

WORCESTER POLYTECHNIC INSTITUTE

# Quantifying form characteristics of abrasive slurry

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## **Abstract**

This experiment looked to identify the impact on grit morphology, granulometry, and angularity as they pertain to changing independent variables of the WPI automated lapping machine, ALM. The experiment used a DOE, design of experiments, approach that called for twelve experimental runs, each of which correlate to unique ALM settings. Methods for quantifying these parameters were developed as a secondary objective. The end result showed that particle granulometry, morphology, and angularity are each uniquely affected by interactions between ALM settings.

## 1. Introduction

### 1.1 Objective

The objective of this experiment is to identify independent variables of the WPI Automated Lapping Machine (ALM) that have a dominant impact on grit morphology, granulometry, and angularity. The development of methods to quantify these parameters is a secondary objective critical to the development of this research.

### 1.2 Rationale

The development of a manufacturing process that reliably produces a class VI metal to metal seal for quarter turn ball valves is a sought after task. High temperature and corrosive environments make the use of soft seat or grease based sealing systems impractical to use. Traditionally the lapping process of ball valves has used a trial and error based approach that relies heavily on operator experience. This proves costly and time consuming when valves do not meet client specified standards. After failing a bubble test, valves are dismantled, lapped a second time, reassemble, and tested again. This process may repeat indefinitely until a valve meets specified standards. The development of a process that reduces production time and cost will increase product output with far reaching financial implications for Metso Automation.

Critical to the production of quality valves is the application and use of abrasive slurry. The grits contained within the slurry are the driving force behind changes in roughness and form for ball and seat sealing surfaces. In the absence of the abrasive, material removal would be limited and inadequate changes in valve geometry would occur.

Designing a process that produces a specified seal class is built around the hypothesis that changes made to lapping parameters produce different roughness values on the sealing regions of the valve. Further extrapolating this hypothesis is the inference that different roughness values correlate to different leak rates in the sealing region. Based on this assumption there may be a roughness that dramatically reduces or eliminates leak paths in the region where the ball and seat form a seal.

### 1.3 State-of-the-art

Lapping is a micromachining technique that incorporates three abrasive mechanisms of rolling, sliding, and micro cutting to produce a desired surface finish. The profile lapping process used for quarter turn ball valves engages a lapping tool profiled according to a target shape against a work piece. Critical to this process is the inclusion of slurry in which abrasive grits are freely mounted. It was shown by Lichtenberger that grains blunt with increasing lapping time and break into small sharp-edged lapping grains capable of cutting that consequently change the surface finish of the work piece. While extensive research has been conducted to understand the relationship between grit and material removal of a work piece, no work has been done to correlate the changes in grit morphology, granulometry, and angularity with independent variables of the lapping process (Marinescu 2007).

The well researched field of experiment design is the driving mechanism behind correlating grit morphology, granulometry, and angularity with valve performance. Design of Experiments, DOE, is a

planned approach for determining cause and effect relationships making it a perfect framework for correlating valve performance with grit characteristics (Anderson and Whitcomb 2007). Within the DOE structure a statistical framework is used to extract information from the collected data. The procedural outlines explored by Montgomery (2001) help create robust processes affected minimally by external sources of variability.

Using DOE as a framework allows for the grit characteristics to be quantified according to a variety of techniques. The techniques used in this experiment were designed for describing the varying grit structures found in different types of soil samples. The work of Kaerdi and Mikli showed that a Legendre ellipse can be used to describe a particle by means of geometric and shape parameters. The shape parameter characterizes mainly the shape, without considering its size. This generates a clear distinction between the geometric features of morphology and granulometry. It was shown by Stachowiak that sharpness and size directly relate to particle abrasivity and subsequently geometric changes in the sealing areas of a valve (Stachowiak 2000). A variety of numerical descriptors have been developed to describe the angularity of a particle. One such example is the spike parameter–linear fit. This method is based on representing the particle boundary by a set of triangles constructed at different scales (Stachowiak 2000). This method generates a spike parameter that can be compared to with other particles.

## 1.4 Approach

To correlate ALM factor settings with responses of morphology, granulometry, and angularity a design of experiments, DOE, framework was implemented. The experiment used a two level fractional factorial design with the number of factors dictating the design layout. The DOE structure limited the number of experimental runs to 12. High and low factor settings were chosen according to the maximum functional range for each of the four factors. The final experiment took the form of a 12-run irregular fraction factorial design.

## 2. Methods

Development of the DOE began with identifying factors of interest from the ALM. The four chosen factors were seat motor speed, bore tilt arm range, joint tilt arm range, and applied force. Each factor was given a low and high setting according to its range.

Factor	Name	Units	Low (-)	High (+)
A	Speed	RPM	38	150
B	Bore Tilt Arm Range	Degrees	0	128
C	Joint Tilt Arm Range	Degrees	0	672
D	Applied Force	PSI	0	20

Table 1: ALM DOE factors

Three responses were chosen to address the areas of interest of particle shape, size, and sharpness. Particle shape is addressed through morphology using a Legendre ellipse method. The size of particles was addressed using granulometry by implementing an irregularity parameter and sharpness addressed using angularity using Richardson's technique.

Name	Coded Value	Data Acquisition Method	Characterization method
Morphology (shape)	Y1	Lext	Legendre ellipse
Granulometry (size)	Y2	Lext	Irregularity parameter
Angularity	Y3	Lext	Richardson's technique

Table 2: Grit DOE responses

With factors and responses identified the design summary was generated using Design Expert 8, design of experiments statistical analysis software. DE8 was used to generate the random run order for conducting the experiment as to not introduce operator influence on run order.

File Version 8.0.7.1										
Study Type		Factorial	Runs		12					
Design Type		Irregular Fraction	Blocks		No Blocks					
Center Point 0										
Design Mode		2FI	Build Time (ms)		0.43					
Factor	Name	Units	Type	Subtype	Minimum	Maximum	Coded Values	Mean	Std. Dev.	
A	Duty Cycle	RPM	Numeric	Continuous	38.00	150.00	-1.000=38.00 1.000=150.00	94.00	56.00	
B	Bore Tilt Arm Range	Degrees	Numeric	Continuous	0.00	144.00	-1.000=0.00 1.000=144.00	72.00	72.00	
C	Joint Tilt Arm Range	Degrees	Numeric	Continuous	0.00	672.00	-1.000=0.00 1.000=672.00	336.00	336.00	
D	Applied Force	PSI	Numeric	Continuous	5.00	20.00	-1.000=0.00 1.000=20.00	12.50	7.50	
Response	Name	Units	Obs	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Trans
Y1	Morphology (shape)		0	Factorial	No Data	No Data	No Data	No Data	N/A	None
Y2	Granulometry (size)		0	Factorial	No Data	No Data	No Data	No Data	N/A	None
Y3	Angularity		0	Factorial	No Data	No Data	No Data	No Data	N/A	None

Table 3: Design Expert 8 experiment design summary

With a run order generated balls and seats were cleaned using isopropyl alcohol and a lint free cloth. Loctite 320 clover compound was applied to the ball surface and mounted in the ALM. Before starting the machine servo controller code was loaded in accordance with high and low factor settings dictated by each run. The time of each run was standardized to five minutes.

From each experimental run two abrasive samples were collected. One sample was taken from the ball sealing surface while the other was taken from the seat sealing surface. The collected grit samples were then measured using an Olympus LEXT OLS 4000 confocal microscope. Grit samples were measured using a 20x lens at three times digital zoom generating a measurement at 60x magnification. A two dimensional analysis of the resulting Lext measurements is the foundation for characterizing the grit particles according to morphology, granulometry, and angularity.



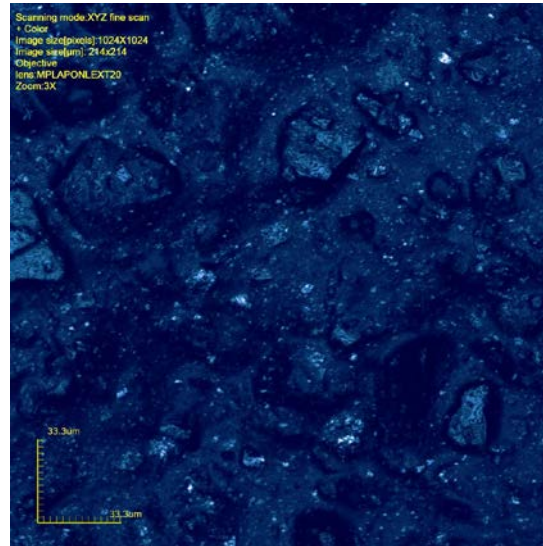


Figure 1: Lext measurement of lapped grit sample

A 2-dimensional analysis of the lapping compound was chosen over a 3-dimensional system. This is a product of the nature of the lapping compound and its availability to measurement using the LEXT. Compound samples were collected from valves in regions identified as sealing regions. Attempts to produce a more uniform surface, that would help in measurement under with the LEXT, disturbed particle distribution. It became a concern that un-lapped particles would be introduced into regions of focus effecting experimental results. The 3D rendering below illustrates spike problems that arise from the measurement of the compound. The height variability of the compound did not allow the LEXT to cast adequate light into valley regions of samples. The lack of light produced false geometries called spikes. Additionally, 3D analysis of grit samples required more complex methods of quantifying grit particles and ideally their removal from the slurry housing them.

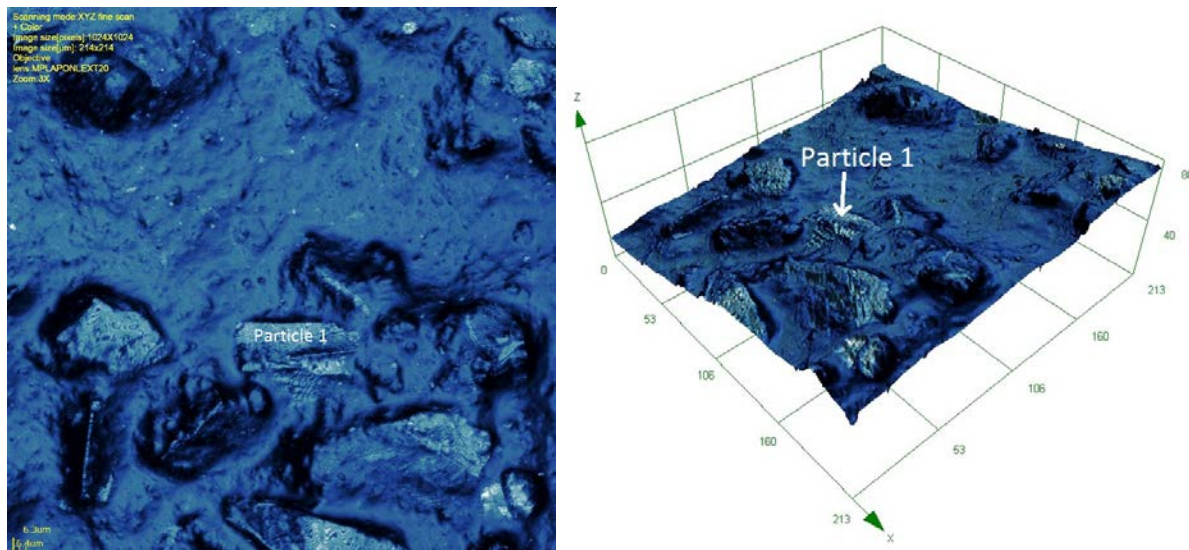


Figure 2: Comparison illustrating problems introduced by three dimensional analysis of abrasive slurry. A large rendering of both images can be found in the appendix of this report

Grit morphology is an examination of a particles shape. A Legendre ellipse method was used to quantify the morphology of the grit particles. The method generates an elongation shape factor, EL, dispersion value, DP, and aspect ratio, AS, to characterize the response. The aspect ratio, AS, is the ratio of the ellipse length,  $a$ , to its width,  $b$ . The average of the three parameters generates a representative value of grit morphology for the identified particles of interest.

$$AS = a/b \quad EL = \log_2(a/b) \quad DP = \log_2(\pi ab)$$

Equation 1: Numeric calculation of a) aspect, AS b) elongation shape factor, EL and c) dispersion factor, DP

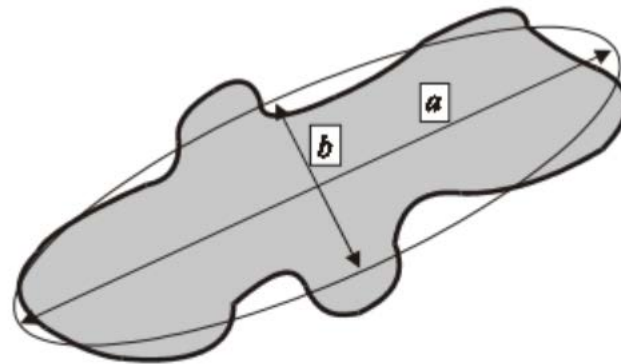


Figure 3: Morphology study based on Legendre ellipse

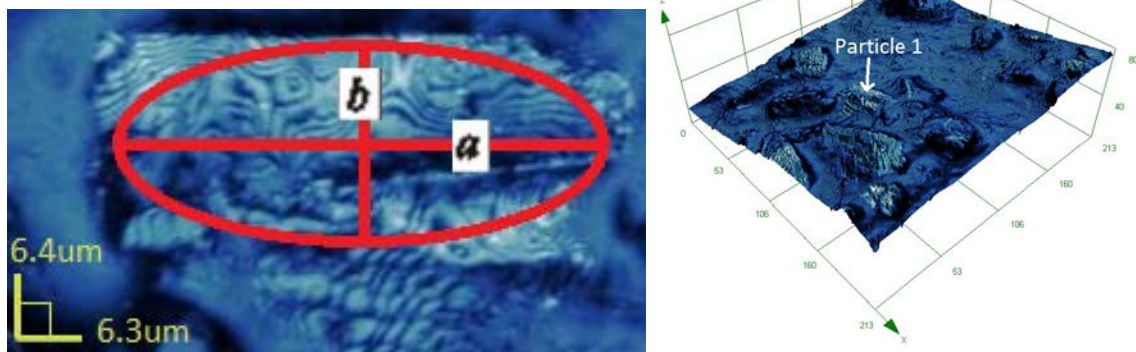


Figure 4: Morphology study of grit particle using LEXT measurement

Granulometry looks to identify particle size. This response was quantified using an image analysis method based on inscribed circles. Particle sizes were determined by the diameter,  $d$ , of the maximum inscribed circle of an abrasive grit. The same particles identified selected for use in quantifying this response were the same ones used to quantify grit morphology.

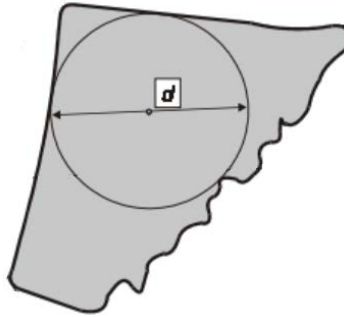


Figure 5: Granulometry study based on the maximum inscribed circle of grit particle

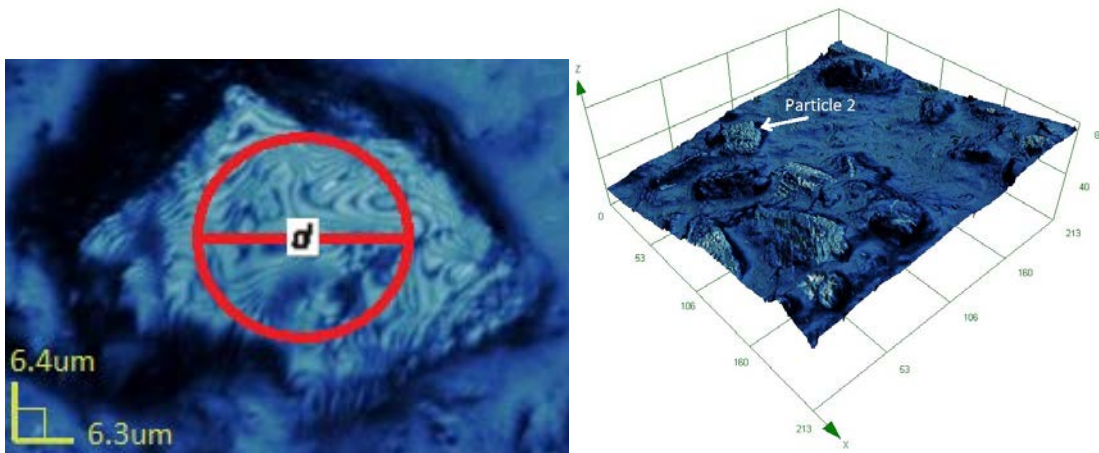


Figure 6: Granulometry study of grit particle 2 using LEXT measurement

The classification of particle sharpness was developed using an angularity spike parameter. For this application angularity was examined using a spike parameter-quadratic fit. This method first defines a particle boundary around a fixed step size. Points of interest, spikes, are geometries that fall outside the boundary. The local maximum radius for each spike is found and identified as the spikes apex. The resulting apex angle,  $\theta$ , was used in the spike value formula to calculate spike value, SV.

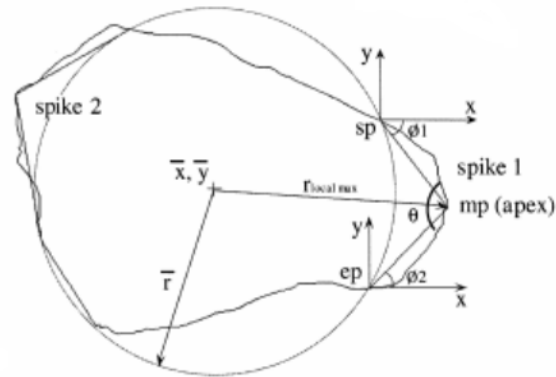


Figure 7: Schematic illustration of spike parameter-quadratic fit from Particle angularity and its relationship to abrasive and erosive wear by Stochowiak (215)

$$SV = \cos\left(\frac{\theta}{2}\right)$$

Equation 2: Spike value formula

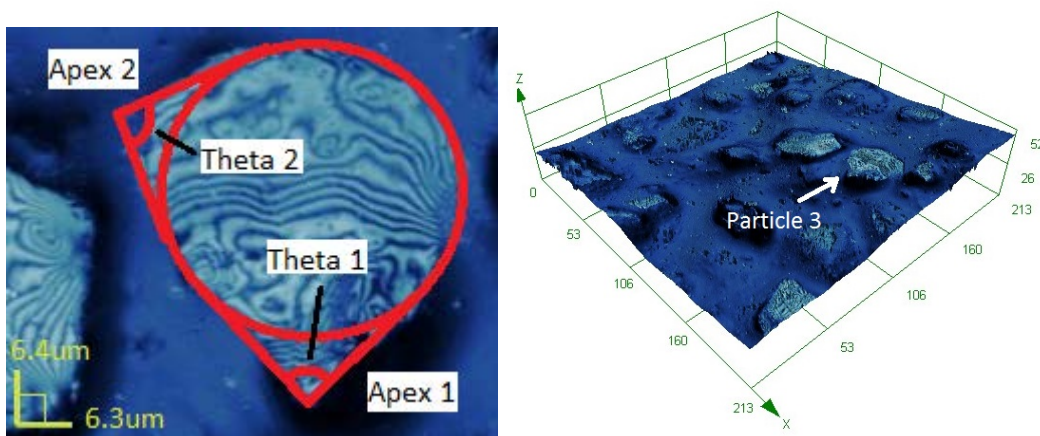


Figure 8: Angularity study of grit particle using LEXT measurement

The measured values for each experimental run describing granulometry, morphology, and angularity were added to the Design Expert 8 project file. Using this software a half-normal plot is generated and factors selected for inclusion in the analysis of the analyzed response. From the half-normal plot Design Expert generated a Pareto plot for each response. The plot indicated the significance of each factor as it pertains to the response under study. As a means of protecting against spurious outcomes the results of the Pareto plot are verified using an analysis of variance (ANOVA) test. This test was also conducted using Design Expert 8.

## 3. Results

### 3.1 Morphology

A joint interaction between the speed factor, A, and applied force factor, D, had the strongest influence on grain morphology. The factor approaches, but does not exceed, the Bonferroni limit indicating AD is likely to have significant influence but this influence is open to variability. Factors that surpass the Bonferroni limit are certain to have an effect on an analyzed response. The ANOVA test indicates that a model F-value of 2370.50 implies the model is significant with a 1.60% chance that this value could occur due to noise.

Design-Expert® Software  
Morphology: average

A: Speed  
B: Bore Tilt Arm Range  
C: Joint Tilt Arm Range  
D: Applied Force  
■ Positive Effects  
■ Negative Effects

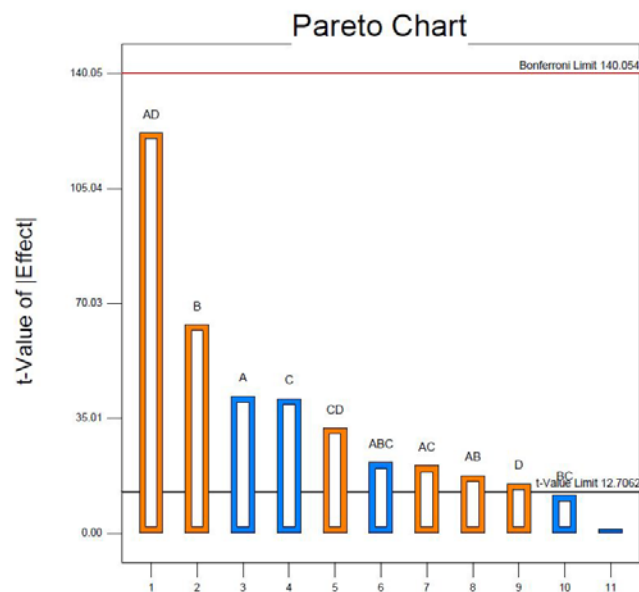


Figure 9: Morphology Pareto Chart

### 3.2 Granulometry

A joint interaction between factor A, speed, and factor C, joint tilt arm range, looks to play a significant roll in particle granulometry. Additionally factors AB, BCm B, and BD play a significant role in particle granulometry. All five of these values surpass the Bonferroni limit indicating a significant influence on granulometry. The ANOVA test shows a model F-value of 369.50. There is only a 0.02% chance that a model F-value this large could occur from noise.

Design-Expert® Software  
1/Sqrt(Granulometry)

- A: Speed
- B: Bore Tilt Arm Range
- C: Joint Tilt Arm Range
- D: Applied Force
- Positive Effects
- Negative Effects

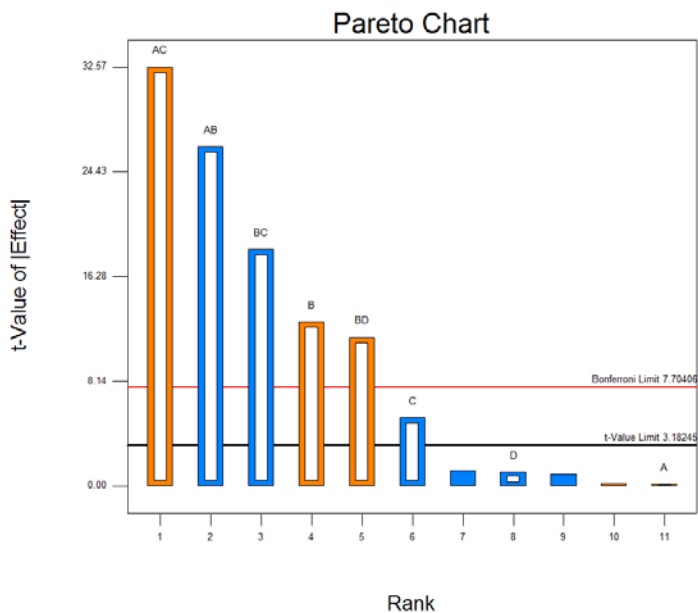


Figure 10: Granulometry Pareto Chart

### 3.3 Angularity

A joint interaction between factor B, the bore tilt arm range, and factor C, the joint tilt arm range, shows significant effects on particle angularity. Additionally factors AB and BD play a significant roll in this response. The ANOVA test shows that a model F-value of 53.49 implying that the model is significant. There is a 0.38% chance that an F-value this large could occur due to noise.

Design-Expert® Software  
Angularity SV

- A: Speed
- B: Bore Tilt Arm Range
- C: Joint Tilt Arm Range
- D: Applied Force
- Positive Effects
- Negative Effects

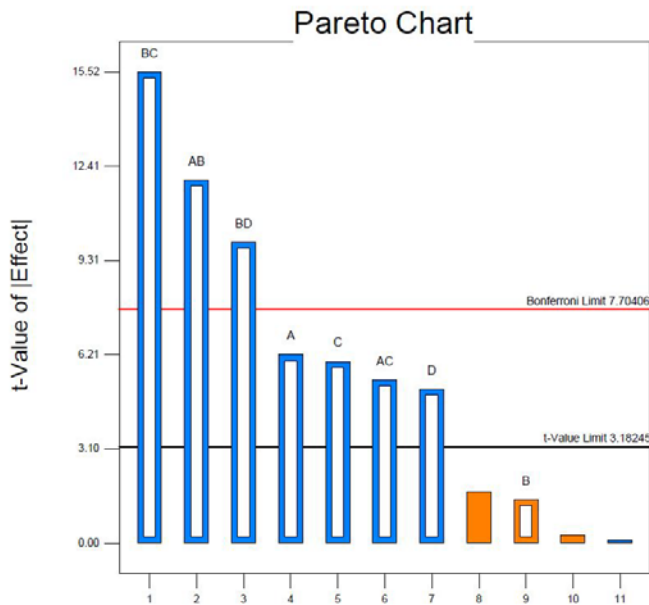


Figure 11: Angularity Pareto Chart

## 4. Conclusions

The design of experiments methodology implemented in this experiment was successful. The experiment showed each response is influenced by a unique set of factors. Joint factor interactions dominate the effect on the responses. Factor interactions that surpass the Bonferroni limit indicate a factor had significant influence on the response under study. Factor interactions that surpass the t-value limit but did not exceed the Bonferroni limit had a significant role but are susceptible to variance.

## 5. Acknowledgments

The author would like to gratefully acknowledge the support of Metso Automation for its support of this research. Additionally the author would like to acknowledge Olympus for the use of LEXT OLS4000 and DigitalSurf for the use of Mountains Map.

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## 7. Appendix

### 7.1 Grit Removal from slurry

Initially it was of significant interest to remove the grit particles from the abrasive slurry. Several attempts were made to remove the particles from the slurry. Initially it was thought that a simple water mixture would produce adequate results. After submerging a sample overnight the slurry had not dissolved. A second test was conducted by introducing liquid dish soap into the water. Again the sample was left to dissolve in the solution overnight but produced no results. This process was repeated using isopropyl alcohol and acetone. Again this produced no results. In the interest of expediting this process Loctite, the makers of the clover compound abrasive slurry were contacted. It was hoped that they may be able to provide some insight into how the compound could be better broken down. They provided no insight into this process. For that reason grit particles were retained in the abrasive slurry and measured using the previously described 2D methods.

### 7.2 Analysis of variance (ANOVA) Results

#### 7.2.1 Morphology

Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.19	10	0.12	2370.50	0.0160
A-Speed	0.087	1	0.087	1736.26	0.0153
B-Bore Tilt Arm R	0.20	1	0.20	4032.25	0.0100
C-Joint Tilt Arm R	0.084	1	0.084	1677.03	0.0155
D-Applied Force	0.011	1	0.011	225.00	0.0424
AB	0.015	1	0.015	306.25	0.0363
AC	0.021	1	0.021	420.25	0.0310
AD	0.74	1	0.74	14884.00	0.0052
BC	6.667E-003	1	6.667E-003	133.33	0.0550
CD	0.051	1	0.051	1024.00	0.0199
ABC	0.023	1	0.023	462.25	0.0296

Figure 12: ANOVA results for morphology response

## 7.2.2 Granulometry

Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.13	8	0.017	369.50	0.0002
A-Speed	1.155E-006	1	1.155E-006	0.026	0.8830
B-Bore Tilt Arm R	7.342E-003	1	7.342E-003	162.92	0.0010
C-Joint Tilt Arm R	1.275E-003	1	1.275E-003	28.30	0.0130
D-Applied Force	5.462E-005	1	5.462E-005	1.21	0.3513
AB	0.031	1	0.031	695.34	0.0001
AC	0.048	1	0.048	1060.71	< 0.0001
BC	0.015	1	0.015	338.79	0.0003
BD	6.042E-003	1	6.042E-003	134.07	0.0014

Figure 13: ANOVA results for granulometry response

## 7.2.3 Angularity

Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4.98	8	0.62	53.49	0.0038
A-Speed	0.45	1	0.45	38.55	0.0084
B-Bore Tilt Arm R	0.024	1	0.024	2.06	0.2470
C-Joint Tilt Arm R	0.42	1	0.42	35.80	0.0093
D-Applied Force	0.30	1	0.30	25.69	0.0148
AB	1.66	1	1.66	142.96	0.0013
AC	0.34	1	0.34	28.80	0.0127
BC	2.80	1	2.80	240.81	0.0006
BD	1.14	1	1.14	98.11	0.0022

Figure 14: ANOVA results for angularity response

## 7.3 Servo Controller Code

### 7.3.1 BTA/JTA Zero Code

```
# Sequence 0
begin
  500 7768 5364 frame_0_1 # Frame 0
repeat

  sub frame_0_1
    1 servo
    0 servo
    delay
  return
```

### 7.3.2 BTA/JTA Max Code

```

# Sequence 0
begin
    500 6464 5184 frame_0_1 # Frame 0
    500 9152 5696 frame_0_1 # Frame 1
repeat

sub frame_0_1
    1 servo
    0 servo
    delay
    return

```

### 7.3.3 BTA Code

```

# Sequence 0
begin
    500 6464 5364 frame_0_1 # Frame 0
    500 9152 frame_0 # Frame 1
repeat

sub frame_0_1
    1 servo
    0 servo
    delay
    return

sub frame_0
    0 servo
    delay
    return

```

### 7.3.4 JTA Code

```

# Sequence 0
begin
    500 7768 5184 frame_0_1 # Frame 0
    500 5696 frame_1 # Frame 1
repeat

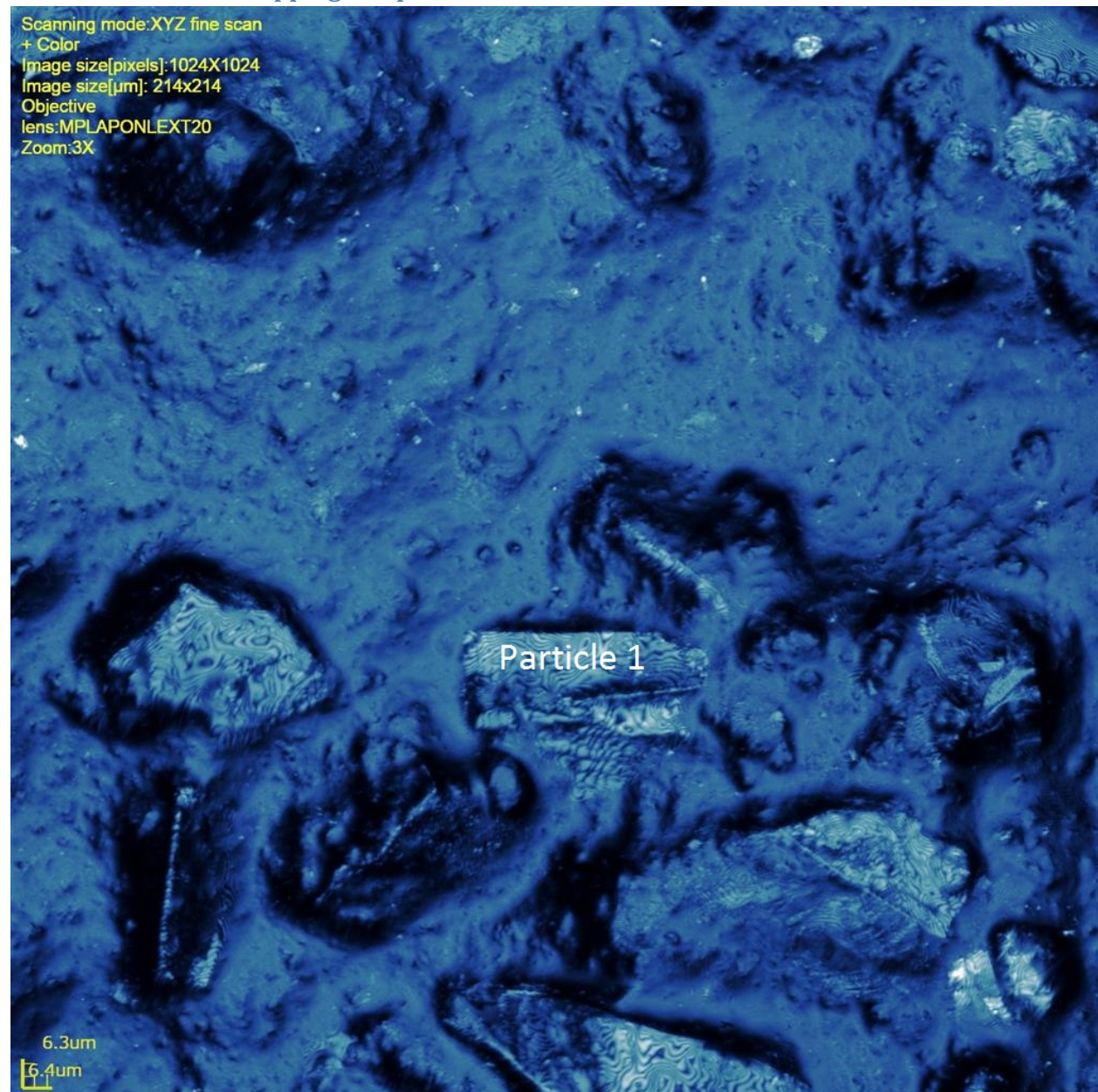
sub frame_0_1
    1 servo
    0 servo
    delay
    return

sub frame_1
    1 servo
    delay
    return

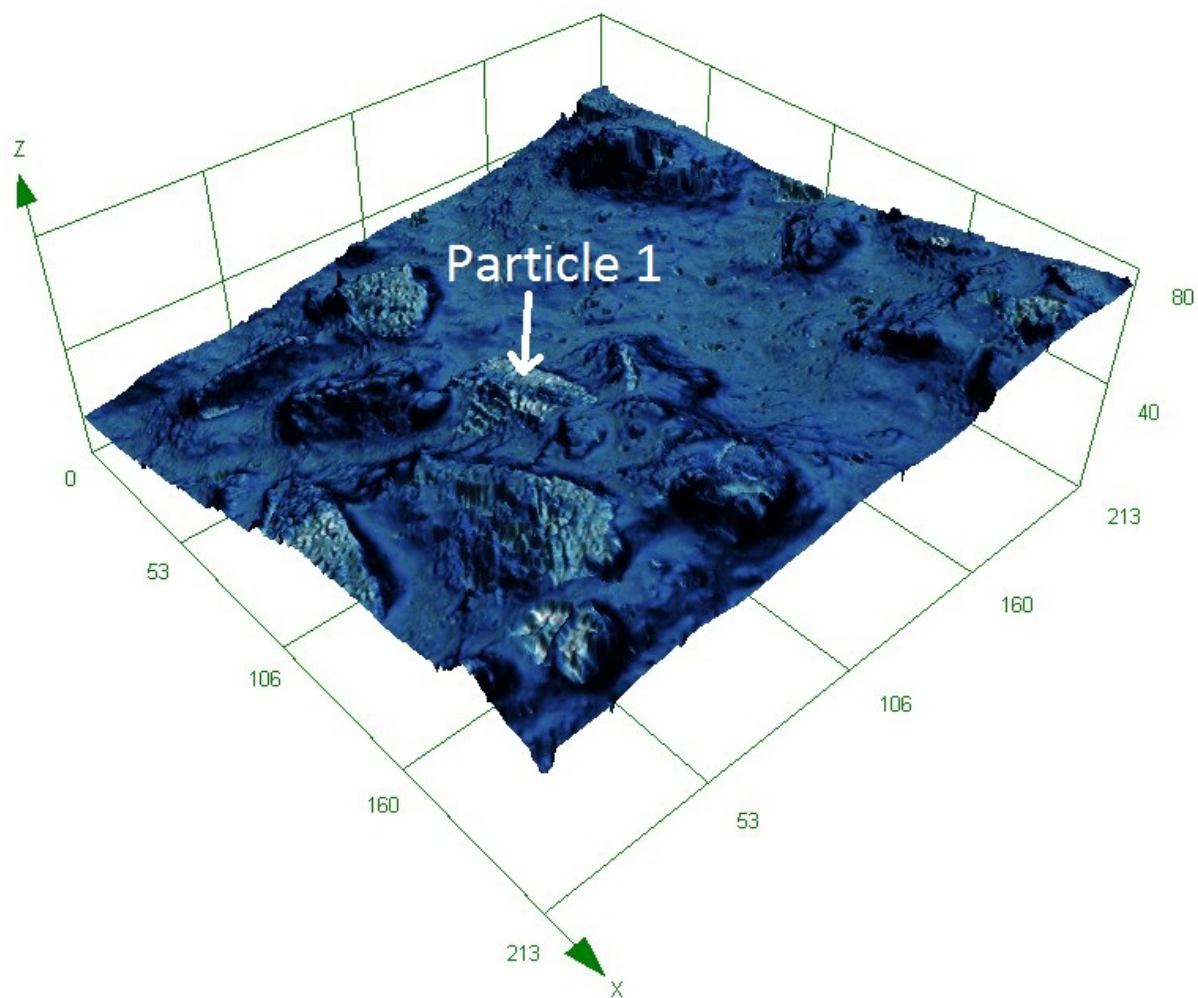
```

## 7.4 Measurements

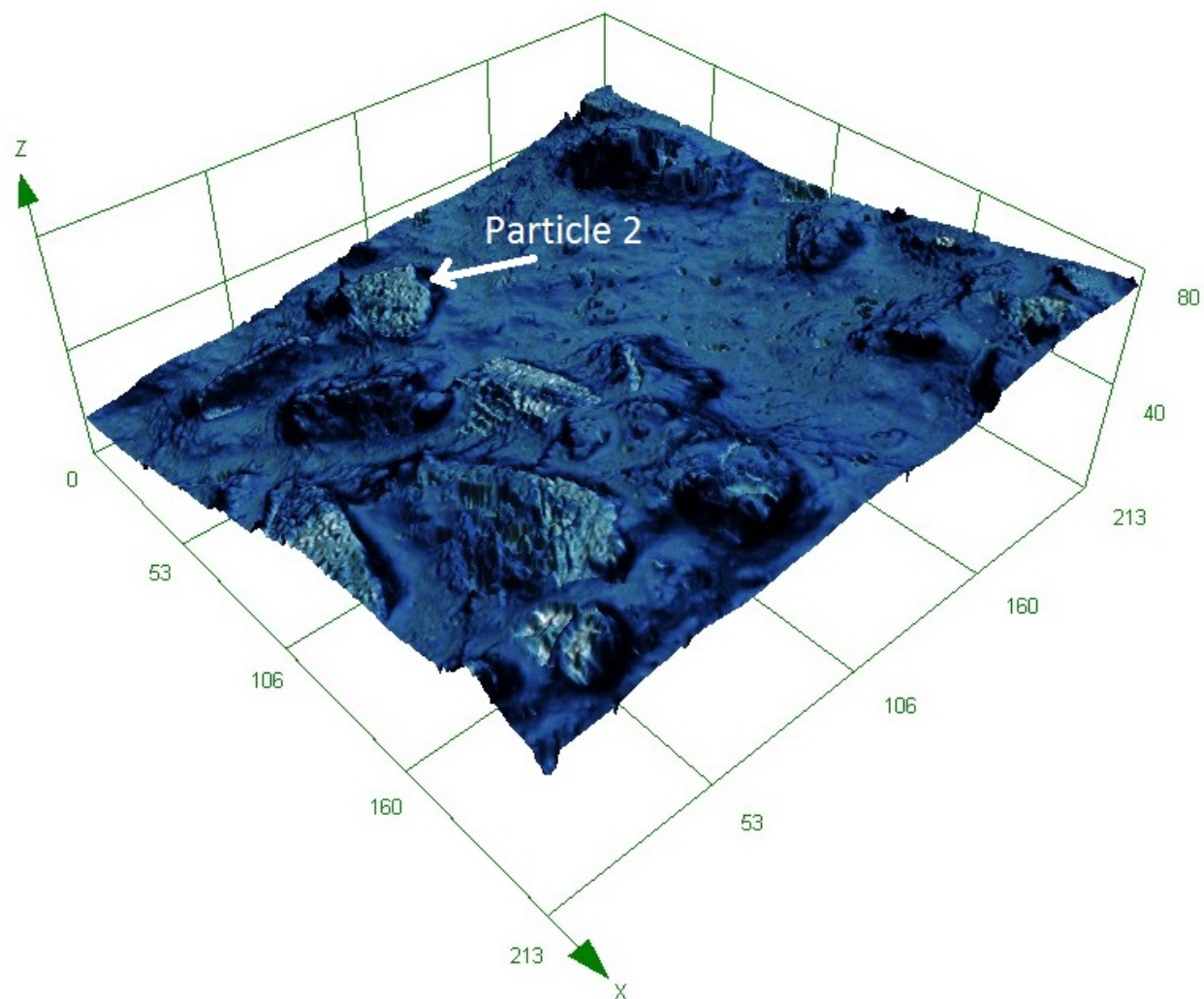
### 7.4.1 2-Dimensional lapping compound measurement



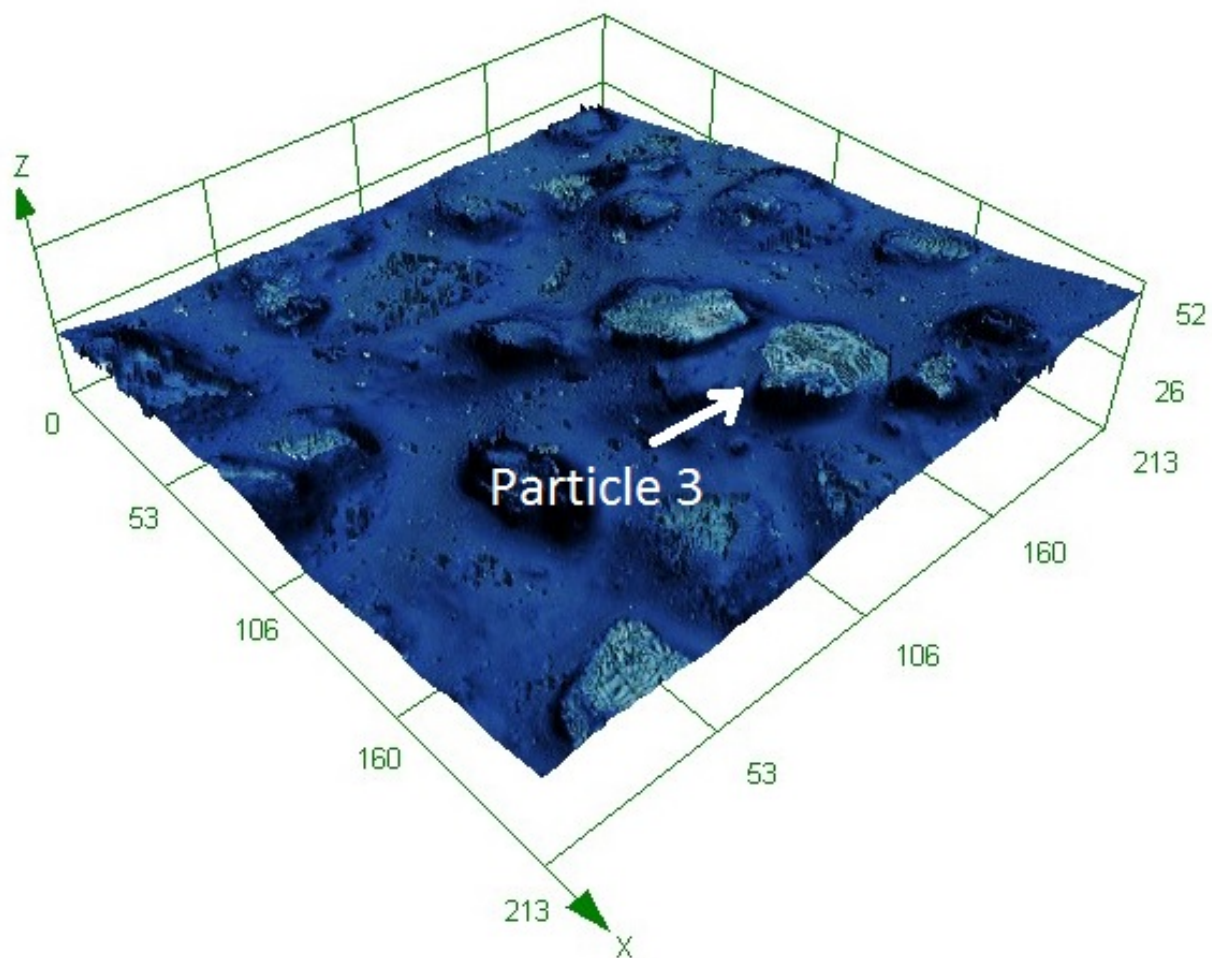
### 7.4.2 3-Dimensional lapping compound measurement



### 7.4.3 3-Dimensional lapping compound measurement



#### 7.4.4 3-Dimensional lapping compound measurement



## 7.5 Pareto Charts

### 7.5.1 Morphology

Design-Expert® Software

Morphology: average

A: Speed

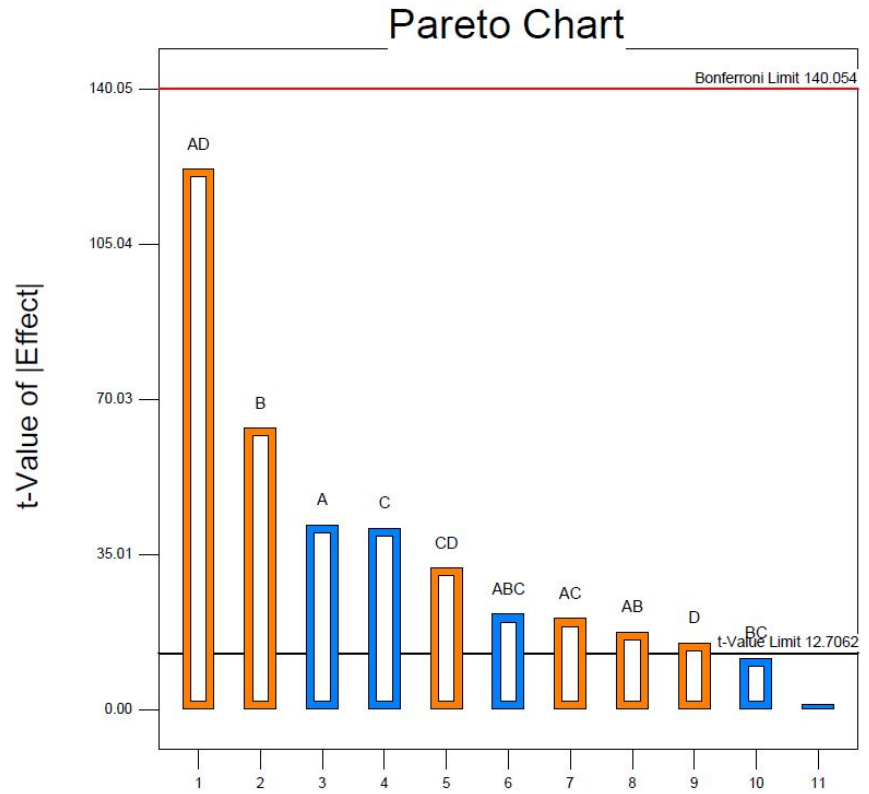
B: Bore Tilt Arm Range

C: Joint Tilt Arm Range

D: Applied Force

■ Positive Effects

■ Negative Effects

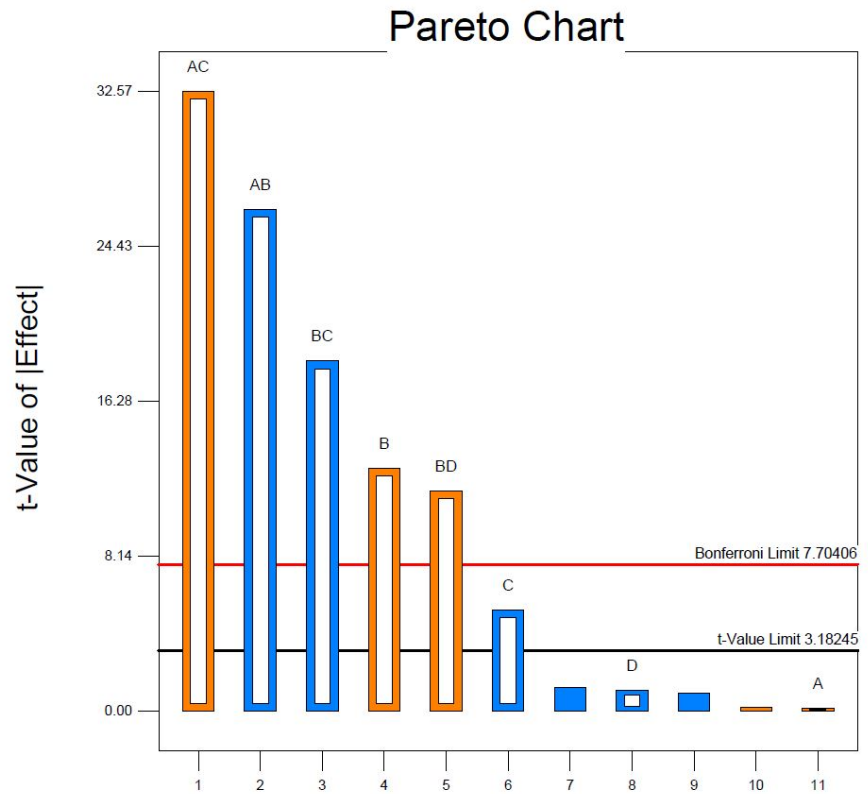




## 7.5.2 Granulometry

Design-Expert® Software  
1/Sqrt(Granulometry)

- A: Speed
- B: Bore Tilt Arm Range
- C: Joint Tilt Arm Range
- D: Applied Force
- Positive Effects
- Negative Effects



### 7.5.3 Angularity

Design-Expert® Software  
Angularity SV

- A: Speed
- B: Bore Tilt Arm Range
- C: Joint Tilt Arm Range
- D: Applied Force
- Positive Effects
- Negative Effects

