]

2nd pass required because of too much -53% in revert, +53% increased above specification on 2nd pass.

Results; -53 Micron, X-Line 1.

Product: 18Ni300, Size: -500 μ m, Batch Number: 2050064-0065, Date: 24/02/20, Powder Temperature: 18°C Sieve Mesh: -53 μ m, Sieve Station Number: 5, Sieve Weight Angle: N.A (°)

Paul Davies (P151993)

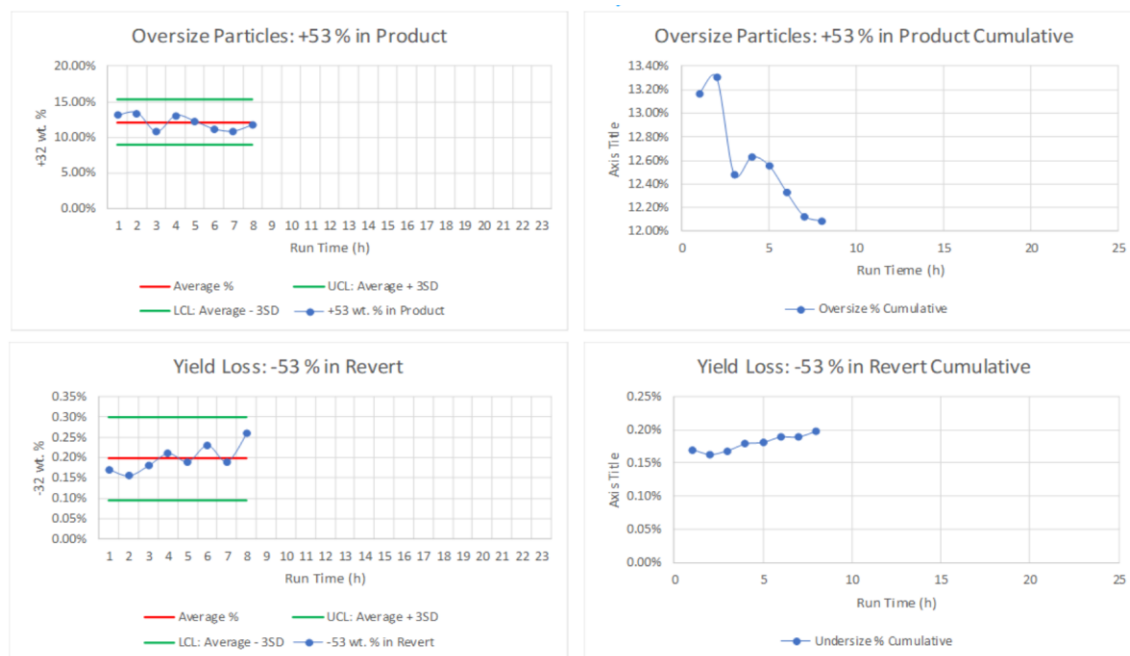


Fig.45. Excel: -53 Micron, X-Line 2. [70]

+53% above required specification throughout with a process average of 12.09% oversize of +53 microns in product. -53% in revert below 0.2% through out.

Results; -53 Micron, Vibrosonic 2.

Product: 18Ni300, Size: -500 μ m, Batch Number: 2050103-0104, Date: 16/03/20, Powder Temperature: 20°C Sieve Mesh: -53 μ m, Sieve Station Number: 5, Sieve Weight Angle: 110(°)

Paul Davies (P151993)

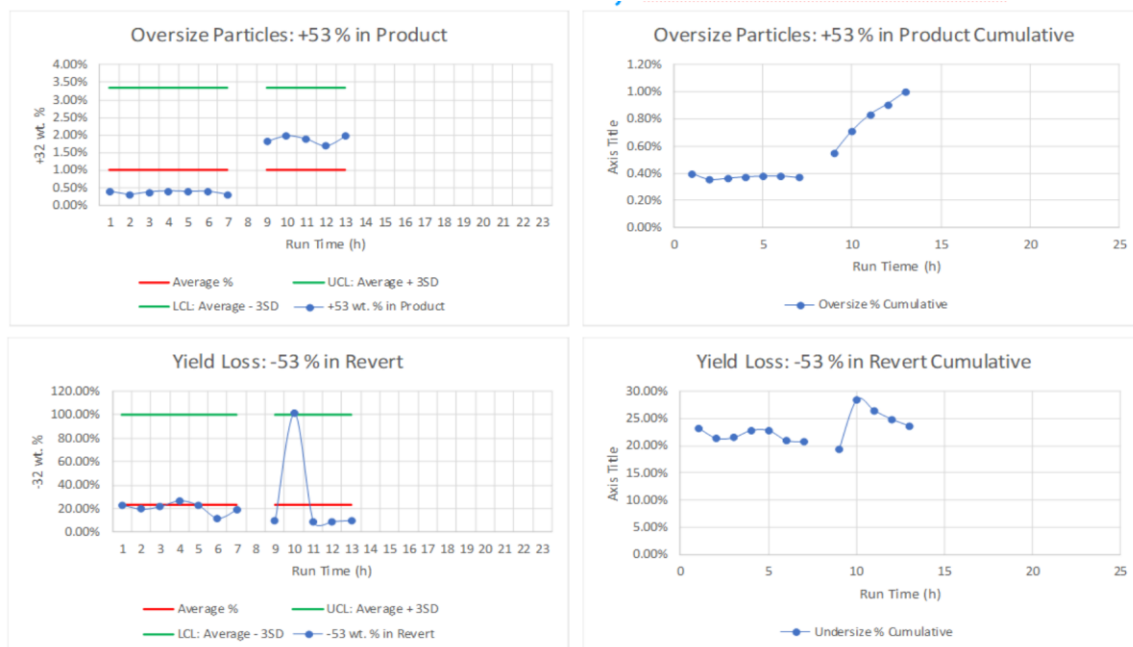


Fig.46. Excel: -53 Micron, Vibrosonic 2. [70]

2nd pass required because of too much -53% in revert, +53% maintained specification on 2nd pass but increased above 1.5%.

Results; -53 Micron, X-Line 2.

Product: 18Ni300, Size: -500 μ m, Batch Number: 2050103-0104, Date: 17/03/20, Powder Temperature: 20°C Sieve Mesh: -53 μ m, Sieve Station Number: 5, Sieve Weight Angle: N.A (°)

Paul Davies (P151993)

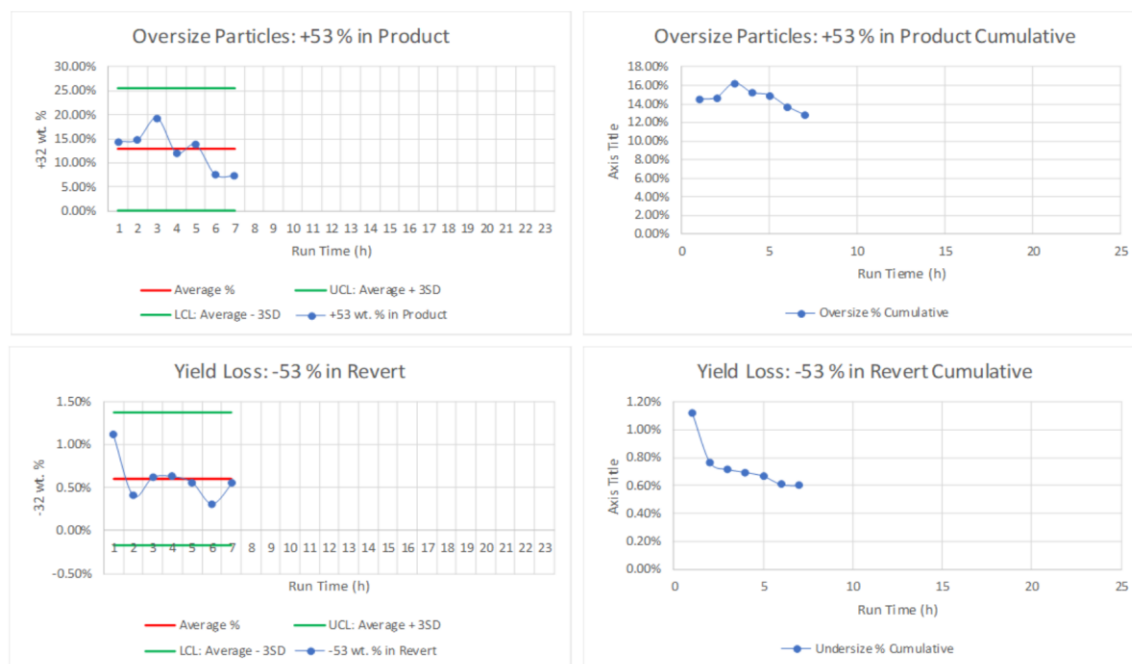


Fig.47. Excel: -53 Micron, X-Line 2. [70]

+53% above required specification throughout with a process average of 12.84% oversize of +53 microns in product. -53% in revert below 0.8% throughout except the first hour exceeded above 1%.

Results; -53 Micron, Vibrosonic 3.

Product: 18Ni300, Size: -500 μm, Batch Number: 2050109-0110, Date: 18/03/20, Powder Temperature: 20°C Sieve Mesh: -53 μm, Sieve Station Number: 5, Sieve Weight Angle: 110(°)

Paul Davies (P151993)

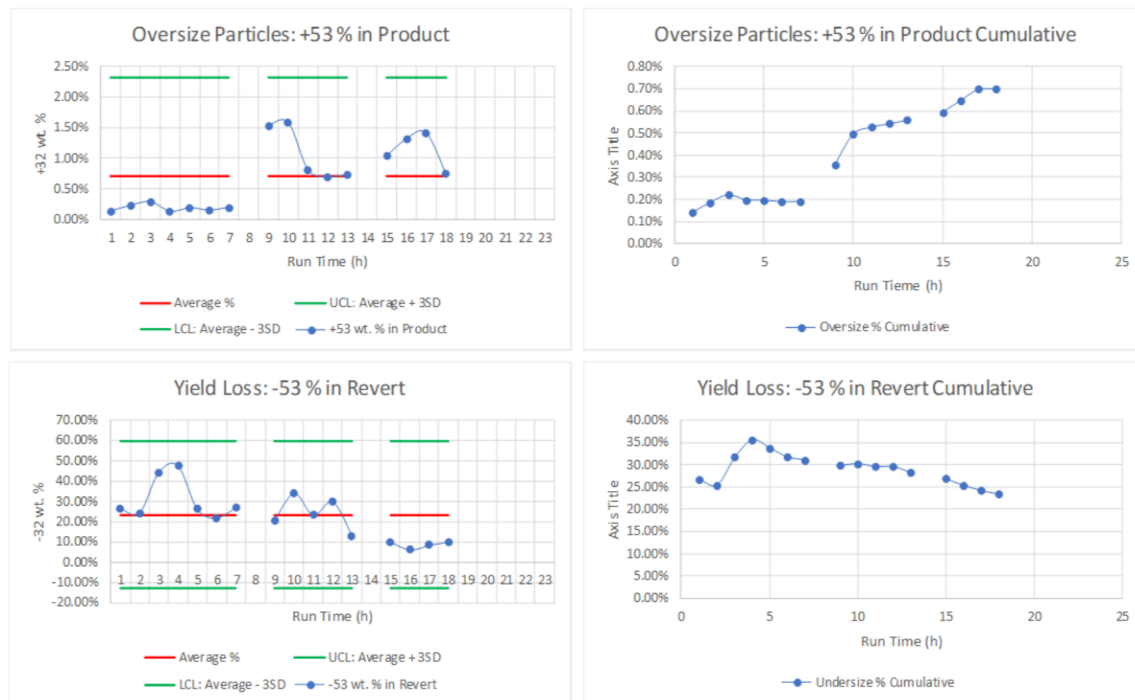


Fig.48. Excel: -53 Micron, Vibrosonic 3. [70]

2nd and 3rd pass required because of too much -53% in revert, +53% maintained in specification throughout but 1st pass below process average, 2nd and 3rd above.

Results; -53 Micron, X-Line 3.

Product: 18Ni300, Size: -500 μ m, Batch Number: 2050109-0110, Date: 18/03/20, Powder Temperature: 20°C Sieve Mesh: -53 μ m, Sieve Station Number: 5, Sieve Weight Angle: N.A (°)

Paul Davies (P151993)

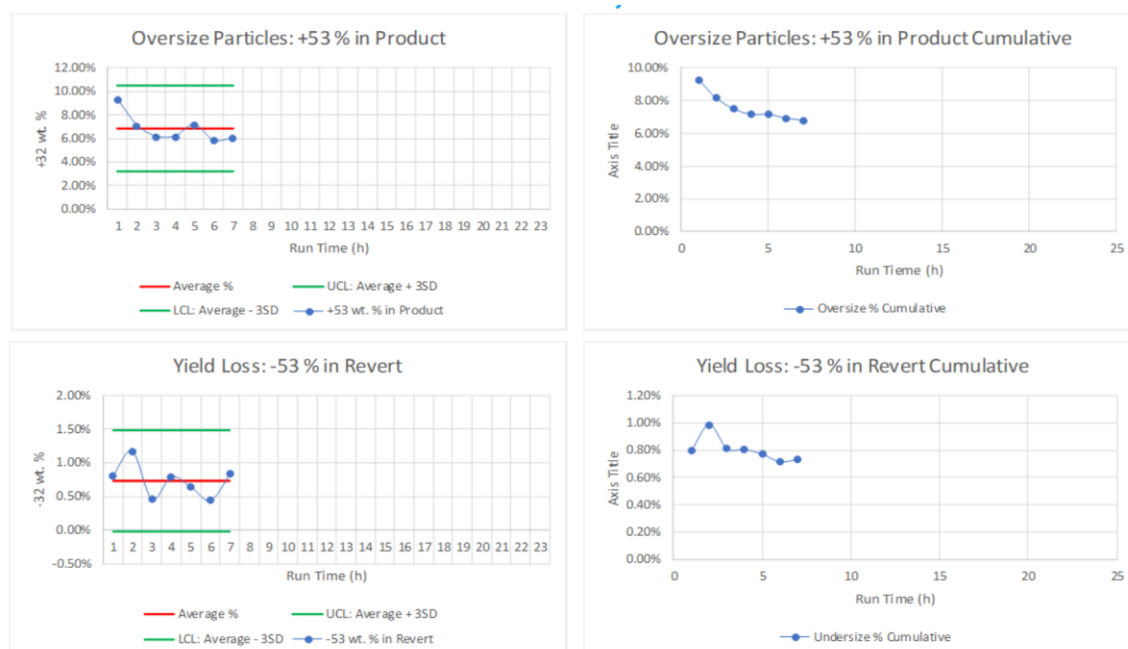


Fig.49. Excel: -53 Micron, X-line 3. [70]

+53% above required specification throughout with a process average of 6.84% oversize of +53 microns in product. -53% in revert below 0.8% throughout except the 2nd hour exceeded slightly above.

5.3. Results Summary

Results Summary of Average % Oversize Particles and % Yield Losses

Oversize Particles	Vibrosonic	X-line
-32	0.42%	3.37%
-32	0.45%	3.73%
-53	3.77%	12.09%
-53	1.00%	12.84%
-53	0.70%	6.84%
Yield Losses	Vibrosonic	X-Line
-32	1.66%	0.78%
-32	4.68%	3.51%
-53	10.99%	0.30%
-53	23.58%	0.60%
-53	23.23%	0.73%

Fig.50. Results summary. [70]

Mean Average Results from Composite Blended Vs Hopper Blended Sample

-32	D10 Comp.	D10 Hoper	D50 Comp.	D50 Hopper	D90 Comp.	D90 Hopper	-22 Comp.	-22 Hopper
Vibro.1	4.733	4.695	14.134	13.926	31.382	31.017	74.423	75.087
Vibro.2	4.400	4.473	12.980	13.020	28.857	29.553	78.553	78.153
X-Line.1	4.221	4.323	13.646	13.013	32.795	29.604	73.700	77.700
X-Line.2	4.401	4.503	14.261	13.257	34.565	29.586	71.383	77.127
-53	D10 Comp.	D10 Hopper	D50 Comp.	D50 Hopper	D90 Comp.	D90 Hopper	-15 Comp.	-15 Hopper
Vibro.1	13.587	11.130	33.973	29.320	63.163	57.033	11.913	16.740
Vibro.2	13.443	9.990	31.533	26.173	57.980	52.133	12.300	20.430
Vibro.3	18.083	10.297	36.210	26.457	62.420	52.257	16.143	19.580
X-Line.1	14.023	13.020	36.427	34.620	67.963	66.560	11.210	12.803
X-Line.2	13.313	11.417	36.593	31.517	68.443	62.557	12.067	15.967
X-Line.3	13.82	11.427	35.163	31.523	64.240	62.217	11.770	15.583

Fig.51. Mean average results from composite blended Vs hopper blended sample. [70]

For accuracy with Malvern results accuracy is needed to be below 1% (Black). Inaccuracies (Red) shown in D90 Composite and Hopper Blended samples and with -22% micron values with -32 X-Line sieves. Major inaccuracies shown in all field of -53, although X-Line.1 was not that far out.

5.3.1. Further Testing Carried out in the Measurement Stage from Experiences Learned

It was noticed that when carrying out another pass the balance of product is not the same amount as the 1st pass. It was decided to carry out a different type of sampling method which would be to weigh the balance of product in the hopper from each pass and then downscale for the sample size for a composite sample of blended passes.

To down scale, divide weight of each pass by 100, then add together and blend for composite sample.

The total weight for the first pass was 130.40 kg, downscaled would be 1.304kg

The total weight for the second was 15.60 kg, downscaled would be 0.156kg

The total of passes= 1.46kg

-53 Micron, Vibrosonic 1. Malvern Results for 1st and 2nd pass weight blended Composite sample method

BLENDING SAMPLE 1 D10	BLENDING SAMPLE 1 D50	BLENDING SAMPLE 1 D90	AIM 5%-15
12.62	30.86	58.17	13.75

BLENDING SAMPLE 2 D10	BLENDING SAMPLE 2 D50	BLENDING SAMPLE 2 D90	AIM 5%-15
12.58	30.72	57.96	13.85

BLENDING SAMPLE 3 D10	BLENDING SAMPLE 3 D50	BLENDING SAMPLE 3 D90	AIM 5%-15
12.67	30.82	58.19	13.71

Fig.52. -53 Micron, Vibrosonic 1. Malvern Results for 1st and 2nd pass weight blended Composite sample method. [70]

Results are not as accurate as the final hopper blended samples but are closer than SWP-044 composite sampling method.

It was decided to blend the other batches required for testing to see if better accuracy would be achieved if more than 1 pass was required.

-53 Micron, Vibrosonic 2. Malvern Results for 1st and 2nd pass weight blended Composite sample method

The total weight for the first pass was 106.4 kg, downscaled would be 1.064kg

The total weight for the second was 18.60 kg, downscaled would be 0.186kg

The total of passes= 1.25kg

BLENDING SAMPLE 1 D10	BLENDING SAMPLE 1 D50	BLENDING SAMPLE 1 D90	AIM 5%-15
11.12	26.72	51.99	18.01

BLENDING SAMPLE 2 D10	BLENDING SAMPLE 2 D50	BLENDING SAMPLE 2 D90	AIM 5%-15
11.12	26.87	52.28	17.91

BLENDING SAMPLE 3 D10	BLENDING SAMPLE 3 D50	BLENDING SAMPLE 3 D90	AIM 5%-15
11.18	26.88	52.25	17.81

Fig.53. -53 Micron, Vibrosonic 2. Malvern Results for 1st and 2nd pass weight blended Composite sample method. [70]

Although results are not as accurate as the final hopper blended samples, they are closer than the sampling method. Results are slightly out on D10 and the aim 5%-15um values are out by 2%, but the same for D50 and D90.

-53 Micron, Vibrosonic 3. Malvern Results for 1st, 2nd and 3rd pass weight blended Composite sample method

The total weight for the first pass was 98 kg, downscaled (/100 would be 0.98 kg)

The total weight for the second was 23.26 kg, downscaled would be 0.2326 kg

The total weight for the third was 8.2 kg, downscaled would be 0.082 kg

The total of passes= 1.2946kg

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BLENDED SAMPLE 1 D10	BLENDED SAMPLE 1 D50	BLENDED SAMPLE 1 D90	AIM 5%-15
11.50	27.21	52.63	17.03

BLENDED SAMPLE 2 D10	BLENDED SAMPLE 2 D50	BLENDED SAMPLE 2 D90	AIM 5%-15
11.27	27.04	52.45	17.50

BLENDED SAMPLE 3 D10	BLENDED SAMPLE 3 D50	BLENDED SAMPLE 3 D90	AIM 5%-15
11.47	27.27	52.88	17.06

Fig.54. -53 Micron, Vibrosonic 3. Malvern Results for 1st, 2nd and 3rd pass weight blended Composite sample method. [70]

Results not as accurate as the final hopper blended samples but are closer than SWP-044 sampling method. Slightly out on D10% but the same with D50 and D90 values. Slightly over 2% with 5%-15um value.

Mean Average Results from Blended Passes Vs Hopper Blended Sample

-53	D10 Blended Pass	D10 Hopper	D50 Blended Pass	D50 Hopper	D90 Blended Pass	D90 Hopper	-15 Blended Pass	-15 Hopper
Vibro.1	12.623	11.130	30.800	29.320	58.106	57.033	13.770	16.740
Vibro.2	11.140	9.990	26.823	26.173	52.173	52.133	17.916	20.430
Vibro.3	11.413	10.297	27.173	26.457	52.653	52.257	17.190	19.580

Fig.55. Mean Average Results from Blended Passes Vs Hopper Blended Sample. [70]

5.3.2. Rotap Analysis Tests

It was noticed that Batch 2050103-0104 final product was blended from X-Line and Vibrosonic sieve operations and further processed on to classification for the 2nd cut required. From the testing carried out it is clear to see that vibro-sonic sieved powder was suitable to do so but X-sieve was not because out the amount of +53um obtained in the final product. A Rotap test was carried out on the finished product after classification to see if it was suitable.

Finished product blended X-Line and Vibrosonic Rotap Results.

Batch: 2050103-0104

Alloy: 18Ni300

Size: 53+15

Rotap stack

-75+63= 0.00%

-63+53=3.98%

-53+0=96.02%

Still too much -63+53 in product, customer specification is 2.0% max.

It was decided to carry out Rotap on batch 2050109-0110 after X-Line blended hopper process, after each pass on vibro-sonic, and the blended hopper process after vibro-sonic.

X-Sieve Final Hopper Blend Rotap

Batch: 2050109-0110

Alloy: 18Ni300

Size: 53+15 microns

Rotap stack

-75+63= 0.00%

-63+53=5.79%

-53+0=94.21%

This has failed customer specification.

Vibro-sonic Passes

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Batch: 2050109-0110

Alloy: 18Ni300

Size: 53+15 microns

1st

Rotap stack

-75+63= 0.00%

-63+53=0.35%

-53+0=99.65%

2nd

Rotap stack

-75+63= 0.00%

-63+53=1.14%

-53+0=98.86%

3rd

Rotap stack

-75+63= 0.00%

-63+53=1.94%

-53+0=98.06%

All passes are still within customer specification requirements, so should pass the final hopper blend Rotap.

Vibro-sonic Final Hopper Blend Rotap

Rotap stack

-75+63= 0.00%

-63+53=0.95%

-53+0=99.05%

This has Passed customer specification.

6. Analyze

In the Analyze phase the aim is to study data generated in the process and to understand root causes of problem, solutions are identified for removing discrepancies between the current performance and desired goal. [81] [64] Activities and various tools can be applied to help root out causes and develop capabilities of a process. [64]

Looking at (fig.50.), both 17-4PH results sieving -32microns on Vibrosonic Sieves results looks to be a stable process when following SWP-044 and the Malvern results of composite blended samples vs hopper blended samples (fig.51.) are the same in D₁₀, D₅₀, D₉₀ and -22 values. Results for X-Line shows the process to be unstable because of there being too much +32 microns being passed through into the product. (fig .42. and fig.43.) X-Line graphs seem to start off being out of spec but further into the process the +32 oversize falls into speculation which could be from the mesh starting to blind the Malvern results (D₁₀, D₅₀ are the same but are out on D₉₀ and the -22 which could be because of the oversize at the start of the process. Also, (fig.43.) shows a large increase of -32 product going in to the revert after 21 hours which would indicate the mesh being blinded because the feed rate was controlled throughout. In all process yield loss increases over time, which highlight this.

With X-Line Sieve machinery higher product yield is being achieved because of too much oversize in the product. There is more yield loss achieved with Vibrosonic but +32 in product maintains speculation. 18Ni 300 results show to also maintain speculation except on one occasion shown in (fig.44.), a second pass was required in because of there being too much product in the revert. When being processed +53 in product was above 2% for the whole of the 2nd pass process, which could have been because of too much oversize staying on top of the mesh and not passing off quick enough, however this did not occur with the other alloys measured which could indicate Vibrosonic equipment might not have been working properly.

Following SWP-044 sampling method is suitable for Vibrosonic machines if only one pass is required but does not if there are other passes are required. This is due to the fact it states that 20g should be collected every hour [58] not taking into consideration that product after each pass becomes coarser and not the same amount of product in revert put back up is the same as the atomized powder in the first pass, which means not the correct balance of powder used for composite sample for singing a job is being collected.

Vibrosonic 18Ni300-53micron mean average Malvern results of composite vs hopper blended samples (fig.51.) show major inaccuracies when being compared to each other.

The extra step taken in the measuring phase which was not decided before hand when developing the data collection sheet (fig. 36.) was to weigh each pass and take a down scaled sample and blend to compare against the other hopper sample results (fig.55.), results still not accurate even when doing this but slightly better than the composite product sample when following SWP-044.

The Rotap results in section (5.2.4.1) were done because it was noticed that batch 2050103-0104 18Ni300 alloy that was sieved both on X-Line and Vibrosonic to achieve -53microns product for this study, had been blended back together and further processed on a classifying machine. A Rotap analysis test was carried out on a sample of product after it had finished to see what the results would be of oversize +53 in the product. Results from the stack show to have no oversize above -75+63microns but is 3.98% over -63+53 microns, this is still above required customer speculation of being under 2% +53 microns.

With the last trial of the study, it was decided to carry out Rotap on Vibrosonic.3 sieving 18Ni300 alloy after the hopper containing the product had been blended and to carry out a Rotap on each pass. Results from each pass collected maintained speculation, and when the hopper was blended results showed to be in speculation. This would mean that Vibrosonic sieves are fit for the task of sieving 18Ni300 alloys, because customer specification is maintained. However, when following SWP-044 of collecting a composite sample for a Malvern result, it shows it does not work because the SWP is only suited to product if only one pass is required.

Following SWP-044 does not work at all for when Sieving 17-4PH -32 microns because the difference in Malvern results. It does not work for 18Ni300 -53microns because there is a problem with the mesh because of too much over size passing through the mesh in both.

6.1. 5 Why Analysis

5 whys analysis is used as a method to get to the root of a problem quickly by identifying the root cause from analyzing the symptoms. [82] [83] Two five why diagrams (Fig.56. and Fig.57.) have been developed for Vibrosonic and X-Line machinery to get to the root cause of why blend failures have been occurring.

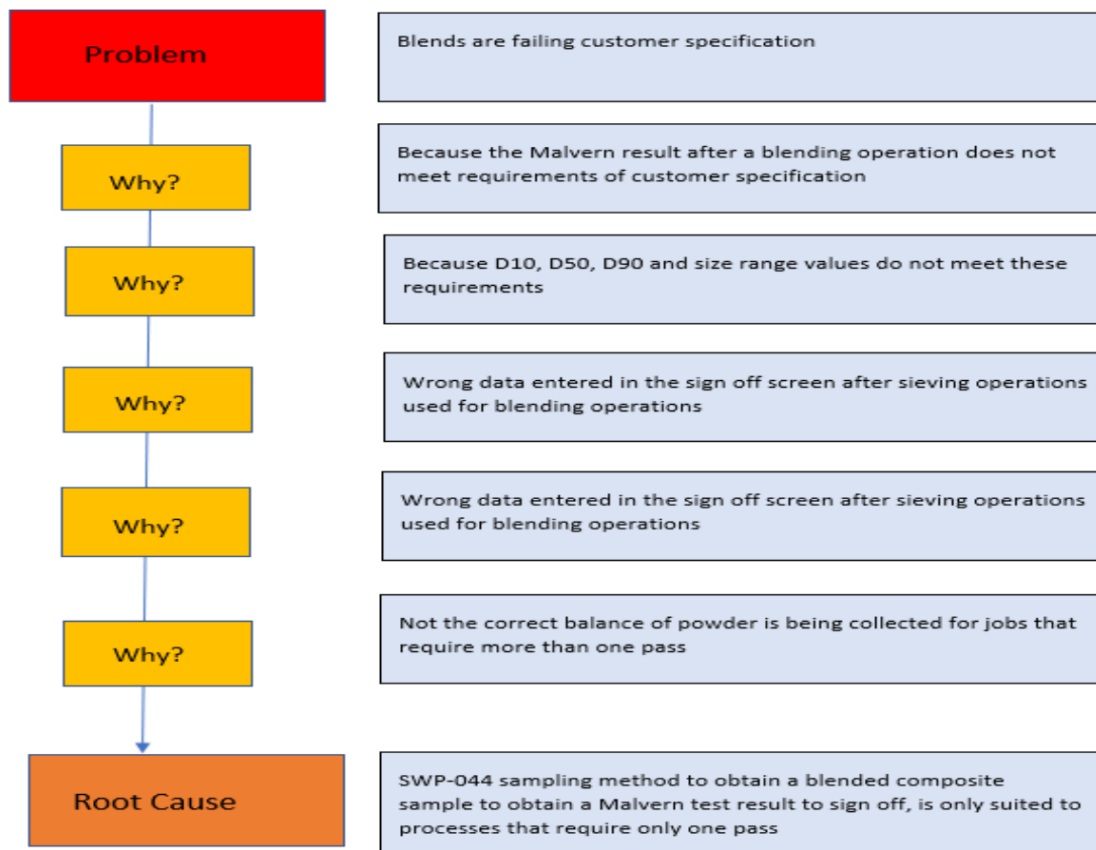
5 Whys Analysis of blend failures with Vibrosonic Machinery

Fig.56. Vibrosonic, 5 Why Analysis. [70]

To improve the current situation SWP-044 must account for these other passes in the document. The extra measurement for 18Ni300 alloys in the study for blending each pass was closer but still was not accurate when compared to hopper blended sample and even when hoppers were blended after a sieving process. Hoppers containing 'As Atomized' powder were blended on two occasions before being processed on sieving machinery and still showed no difference, so another sampling method is needed.

Tube samples are available shown in section (2.9.2.1) to collect top, middle and bottom of stationary powder, but the study shows that the only real accurate way would be to blend the hopper containing the product after a sieve process and collect a sample, before a Malvern result is achieved. This however is not possible because of the high demand of blending machinery in the packing area for product to be sent to a customer to meet lead times agreed.

5 Whys Analysis of blend failures with X-Line Machinery

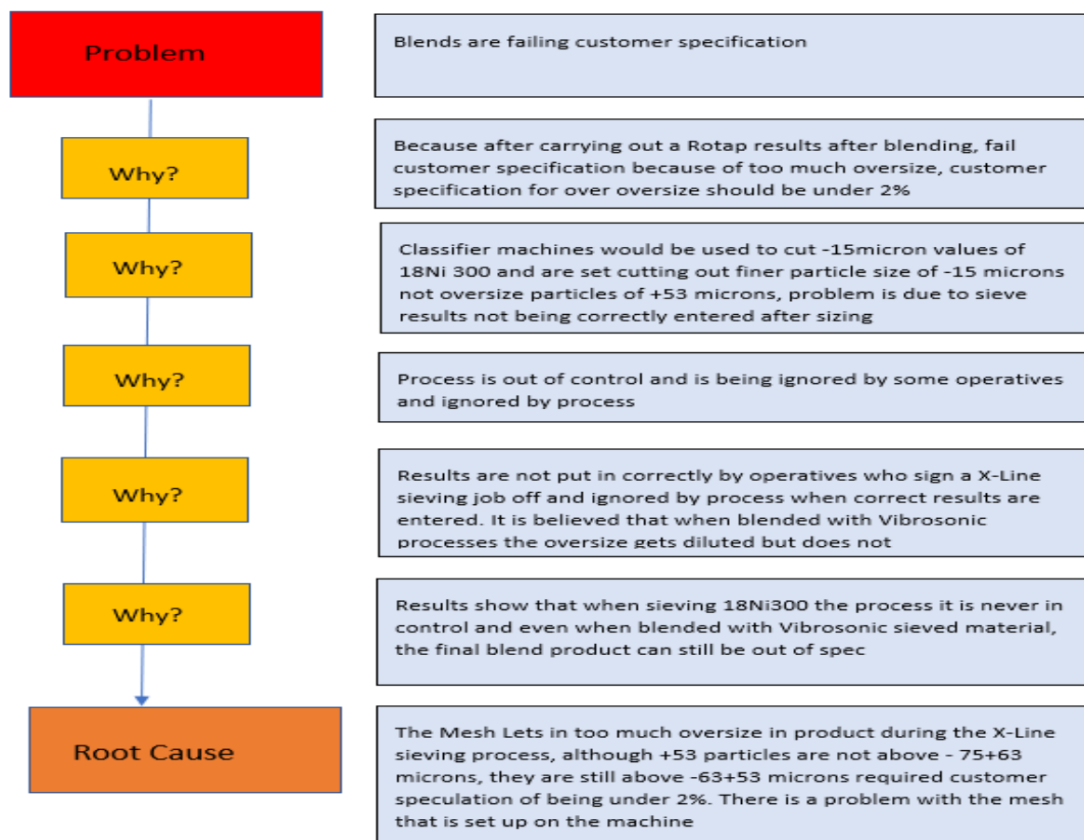


Fig.57. X-Line, 5 Why Analysis. [70]

The X-Line sieving process is not suitable to the task in the current process, blend failures have most probably occurred from oversize particles obtained in product when it has been sieved using this process. In SWP-044 it states to stop the sieving process if oversize is found over the customer specification [58] but has been ignored by operatives on the shop floor and process department. X-Line machines sieving 18Ni 300, -53 microns a coarser powder that is never in control, but some control is shown further in 17-4PH, -32 microns a finer graded powder. They seem better for finer graded powder, but the process is still out of control. The reason for this could be because the meshes being self-made by operatives are not being correctly tensioned. Information in section (2.9.2.1) from the X-Line sieve manual, states that a working mesh should be pulled and tightened around the intermediate mesh, glued, and fixed in to place by using double sided tape to achieve light tension. [41] this is not happening in the current process, meshes are just put over the intermediate mesh with a band just put around them.

The actual allowable tolerance for mesh size falls in the limits shown in section (2.3.) ISO-09044 of mesh standard size for 53micron size, particle size seems to not go over 63microns, but customer specification requires to be 2% under +53microns and product is shown to be out of spec.

7. Potential Improvement to Overcome Before Taking Place

Unfortunately, due to COVID-19 there has not been opportunities to carry out improvement ideas because of there being limited time to trial the ideas found from analysis stage. This section is going to look at potential improvements that could be beneficial to the current process and how to overcome potential problems before improvements take place. Cause and Effect diagrams have been used to show a better understanding. The diagram is a useful tools to help capture possible causes of a problem. [84] It can be used in the improve stage to identify potential failures or can be used in the analyze stage to determine the causes that are underlying within a problem. [84] [83]

It has been found that the root cause in (fig.56.) blends fail with Vibrosonic machinery if there is more than one pass required. The SWP-044 for retrieving a product composite sample is only suitable if only one pass is required. Balance of product from each pass was weighed out in the study but still was not accurate and the only accurate way to retrieve a sample is if it is blended before taking a sample. In section (2.10) of the literature review it was found that Post Hopper Blending Machinery is available, SaintyCo make this type of machinery that can deal with weight retrieved after a sizing process. [61] This type of machinery could improve the current process because there would not be a need to use blending machines already in use in the packing and blending area.

The root cause found in (fig.57.) Blends fail with X-Line machinery because there is a problem with the mesh because they are not well tensioned and are not made the correct way they should be. The manual in section (2.2.1) should be followed as soon as possible because currently the process does not work and if this problem is not rectified sooner it more negative costs to the business are going to occur.

7.1. Cause and Effect Diagrams

Potential Causes that Could Affect Having Post Blending Machinery

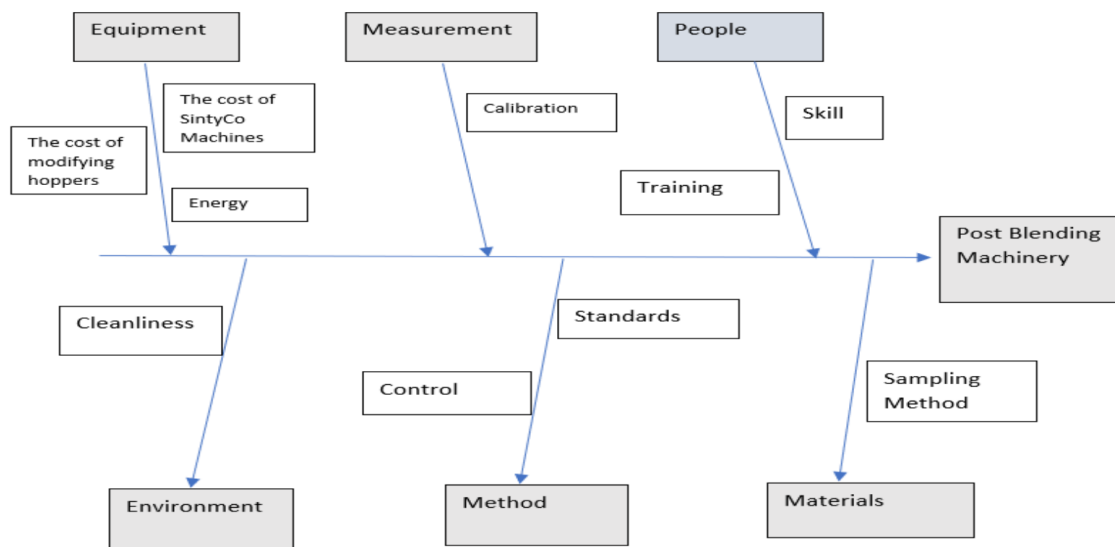


Fig.58. Post blending machinery cause and effect diagram. [70]

- **Equipment:** The cost of SintyCo machines are unknown at this moment. 'Organization X' would most probable rather modify their hoppers instead of buying new which would most probably cost save, but the cost to modify them is unknow and more energy would be used because of product being post blended after sieving. If success were shown and re-work was reduced or eliminated this could benefit them more in the long run. Maybe investigate prototype development and trial for a period at a smaller scale to see if success is shown, then a cost analysis can be developed to understand capabilities.
- **Measure:** Machine would have to be calibrated to make sure machine is working properly and safely, might be difficult for engineering operatives to do on their own so SintyCo personnel would have to be present to make sure there are no errors.
- **People:** Only skilled personnel would be able to operate the machinery, so operatives would have to be trained.

- **Environment:** Machine must be cleaned before moving on to next alloy. Cleaning Equipment and extraction must be available for operatives to carry out cleaning activities.
- **Method:** Standard Working practice must be developed to set a level of control in the process. The service must also have some control of management and allow downtime maintenance.
- **Material:** The product of powder would still have to be in spec before being blended, otherwise it would be a waste of time blending. Hourly tests already carried out in sieving processes to make sure the operation is running smoothly, should still be followed i.e. making sure the mesh has not blinded, mesh is not damaged and particle size remains in required speculation.

Potential Causes that Could Affect Building X-Line Meshes from Machine Manual

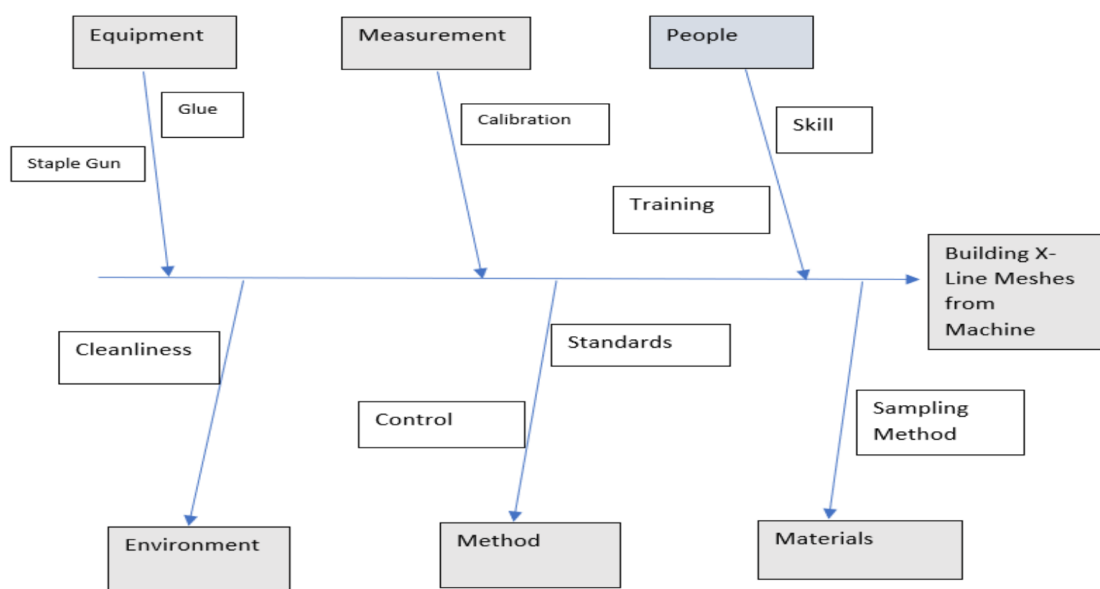


Fig.59. Building X-Line Meshes from the machine manual cause and effect. [70]

- **Equipment:** Gluing equipment and a staple gun must be purchased when following the X-Line machine manual which would occur costs, but when weighed

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- against the cost of re-work it would be less if the process is improved and there is not a need to re-work.
- **Measurement:** Machine might still need to be calibrated to suit this method because machines were put in by 'Organization X' not SaintyCo.
 - **People:** Operatives need to be trained the skill in how to build a mesh the correct way. If Virto Ciccolini personnel came to demonstrate how it is done correctly it would be more beneficial to learning.
 - **Environment:** The meshes must be kept clean and away from dust for when being glued to the intermediate mesh.
 - **Method:** Standard working Practice must be developed that includes the information in the X-Line manual, to control the process and make sure it is adhered towards correctly.
 - **Material:** SWP-044 should be followed for testing the product during a sieving process, because it is unknown if this procedure works when the mesh is correctly tensioned. A period of trials should be carried out to understand the process more when changes have been made.

8. Conclusion

Customers who buy who buy gas atomized powder as a raw material feedstock from 'Organization X', need particle size to be in the required specification agreed because it negatively effects their manufacturing purpose. 17-4PH for MIM applications need to be in the correct specification for flowability from when being feed through a mold cavity, 18Ni300 for DMLS needs to have good flowability for when being spread in layers on a fusion bed to create a 3D component. Parts made are complex and both need to achieve full density during the sintering stage.

Gas atomized powder is the preferred choice compared to water atomization because gas atomized powder particles are more spherical unlike water atomized which is more rigid, so there is a high demand for 'Organization X's' product because it offers more quality. But organization encounter a lot of rework in their process due to the fact final blends are failing customer specification, due to the sieve sizing process being out of control.

The sieve type machinery 'Organization X' use in their sieve sizing process are Russell Finex Vibrosonic sieves that use an ultrasonic deblending system and X-Line multifrequency, that operates at a faster RPM without the use of electronic pulses. Both companies state success with their machines for wanting to achieve high product yield when sieving at fine particle size. Vibrosonic state that the can sieve below 20 microns and X-Line states to achieve below 10 microns with 99% efficiency. This is highly debatable because classifying machines are developed to achieve these types of cuts, and 'Organization X' do no sieve anything below -32 microns.

X-Line meshes have been understood to let too much oversize in a sieving process, but standard ISO-9044 show that aperture size is in allowable tolerance limits of standard mesh size. The X-Line manual states to never start a process on a machine if a mesh has not been well tensioned, which has not been followed in the current process and is the reason why it is failing the customer specification.

The standard for moving powder ASTM-B215 when compared to SWP-044 seems to have similarities, however ASTM-B215 standard says to collect a blended sample of moving powder, when collecting from underneath a mesh it is not the same because the aperture sizes of the mesh. Also, both standards do not account operations that require more than one pass. Blending the product after a sieving process looks to be the most accurate way for achieving a final composite sample.

The study shows when following SWP-044 for how operatives should carry out sampling methods for X-Line sieves that the current process is not working. This problem needs to

be addressed and improvements made as soon as possible and should not carry on until a solution is found. Currently there is a high burden of negative costs occurring in 'Organization X's' business but seems to be getting ignored due to them still making a large profit, if they rectified the problems in sieving it would generate even more because rework would be reduced or eliminated.

9. Recommendations

X-Line meshes need to improve, another study should be undertaken when the method shown in the X-line manual has been followed and trialed to understand process capabilities. When COVID-19 restrictions have been lifted it would be beneficial if the supplier visited the site, to see what needs to be done and to understand what is going wrong.

Post hopper blending machinery would be beneficial because a more accurate composite sample would be achieved, that would help when being selected to be blended with others to create a larger blend. SaintyCo should be contacted to find out more about the post blending machine that they manufacture.

The Malvern machine used by 'Organization X' Master Sizer 2000 is an older machine version because there is Master Size 3000, that offers more accuracy when delivering PSD results. An upgraded machine could be more useful if blends just fail under specification in the current process, it might show that the product is in spec on some occasions where it has failed on the older type machinery.

There is other sieve type machinery such as Farley Green's Sieve Master Multi-Screener that offer a free one-week trial to see if their machinery is suitable before purchase. There is nothing to lose if no cost will occur during that trialing period, their ultrasonic de-blinding machine is like a hybrid of both Vibrosnic and X-Line sieves. Even if not successful an opportunity could be learned with how other type machinery operates, that could influence other ideas to make the current process better. Sieving with an extra stack could reduce the amount of passes needed for when sieving 18Ni300 on Vibrosonic machines, because more coarse powder is taken away on the stack above. Machines are built so they can include an extra stack but because of the structure of the sieve line it would not be possible to do straight away. However, it would be worth finding out if the need for a second pass is removed, jobs being processed would finish quicker which would make the system Leaner.

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REDUCING RE-WORK FROM SIEVE SIZING OPERATIONS AND STILL OPTIMIZING YIELD

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Appendix A: Data for -32microns

Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Product Sample Weight (g)	Product Sieve Test +32 µm Residue (g)	+32 wt. % in Product	Oversize % Cumulative	UCL: Average + SSD	Average %	LCL: Average - SSD	Product Malvern Test % -22 µm (yield)	Revert Sieve Test -32 µm Sieve Residue (g)	-32 wt. % in Revert	Undersize % Cumulative	UCL: Average + SSD	Average %	LCL: Average - SSD
1	46	46	200	0.86	0.43%	0.43%	1.08%	0.42%	-0.24%	72.91	2.56	1.28%	1.28%	3.23%	1.66%	0.10%
2	48	94	200	1.20	0.60%	0.52%	1.08%	0.42%	-0.24%	71.88	2.37	1.19%	1.23%	3.23%	1.66%	0.10%
3	48	142	200	2.01	1.01%	0.68%	1.08%	0.42%	-0.24%	69.88	1.53	0.77%	1.08%	3.23%	1.66%	0.10%
4	48	190	200	1.52	0.76%	0.70%	1.08%	0.42%	-0.24%	72.33	1.85	0.93%	1.04%	3.23%	1.66%	0.10%
5	49	239	200	1.54	0.77%	0.71%	1.08%	0.42%	-0.24%	72.49	2.85	1.43%	1.12%	3.23%	1.66%	0.10%
6	48	287	200	0.86	0.43%	0.67%	1.08%	0.42%	-0.24%	74.00	3.20	1.60%	1.20%	3.23%	1.66%	0.10%
7	48	335	200	0.90	0.45%	0.64%	1.08%	0.42%	-0.24%	72.21	3.00	1.50%	1.24%	3.23%	1.66%	0.10%
8	48	383	200	0.44	0.22%	0.58%	1.08%	0.42%	-0.24%	72.81	3.10	1.55%	1.28%	3.23%	1.66%	0.10%
9	45	428	200	0.40	0.20%	0.54%	1.08%	0.42%	-0.24%	71.39	3.20	1.60%	1.31%	3.23%	1.66%	0.10%
10	45	473	200	0.29	0.15%	0.50%	1.08%	0.42%	-0.24%	74.41	3.40	1.70%	1.35%	3.23%	1.66%	0.10%
11	46	519	200	0.40	0.20%	0.47%	1.08%	0.42%	-0.24%	73.91	3.60	1.80%	1.39%	3.23%	1.66%	0.10%
12	46	565	200	0.30	0.15%	0.45%	1.08%	0.42%	-0.24%	74.69	4.20	2.10%	1.45%	3.23%	1.66%	0.10%
13	46	611	200	0.40	0.20%	0.43%	1.08%	0.42%	-0.24%	73.76	4.18	2.09%	1.50%	3.23%	1.66%	0.10%
14	46	657	200	1.00	0.50%	0.43%	1.08%	0.42%	-0.24%	74.16	2.91	1.46%	1.50%	3.23%	1.66%	0.10%
15	46	703	200	0.90	0.45%	0.43%	1.08%	0.42%	-0.24%	74.96	2.93	1.47%	1.50%	3.23%	1.66%	0.10%
16	47	750	200	0.80	0.40%	0.43%	1.08%	0.42%	-0.24%	76.77	2.90	1.45%	1.49%	3.23%	1.66%	0.10%
17	48	798	200	0.80	0.40%	0.43%	1.08%	0.42%	-0.24%	74.59	2.50	1.25%	1.48%	3.23%	1.66%	0.10%
18	48	846	200	0.82	0.41%	0.43%	1.08%	0.42%	-0.24%	71.66	2.55	1.28%	1.47%	3.23%	1.66%	0.10%
19	46	892	200	0.82	0.41%	0.43%	1.08%	0.42%	-0.24%	75.44	4.86	2.43%	1.52%	3.23%	1.66%	0.10%
20	45	937	200	1.30	0.65%	0.44%	1.08%	0.42%	-0.24%	76.46	3.90	1.95%	1.54%	3.23%	1.66%	0.10%
21	45	982	200	0.80	0.40%	0.44%	1.08%	0.42%	-0.24%	77.19	3.89	1.95%	1.56%	3.23%	1.66%	0.10%
22	47	1029	200	0.47	0.24%	0.43%	1.08%	0.42%	-0.24%	77.08	5.20	2.60%	1.61%	3.23%	1.66%	0.10%
23	47	1076	200	0.48	0.24%	0.42%	1.08%	0.42%	-0.24%	76.42	5.90	2.95%	1.66%	3.23%	1.66%	0.10%

Excel: Vibrosonic (-32): 1

REDUCING RE-WORK FROM SIEVE SIZING OPERATIONS AND STILL OPTIMIZING YIELD

Paul Davies (P151993)

Run Time	Feed Rate	Cumulative	Product	Product	Product	Product	UCL:		LCL:	Product	Revert Sieve		Undersize	UCL:		LCL:
(h)	(kg/h)	Weight (kg)	Sample	Sieve	+32 wt. % in	Oversize %	Average +	Average %	Average -	Malvern	Test -32 µm	-32 wt. % in	%	Average +	Average %	Average -
			Weight (g)	Residue (g)	Product	Cumulative	3SD		3SD	Test % -22 µm (yield)	Residue (g)	Revert		3SD		3SD
1	46	46	200	10.50	5.25%	5.25%	11.17%	3.37%	-4.42%	74.49	0.40	0.20%	0.20%	2.20%	0.78%	-0.63%
2	46	92	200	2.60	1.30%	3.28%	11.17%	3.37%	-4.42%	70.88	0.38	0.19%	0.20%	2.20%	0.78%	-0.63%
3	46	138	200	8.60	4.30%	3.62%	11.17%	3.37%	-4.42%	76.44	0.38	0.19%	0.19%	2.20%	0.78%	-0.63%
4	47	185	200	9.40	4.70%	3.89%	11.17%	3.37%	-4.42%	73.6	0.38	0.19%	0.19%	2.20%	0.78%	-0.63%
5	46	231	200	13.50	6.75%	4.46%	11.17%	3.37%	-4.42%	68.22	0.49	0.25%	0.20%	2.20%	0.78%	-0.63%
6	46	277	200	16.32	8.16%	5.08%	11.17%	3.37%	-4.42%	64.96	0.46	0.23%	0.21%	2.20%	0.78%	-0.63%
7	47	324	200	20.20	10.10%	5.79%	11.17%	3.37%	-4.42%	65.1	0.40	0.20%	0.21%	2.20%	0.78%	-0.63%
8	47	371	200	14.80	7.40%	6.00%	11.17%	3.37%	-4.42%	61.73	0.46	0.23%	0.21%	2.20%	0.78%	-0.63%
9	46	417	200	9.81	4.91%	5.87%	11.17%	3.37%	-4.42%	80.47	1.16	0.58%	0.25%	2.20%	0.78%	-0.63%
10	47	464	200	5.25	2.63%	5.55%	11.17%	3.37%	-4.42%	71.92	2.13	1.07%	0.33%	2.20%	0.78%	-0.63%
11	46	510	200	1.66	0.83%	5.12%	11.17%	3.37%	-4.42%	78.71	1.43	0.72%	0.37%	2.20%	0.78%	-0.63%
12	48	558	200	3.63	1.82%	4.84%	11.17%	3.37%	-4.42%	76.18	1.73	0.87%	0.41%	2.20%	0.78%	-0.63%
13	46	604	200	3.80	1.90%	4.62%	11.17%	3.37%	-4.42%	79.54	1.65	0.83%	0.44%	2.20%	0.78%	-0.63%
14	46	650	200	4.11	2.06%	4.44%	11.17%	3.37%	-4.42%	78.36	2.03	1.02%	0.48%	2.20%	0.78%	-0.63%
15	46	696	200	5.58	2.79%	4.33%	11.17%	3.37%	-4.42%	81.48	2.30	1.15%	0.53%	2.20%	0.78%	-0.63%
16	47	743	200	3.54	1.77%	4.17%	11.17%	3.37%	-4.42%	82.98	2.76	1.38%	0.58%	2.20%	0.78%	-0.63%
17	48	791	200	1.98	0.99%	3.98%	11.17%	3.37%	-4.42%	70.77	2.46	1.23%	0.62%	2.20%	0.78%	-0.63%
18	47	838	200	3.52	1.76%	3.86%	11.17%	3.37%	-4.42%	76.36	2.64	1.32%	0.66%	2.20%	0.78%	-0.63%
19	48	886	200	4.28	2.14%	3.77%	11.17%	3.37%	-4.42%	61.16	2.52	1.26%	0.69%	2.20%	0.78%	-0.63%
20	48	934	200	3.24	1.62%	3.66%	11.17%	3.37%	-4.42%	74.09	2.68	1.34%	0.72%	2.20%	0.78%	-0.63%
21	45	979	200	2.36	1.18%	3.54%	11.17%	3.37%	-4.42%	78.54	2.40	1.20%	0.74%	2.20%	0.78%	-0.63%
22	44	1023	200	2.94	1.47%	3.45%	11.17%	3.37%	-4.42%	79.12	2.72	1.36%	0.77%	2.20%	0.78%	-0.63%
23	48	1071	200	3.62	1.81%	3.37%	11.17%	3.37%	-4.42%	73.82	1.98	0.99%	0.78%	2.20%	0.78%	-0.63%

Excel: X-Line (-32):2

Run Time	Feed Rate	Cumulative	Product	Product	Product	Product	UCL:		LCL:	Product	Revert Sieve		Undersize	UCL:		LCL:
(h)	(kg/h)	Weight (kg)	Sample	Sieve	+32 wt. % in	Oversize %	Average +	Average %	Average -	Malvern	Test -32 µm	-32 wt. % in	%	Average +	Average %	Average -
			Weight (g)	Residue (g)	Product	Cumulative	3SD		3SD	Test % -22 µm (yield)	Residue (g)	Revert		3SD		3SD
1	46	46	200	18.30	9.15%	9.15%	14.83%	3.73%	-7.37%	75.5	0.90	0.45%	0.45%	30.01%	3.51%	-22.98%
2	46	92	200	19.02	9.51%	9.33%	14.83%	3.73%	-7.37%	70	1.02	0.51%	0.48%	30.01%	3.51%	-22.98%
3	46	138	200	16.80	8.40%	9.02%	14.83%	3.73%	-7.37%	74.37	0.98	0.49%	0.48%	30.01%	3.51%	-22.98%
4	46	184	200	1.91	0.96%	7.00%	14.83%	3.73%	-7.37%	72.04	1.83	0.92%	0.59%	30.01%	3.51%	-22.98%
5	45	229	200	19.18	9.59%	7.52%	14.83%	3.73%	-7.37%	71.94	1.29	0.65%	0.60%	30.01%	3.51%	-22.98%
6	45	274	200	8.36	4.18%	6.96%	14.83%	3.73%	-7.37%	74.24	1.59	0.80%	0.63%	30.01%	3.51%	-22.98%
7	46	320	200	26.72	13.36%	7.88%	14.83%	3.73%	-7.37%	63.45	3.12	1.56%	0.77%	30.01%	3.51%	-22.98%
8	45	365	200	7.75	3.88%	7.38%	14.83%	3.73%	-7.37%	57.9	3.88	1.94%	0.91%	30.01%	3.51%	-22.98%
9	46	411	200	10.03	5.02%	7.12%	14.83%	3.73%	-7.37%	67.54	3.44	1.72%	1.00%	30.01%	3.51%	-22.98%
10	46	457	200	7.76	3.88%	6.79%	14.83%	3.73%	-7.37%	76.05	2.17	1.09%	1.01%	30.01%	3.51%	-22.98%
11	46	503	200	3.86	1.93%	6.35%	14.83%	3.73%	-7.37%	74.22	0.96	0.48%	0.96%	30.01%	3.51%	-22.98%
12	47	550	200	3.82	1.91%	5.98%	14.83%	3.73%	-7.37%	77.09	1.84	0.92%	0.96%	30.01%	3.51%	-22.98%
13	45	595	200	3.68	1.84%	5.66%	14.83%	3.73%	-7.37%	71.94	2.20	1.10%	0.97%	30.01%	3.51%	-22.98%
14	46	641	200	3.44	1.72%	5.38%	14.83%	3.73%	-7.37%	70.5	1.46	0.73%	0.95%	30.01%	3.51%	-22.98%
15	48	689	200	4.26	2.13%	5.16%	14.83%	3.73%	-7.37%	75.48	1.98	0.99%	0.96%	30.01%	3.51%	-22.98%
16	44	733	200	3.78	1.89%	4.96%	14.83%	3.73%	-7.37%	77.31	1.72	0.86%	0.95%	30.01%	3.51%	-22.98%
17	46	779	200	3.84	1.92%	4.78%	14.83%	3.73%	-7.37%	79.5	2.10	1.05%	0.96%	30.01%	3.51%	-22.98%
18	47	826	200	3.84	1.92%	4.62%	14.83%	3.73%	-7.37%	66.25	1.96	0.98%	0.96%	30.01%	3.51%	-22.98%
19	45	871	200	3.58	1.79%	4.47%	14.83%	3.73%	-7.37%	76.44	1.74	0.87%	0.95%	30.01%	3.51%	-22.98%
20	46	917	200	0.68	0.34%	4.27%	14.83%	3.73%	-7.37%	82.29	3.40	1.70%	0.99%	30.01%	3.51%	-22.98%
21	46	963	200	0.80	0.40%	4.08%	14.83%	3.73%	-7.37%	73.86	3.42	1.71%	1.02%	30.01%	3.51%	-22.98%
22	46	1009	200	0.10	0.05%	3.90%	14.83%	3.73%	-7.37%	85.4	38.68	19.34%	1.86%	30.01%	3.51%	-22.98%
23	45	1054	200	0.12	0.06%	3.73%	14.83%	3.73%	-7.37%	83.78	80.00	40.00%	3.51%	30.01%	3.51%	-22.98%

Excel: Vibrosonic (-32): 2

REDUCING RE-WORK FROM SIEVE SIZING OPERATIONS AND STILL OPTIMIZING YIELD

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Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Product Sample Weight (g)	Product Sieve Test +32 µm Residue (g)	+32 wt. % in Product	Oversize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD	Product Malvern Test % -22 µm (yield)	Revert Sieve Test -32 µm Sieve Residue (g)	-32 wt. % in Revert	Undersize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD
1	46	46	200	0.36	0.18%	0.18%	1.00%	0.45%	-0.10%	77.82	5.20	2.60%	2.60%	8.71%	4.68%	0.65%
2	46	92	200	0.48	0.24%	0.21%	1.00%	0.45%	-0.10%	77.51	5.27	2.64%	2.62%	8.71%	4.68%	0.65%
3	46	138	200	0.69	0.35%	0.26%	1.00%	0.45%	-0.10%	77.72	6.58	3.29%	2.84%	8.71%	4.68%	0.65%
4	47	185	200	0.58	0.29%	0.26%	1.00%	0.45%	-0.10%	78.22	7.48	3.74%	3.07%	8.71%	4.68%	0.65%
5	46	231	200	0.68	0.34%	0.28%	1.00%	0.45%	-0.10%	77.88	8.02	4.01%	3.26%	8.71%	4.68%	0.65%
6	46	277	200	0.72	0.36%	0.29%	1.00%	0.45%	-0.10%	79.54	6.54	3.27%	3.26%	8.71%	4.68%	0.65%
7	47	324	200	0.70	0.35%	0.30%	1.00%	0.45%	-0.10%	78.30	6.86	3.43%	3.28%	8.71%	4.68%	0.65%
8	47	371	200	0.74	0.37%	0.31%	1.00%	0.45%	-0.10%	76.97	7.02	3.51%	3.31%	8.71%	4.68%	0.65%
9	46	417	200	0.68	0.34%	0.31%	1.00%	0.45%	-0.10%	77.69	6.72	3.36%	3.32%	8.71%	4.68%	0.65%
10	47	464	200	0.66	0.33%	0.31%	1.00%	0.45%	-0.10%	83.59	9.00	4.50%	3.43%	8.71%	4.68%	0.65%
11	46	510	200	0.81	0.41%	0.32%	1.00%	0.45%	-0.10%	78.02	8.30	4.15%	3.50%	8.71%	4.68%	0.65%
12	48	558	200	1.00	0.50%	0.34%	1.00%	0.45%	-0.10%	78.60	10.50	5.25%	3.65%	8.71%	4.68%	0.65%
13	46	604	200	0.80	0.40%	0.34%	1.00%	0.45%	-0.10%	78.34	11.00	5.50%	3.79%	8.71%	4.68%	0.65%
14	46	650	200	1.20	0.60%	0.36%	1.00%	0.45%	-0.10%	78.88	12.40	6.20%	3.96%	8.71%	4.68%	0.65%
15	46	696	200	0.90	0.45%	0.37%	1.00%	0.45%	-0.10%	77.53	9.80	4.90%	4.02%	8.71%	4.68%	0.65%
16	47	743	200	0.80	0.40%	0.37%	1.00%	0.45%	-0.10%	78.44	11.80	5.90%	4.14%	8.71%	4.68%	0.65%
17	48	791	200	1.64	0.82%	0.40%	1.00%	0.45%	-0.10%	79.46	10.60	5.30%	4.21%	8.71%	4.68%	0.65%
18	47	838	200	1.56	0.78%	0.42%	1.00%	0.45%	-0.10%	78.83	9.48	4.74%	4.24%	8.71%	4.68%	0.65%
19	48	886	200	1.28	0.64%	0.43%	1.00%	0.45%	-0.10%	78.86	11.54	5.77%	4.32%	8.71%	4.68%	0.65%
20	48	934	200	1.82	0.91%	0.45%	1.00%	0.45%	-0.10%	80.90	10.50	5.25%	4.37%	8.71%	4.68%	0.65%
21	45	979	200	0.77	0.39%	0.45%	1.00%	0.45%	-0.10%	80.11	14.80	7.40%	4.51%	8.71%	4.68%	0.65%
22	44	1023	200	0.90	0.45%	0.45%	1.00%	0.45%	-0.10%	79.81	13.70	6.85%	4.62%	8.71%	4.68%	0.65%
23	48	1071	200	0.84	0.42%	0.45%	1.00%	0.45%	-0.10%	80.44	12.28	6.14%	4.68%	8.71%	4.68%	0.65%

Excel: X-Line (-32): 2

Appendix B: Data for -53microns

Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Product Sample Weight (g)	Product Sieve Test +53 µm Residue (g)	+53 wt. % in Product	Oversize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD	Product Malvern Test % -15 µm	Revert Sieve Test -53 µm Sieve Residue (g)	-53 wt. % in Revert	Undersize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD
1	46	46	200	1.50	0.75%	0.75%	15.13%	3.77%	-7.59%	9.48	20.30	10.15%	10.15%	30.29%	10.99%	-8.31%
2	47	93	200	2.00	1.00%	0.88%	15.13%	3.77%	-7.59%	13.64	36.00	18.00%	14.08%	30.29%	10.99%	-8.31%
3	47	140	200	2.97	1.49%	1.08%	15.13%	3.77%	-7.59%	16.86	46.70	23.35%	17.17%	30.29%	10.99%	-8.31%
4	47	187	200	2.07	1.04%	1.07%	15.13%	3.77%	-7.59%	17.96	36.96	18.48%	17.50%	30.29%	10.99%	-8.31%
5	47	234	200	3.35	1.68%	1.19%	15.13%	3.77%	-7.59%	16.90	28.81	14.41%	16.88%	30.29%	10.99%	-8.31%
6	47	281	200	2.99	1.50%	1.24%	15.13%	3.77%	-7.59%	17.71	17.51	8.76%	15.52%	30.29%	10.99%	-8.31%
7	48	329	200	2.29	1.15%	1.23%	15.13%	3.77%	-7.59%	19.74	7.21	3.61%	13.82%	30.29%	10.99%	-8.31%
8	46	375	200	2.65	1.33%	1.24%	15.13%	3.77%	-7.59%	21.88	2.03	1.02%	12.22%	30.29%	10.99%	-8.31%
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10	46	46	200	20.34	10.17%	2.23%	15.13%	3.77%	-7.59%	9.90	18.44	9.22%	11.89%	30.29%	10.99%	-8.31%
11	45	91	200	16.22	8.11%	2.82%	15.13%	3.77%	-7.59%	2.67	15.00	7.50%	11.45%	30.29%	10.99%	-8.31%
12	45	136	200	16.34	8.17%	3.31%	15.13%	3.77%	-7.59%	2.98	18.00	9.00%	11.23%	30.29%	10.99%	-8.31%
13	46	182	200	17.86	8.93%	3.77%	15.13%	3.77%	-7.59%	0.00	16.78	8.39%	10.99%	30.29%	10.99%	-8.31%
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Excel: Vibrosonic (-53): 1

REDUCING RE-WORK FROM SIEVE SIZING OPERATIONS AND STILL OPTIMIZING YIELD

Paul Davies (P151993)

				Product Sieve Test +53 µm							Product Malvern Test -15 µm	Revert Sieve Test -53 µm					
Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Sample Weight (g)	Sieve Residue (g)	+53 wt. % in Product	Oversize % Cumulative	Average + 3SD	Average %	Average - 3SD	8.89%	10.24	Residue (g)	-53 wt. % in Revert	% Cumulative	Average + 3SD	Average %	LCL: Average - 3SD
1	47	47	200	26.34	13.17%	13.17%	15.28%	12.09%	8.89%	10.24	0.34	0.17%	0.17%	0.30%	0.20%	0.10%	
2	47	94	200	26.89	13.45%	13.31%	15.28%	12.09%	8.89%	10.24	0.31	0.16%	0.16%	0.30%	0.20%	0.10%	
3	45	139	200	21.64	10.82%	12.48%	15.28%	12.09%	8.89%	9.07	0.36	0.18%	0.17%	0.30%	0.20%	0.10%	
4	46	185	200	26.16	13.08%	12.63%	15.28%	12.09%	8.89%	8.36	0.42	0.21%	0.18%	0.30%	0.20%	0.10%	
5	46	231	200	24.54	12.27%	12.56%	15.28%	12.09%	8.89%	15.59	0.38	0.19%	0.18%	0.30%	0.20%	0.10%	
6	44	275	200	22.40	11.20%	12.33%	15.28%	12.09%	8.89%	6.86	0.46	0.23%	0.19%	0.30%	0.20%	0.10%	
7	46	321	200	21.80	10.90%	12.13%	15.28%	12.09%	8.89%	11.08	0.38	0.19%	0.19%	0.30%	0.20%	0.10%	
8	45	366	200	23.60	11.80%	12.09%	15.28%	12.09%	8.89%	9.02	0.52	0.26%	0.20%	0.30%	0.20%	0.10%	
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				Product Sieve Test +53 µm								Product Malvern Test %-15 µm	Revert Sieve Sieve						
Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Sample Weight (g)	Sieve Residue (g)	+53 wt. % in Product	Oversize % Cumulative	UCL: Average + SSD	Average %	LCL: Average - SSD	Average %	Average - SSD	Test % -15 µm	Residue (g)	-53 wt. % in Revert	%	Undersize Cumulative	UCL: Average + SSD	Average %	LCL: Average - SSD
1	46	46	200	0.80	0.40%	0.40%	3.34%	1.00%	-1.35%	22.50	46.32	23.16%	23.16%	99.74%	23.58%	-52.57%			
2	47	93	200	0.62	0.31%	0.36%	3.34%	1.00%	-1.35%	16.44	38.98	19.49%	21.33%	99.74%	23.58%	-52.57%			
3	46	139	200	0.76	0.38%	0.36%	3.34%	1.00%	-1.35%	26.69	43.36	21.68%	21.44%	99.74%	23.58%	-52.57%			
4	46	185	200	0.82	0.41%	0.38%	3.34%	1.00%	-1.35%	22.15	53.56	26.78%	22.78%	99.74%	23.58%	-52.57%			
5	46	231	200	0.78	0.39%	0.38%	3.34%	1.00%	-1.35%	20.26	45.02	22.51%	22.72%	99.74%	23.58%	-52.57%			
6	46	277	200	0.79	0.40%	0.38%	3.34%	1.00%	-1.35%	26.09	23.36	11.68%	20.88%	99.74%	23.58%	-52.57%			
7	46	323	200	0.60	0.30%	0.37%	3.34%	1.00%	-1.35%	17.83	38.62	19.31%	20.66%	99.74%	23.58%	-52.57%			
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9	46	46	200	3.65	1.83%	0.55%	3.34%	1.00%	-1.35%	7.30	19.06	9.53%	19.27%	99.74%	23.58%	-52.57%			
10	45	91	200	3.98	1.99%	0.71%	3.34%	1.00%	-1.35%	0.00	203.00	101.50%	28.40%	99.74%	23.58%	-52.57%			
11	45	136	200	3.80	1.90%	0.83%	3.34%	1.00%	-1.35%	0.00	16.88	8.44%	26.41%	99.74%	23.58%	-52.57%			
12	45	181	200	3.40	1.70%	0.91%	3.34%	1.00%	-1.35%	0.00	17.98	8.99%	24.82%	99.74%	23.58%	-52.57%			
13	45	226	200	3.96	1.98%	1.00%	3.34%	1.00%	-1.35%	2.47	19.88	9.94%	23.58%	99.74%	23.58%	-52.57%			
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Excel: Vibrosonic (-53): 2

Paul Davies (P151993)

Excel: X-Line (-53): 2

Excel: Vibrosonic (-53): 3

REDUCING RE-WORK FROM SIEVE SIZING OPERATIONS AND STILL OPTIMIZING YIELD

Paul Davies (P151993)

Run Time (h)	Feed Rate (kg/h)	Cumulative Weight (kg)	Product Sample Weight (g)	Product Sieve Test +53 µm Residue (g)	+53 wt. % in Product	Oversize % Cumulative	UCL: Average + 3SD	Average %	LCL: Average - 3SD	Product Malvern Test % -15 µm	Revert Sieve Test -53 µm Residue (g)	-53 wt. % in Revert	Undersize Cumulative %	UCL: Average + 3SD	Average %	LCL: Average - 3SD
1	45	45	200	18.64	9.32%	9.32%	10.49%	6.84%	3.19%	12.28	1.60	0.80%	0.80%	1.49%	0.73%	-0.02%
2	45	90	200	14.24	7.12%	8.22%	10.49%	6.84%	3.19%	24.98	2.34	1.17%	0.99%	1.49%	0.73%	-0.02%
3	46	136	200	12.36	6.18%	7.54%	10.49%	6.84%	3.19%	13.66	0.92	0.46%	0.81%	1.49%	0.73%	-0.02%
4	46	182	200	12.38	6.19%	7.20%	10.49%	6.84%	3.19%	10.28	1.58	0.79%	0.81%	1.49%	0.73%	-0.02%
5	46	228	200	14.38	7.19%	7.20%	10.49%	6.84%	3.19%	13.15	1.28	0.64%	0.77%	1.49%	0.73%	-0.02%
6	46	274	200	11.68	5.84%	6.97%	10.49%	6.84%	3.19%	10.91	0.88	0.44%	0.72%	1.49%	0.73%	-0.02%
7	46	320	200	12.04	6.02%	6.84%	10.49%	6.84%	3.19%	17.00	1.68	0.84%	0.73%	1.49%	0.73%	-0.02%
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