

Process Capability Studies in Heat Treatment

By

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[The normal distribution is a bell-shaped curve and is also known as the Gaussian distribution. In process capability studies if a process has six standard deviations between the process mean and the nearest specification limit]

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SUMMARY

Process capability, which is an important concept within statistical process control (SPC), describes the ability of a process i.e. a thermal process to produce components within the tolerance limits.

The purpose of this study was to identify possible methods for how to perform process capability study and temperature uniformity survey. In this essay the capability of the case hardening at continuous furnaces have been studied, considering a number of quality parameters. The outcome from these parameters described how well the process could produce components within the tolerances. The parameters of interest were case depth, core hardness, surface hardness, and surface carbon content. Practical work was done at Volvo Construction Equipment (VCE), *Eskilstuna* and Getrag All Wheel Drive AB, *Köping*. The parameters were measured from dummy test specimens in Getrag All Wheel Drive AB, and were analyzed by statistical software Minitab version 16.

Temperature uniformity surveys (TUSs) were studied for both companies according to standard AMS 2750 D. However, it was not written in it how to make analysis of temperature data. In TUSs, a datapaq with ten thermocouples were used during production from which the temperature could be logged at different positions of the stacking trays and over the entire cross-section of the furnaces. The furnace temperature was within the specified tolerances; however, the significant differences within each track from each of the furnaces were recorded. One of the furnaces was constructed with two parallel tracks while the other was constructed with three parallel tracks. It's related with the ratio of production capacity for the actual furnace, it will also give information of how the degree of production capacity is influenced by temperature uniformity.

The author recommends that both companies perform the same test next year. It is also recommended that further research should be carried out by the methodology that was utilized in this essay.

Keywords: process capability, heat treatment, statistical process control, temperature uniformity survey, analysis of variance, standard deviation

Abstract

Process capability, which is an important concept within statistical process control (SPC), describes e.g. the ability of a heat treatment process to produce components within tolerances.

In this report, the capability of gas carburizing in continuous furnaces has been studied considering a series of quality parameters. The outcome from these parameters describes how capable the process is to produce components within the tolerance limits. The parameters of interest are case hardening depth, core hardness, surface hardness and surface carbon content. These parameters are measured on dummy test samples.

In order to achieve better understanding of process capability for heat treatment processes, other parameters such as furnace temperature, furnace atmosphere or carbon potential and the quality of the steel material should also be included. If e.g. the furnace temperature is too high or too low, it will have influence on the final results.

In this project, temperature uniformity was studied in accordance with standard AMS 2750D. A Data-paq with ten thermocouples was used during the studies with which the temperatures were logged at different positions on the stacking trays and over the entire length of the furnace. The furnace temperature was within the specified tolerances, however, significant differences within each track in each of the furnaces were recorded. One of the furnaces is designed with two parallel tracks, while the other has three parallel tracks. The temperature uniformity survey will give information about how process capability is influenced by the variation of the temperature in the furnace.

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1. Introduction

The requirements and standards which are used for quality control of heat treatment process have been reinforced by the emergence of new standards. CQI-9 ^[1] (Continuous Quality Improvements) which was developed by the AIAG (The Automotive Industry Action Group) addressed to the suppliers in the automotive industry that purchases heat-processed components. AMS 2750D ^[2] is the procedure for which how a temperature uniformity measurement (Temperature Uniform Survey, TUS) should be implemented.

To achieve these requirements, there are a series of tools such as MSA (Measurement Systems Analysis) ^[3], SPC (Statistical Process Control) ^[4], APQP (Advanced Product Quality Planning) and PPAP (Production Part Approval Process) that are used. A application of these tools in heat treatment is complicated and sometimes virtually impossible, as in the case of SPC where heat treatment process would be controlled by a few parameters e.g. hardness and surface carbon content. These two parameters can be measured only after the heat treatment process is finished, thus destructive testing and wasted components are necessary. In most cases it is not enough with only examination of two parameters of the components, but several other parameters should also be included in the analysis to obtain a comprehensive view as to whether the process is under statistical control or not.

Capability studies can evaluate how well a machine or process is capable of producing components within the given tolerance limits. An effective quality management system should assure the quality of the components based on taking appropriate corrective actions and measurement results. The tools used primarily are to determine whether the machine is suitable for producing within the intended tolerance limits. Normally, it is assumed that the process outcomes are normally distributed, which is a great advantage when calculating capability indices, but calculations can also be made for other distributions. However, the normal distribution should be identified at first.

1.1. Background

Surface hardening is defined as a way of improving mechanical properties such as strength, hardness and wear resistance of components. In order to improve these properties of the component surface and maintain the toughness of the core case hardening/carburizing method is widely used.

After surface hardening processes, several parameters are measured on components. These parameters are surface carbon content (wt % C), case hardening depth (CHD), surface hardness and core hardness. Only if the parameters are within the specified tolerance limits, the batch can be approved. The measurement results of these parameters are usually subjected to variations. The process capability is the ability of a process to meet specification limits. Usually process capability is expressed by process capability indices such as Cp, Cpk, Cpm, and process performance indices Pp, Ppk and Ppm. Cp and Cpk indicate process capability indices which take subgroup sizes into account, thus using "standard deviations within", however, process performance indices Pp and Ppk which ignore the variations within subgroup but take the overall process into consideration, thus Pp and Ppk are calculated by "standard deviation overall". The differences of the standard deviation "within" and "overall", see in Section 2.3.3.

CQI-9 (Continuous Quality Improvements), ISO / TS 16949: 2002 and AMS 2750D which are the standards used for evaluation and standardizing heat treatment process, however, none of the standard describes how temperature data should be analyzed and what problems might arise and therefore should be avoided. This report addressed two different cases, one carried out at Getrag AWD AB in *Köping* and the other was performed at VCE (Volvo Construction Equipment) in *Eskilstuna*.

For capability studies in VCE, a complete analysis was carried out which consisted of process capability study and TUS (Temperature Uniformity Survey) in 2010, while at Getrag only TUS was performed in 2010 but the results from 2009 were partly presented for comparison. The sample material used at Getrag and VCE is V-2158 (Volvo Standard hardness class 60) which is a low alloy steel and the sample material is of the same chemical composition.

In process capability study, only the main furnaces were studied which did not include the complete heat treatment process. The results from test samples were compared with the set target and tolerance limits. In this project, there were a series of tools e.g. capably studies, cubes and TUS used to show how these should be applied to heat treatment for the determination of process capability.

1.2. Objectives

1.2.1. Primary Goal

The project aims at exploring the possibility of a suitable method to improve the process capability studies in heat treatment process and identifying the quality parameters that should be included in the analysis. A further aim is to try to develop a methodology for how temperature data should be analyzed in accordance with the standard AMS 2750D ^[2], which is normally used to examine the uniformity of the temperature in the stable working zone.

1.2.2. Secondary Goal

The secondary goal is to try to analyze furnaces to check if there is a problem and find out possible interactions and connections between capability parameters and mean temperatures in the stable zone. Besides, to develop a road map for future process capability studies of hardening processes is also of interest.

1.3. Delimitations

The project was defined to investigate process capability of gas carburizing process. The study does not include other hardening methods, the process change over time, nor considers input raw sample material. For temperature uniformity survey (TUS), only the main furnace is studied which refers to carburizing and diffusion zones, thus pre-oxidizing, pre-heating, oil quenching, post-washing and tempering are not investigated within this study.

2. Theoretical

2.1. Heat Treatment Processes

The definition of heat treatment from IFHTSE (International Federation for Heat Treating and Surface Engineering) is a process subjected to thermal heating (processing) and cooling with the intention of acquiring certain microstructure and properties. ^[5] The thermal heating referred in this definition covers various heat treatment steps which include stress relieving, austenitising, normalizing, tempering, quenching and tempering. According to (Gale, W.F. and Totemeier, T.C., 2004) ^[5], steel is heat treated in order to control the microstructure, change mechanical properties, release residual stresses, prevent cracking, control hardness and improve machinability of the component.

2.1.1. Case Hardening/ Carburizing

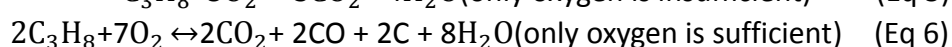
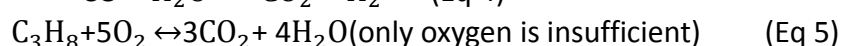
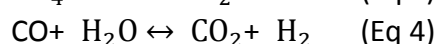
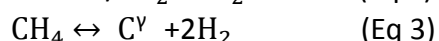
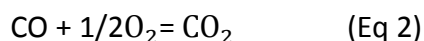
The purpose of carburizing is to obtain a high carbon content martensitic case on components, giving high fatigue resistance and wear resistance to the surface region but maintaining toughness of the core. The principle of carburizing in heat treatment process is to increase the surface carbon content of low-carbon steel by exposing it under a certain atmosphere at the temperature just above the austenitic temperature (between 850°C to 950°C). ^[6] Hardening is achieved by quenching of high-carbon surface layer in order to transform microstructures from austenite into martensite.

Generally, there are two factors that affect introduction of carbon atoms into austenite during carburizing. One is the chemical reaction that causes carbon to absorb at the surface of the steel. The other one is the diffusion from the surface to the interior of the steel. ^[7] Carbon atoms are introduced into the steel by gaseous atmospheres. In this project, gas carburizing was performed for mass production, accurately controlled and minimum special handling. The most important chemical reaction in such a furnace atmosphere is shown in Eq. 1 ^[8]



Where, C^γ is carbon introduced into austenite. The carbon ratio of CO and CO_2 gives a certain level of carbon in the austenite at equilibrium condition of the reaction. If the CO content in the atmosphere exceeds the partial pressure required to maintain the given carbon content, the reaction above will leftward shift and carburizing will occur until a new equilibrium reached ^[8]. This method is mainly used for increasing the carbon content of low carbon steels to a higher desired value. On the contrary, if CO_2 content in the atmosphere exceeds a certain value, then the

reaction above will rightward shift to achieve a new equilibrium condition. During this reaction decarburization will occur. That is to say, the amount of C^γ in the reaction above will decrease. The latter case can be used during heat treating process when the carburizing exceeds from a set value, thus reducing the carbon content in the steel is needed, for example from 1.3 wt% C to 0.8 wt% C. In diffusion step, the initially high carbon content in the austenite immediately adjacent to the surface diffuses into the interior to produce deeper case. ^[7] Except for the CO, CO₂ reactions, other reactions will occur involving CH₄, C₃H₈, H₂, H₂O and N₂. These reactions are:



Generally, methane (CH₄) can only achieve carbon potential at a value lower than 0.8wt% C, therefore propane (C₃H₈) is added for higher carbon potential purpose.

2.1.2. Quenching

Quenching is described as the rapid cooling of the steels to transform microstructure from austenite into martensite. Generally, quenching could give cooling rate high enough to avoid the formation of soft phases e.g. pearlite or bainite. The hardness of the component is improved mainly because of the transformation from austenite to martensite. The cooling rate at which the hardness achieves the highest value is called critical cooling rate and this is probably due to the maximum transition of martensitic phases which is the hardest phase in the steels. However, in practical production, the cooling speeds for the outer and inner part of a component are not the same. In other words, the surface has already cooled down but the core still stayed at a relatively high temperature during quenching. The consequence is that the hardness is not uniform from the surface to the interior part.

The hardness is a function of quenching rate, and there are two approaches to overcome lack of through hardening. The first method is by introducing higher amount of alloy elements. The second way is by increasing the quenching speed (cooling rate). According to Nyborg (2009) ^[9], by introducing certain alloy elements such as Cr, Ni and V often put off the transition of pearlite and bainite and decreases MS (martensite starting transition temperature) on the surface which can affect hardness and mechanical properties of the component, however he also mentioned that some alloys are rare elements that are expensive and can also decrease the machinability and formability of the steels during cutting and forging. ^[9] The other way of changing the cooling speed is by choosing a proper type of quenchant. ^[5] Cooling generally occurs in three distinct stages are shown in Figure 1.

They are:

- The first stage: “Vapor blanket effect” is caused by a thin vapor film of the component surface and heat transfer is hindered by the vapor thus giving a relatively slow cooling rate.
- The second stage: “Nucleate boiling stage” occurs when the vapor film collapses and the hot metal surface is directly in contact with the quenchant, thus in this stage high cooling rate is achieved.
- The last stage: Convective cooling stage, the stage with decline cooling rate and heat is removed by heat convection to the quenchant.

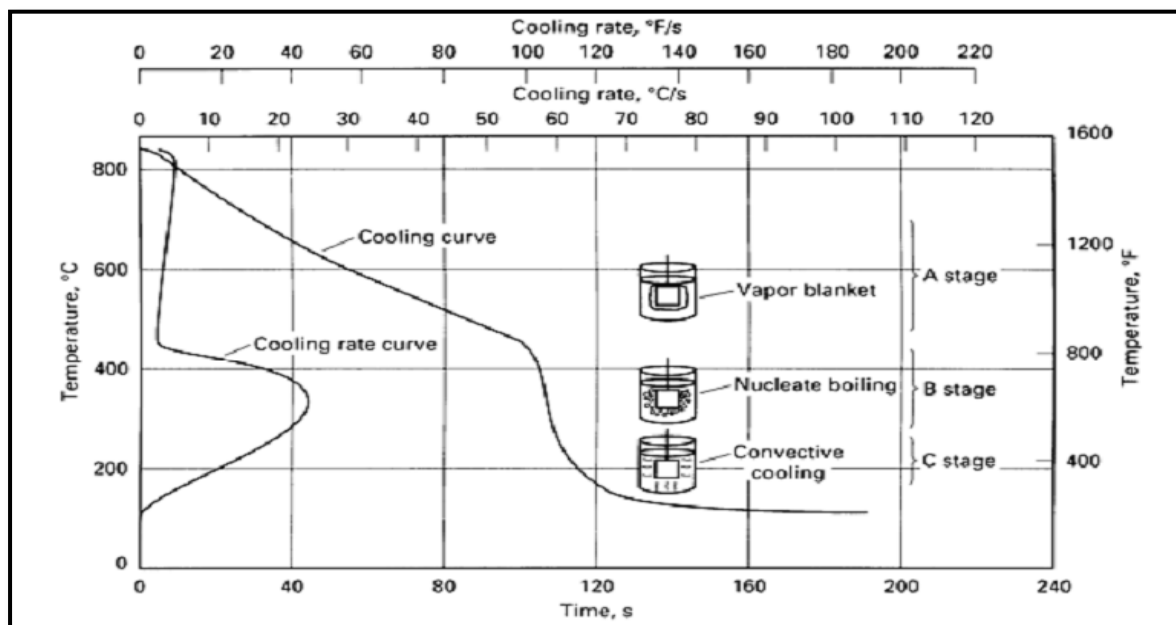


Figure 1 Three Stages of heat removal during quenching in liquid [9]

2.1.3. Causes of Variations

Douglas C. M. (2009, pp.64)^[10] states that “Variation surrounds us. No two units of product produced by a process are identical”. If you buy two bottles of Coca Cola, you may not get exactly the same volume, and the height of a Cola varies from time to time to a certain extent. Statistics is an art of analyzing data and drawing conclusions, taking variations of the data into account.^[11] The existence of variation makes it imperative to use statistical process control (SPC) of process. In general, there are two types of variations. They are: a common cause variation which is inherent in a process and always present. The other is a special cause variation that refers to unusual cases of variation that are not a typical part of a process. However, not all special causes are detrimental to a process, some of them are beneficial.

There are many causes that have influences on the final results, such as manpower, machine, methods and materials, etc. The cause-and-effect diagram is an informative

way for illustrating various causes of failures. Figure 2 shows the possible causes of variation which result in failure to satisfy customer's requirements. There are four aspects used which can lead to dissatisfaction of the customers. They are: manpower, machine, method and materials. Each division has many sub-divisions, e.g. the factor of method used for statistical analysis whether is correct or not, the way of collecting data and the behavior of the data.

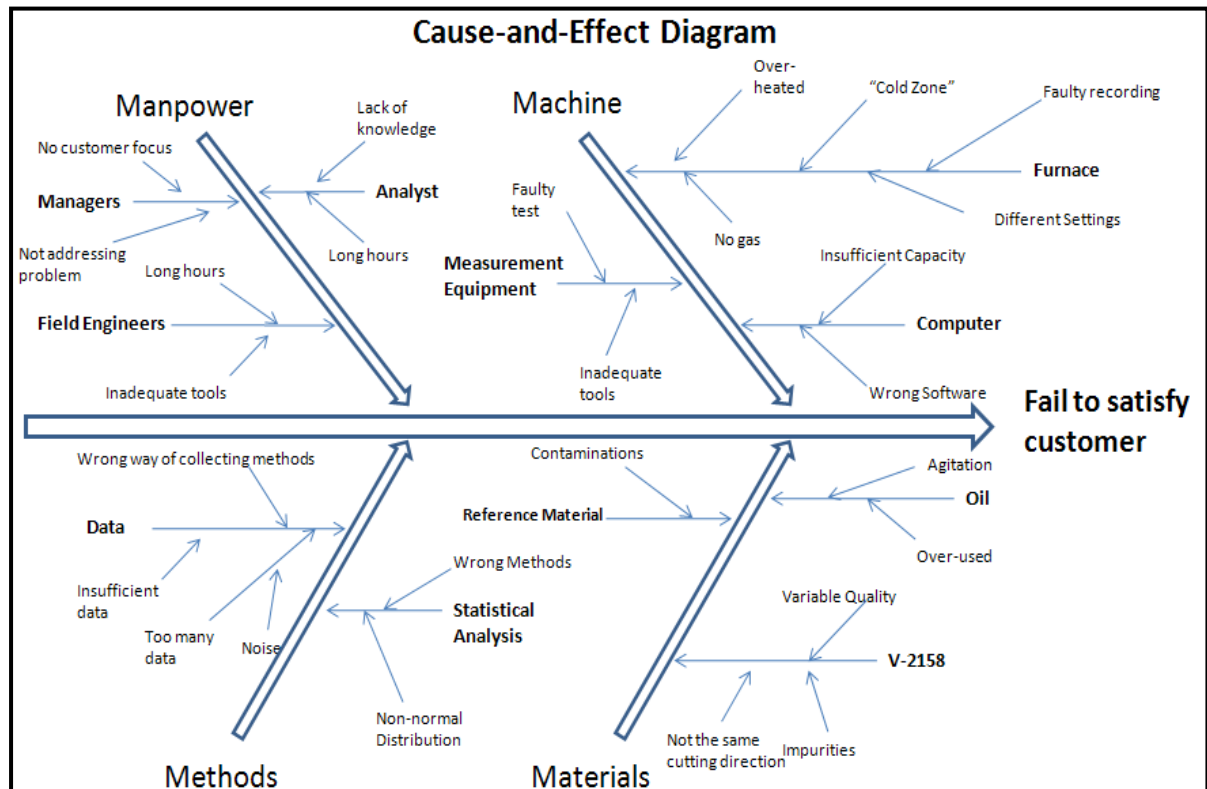


Figure 2 Cause-and-Effect Diagram

2.2. Investigated Heat Treatment Parameters

For quality control of heat treated products several parameters are used. The parameters used in this project are case hardening depth (CHD), surface carbon content (wt% C), surface hardness and core hardness.

2.2.1. Case Hardening Depth (CHD)

Case hardening depth can be defined in different ways e.g. the depth to a given hardness value, or the depth at which a certain carbon content is achieved.

According to *Volvo Standard (STD 1094, 1)* ^[15], case depth is defined as the depth at which 550 Hv1 is exceeded from hardness curves. Case depth is an important parameter in heat treatments since it can be correlated to the mechanical properties of the surface-hardened steel components. Figure 3 illustrates the hardness profile of case hardened steel of V-2158 and how case depth is determined from hardness profile.

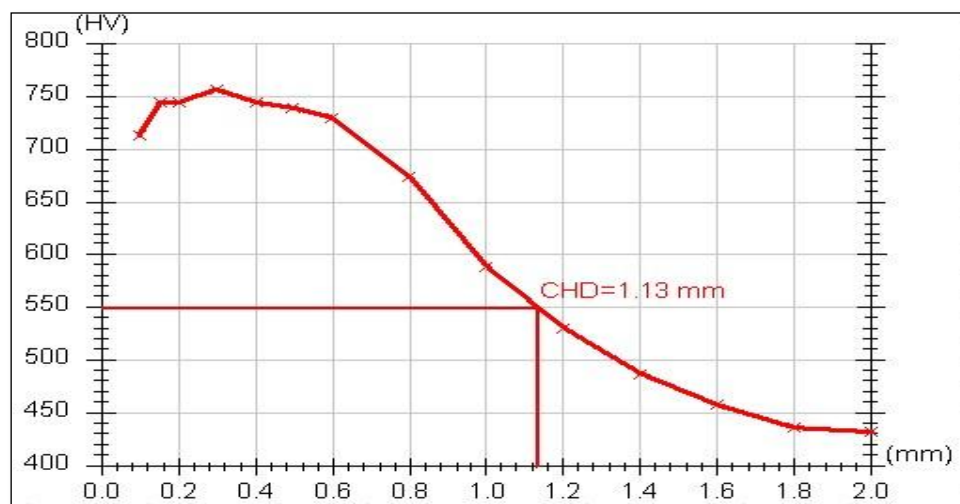


Figure 3 Example of Hardness profile and case depth (CHD); CHD=1.13mm with Hv 550

2.2.2. Surface Carbon Content

Before surface carbon content measurement, all samples are heated in a small oven at temperature around 550°C for 1 hour followed by air-cooling to soften hard surface and improve machinability, and then the samples are polished manually with polishing paper in order to eliminate undesirable surface defects. After that lathe turns on sample at three depths (0.15 mm in three steps, 0.25 mm in three steps, and 0.4 mm in 4 steps). The total cut is 2.8 mm in diametrical direction, and metal chips are collected for chemical analysis. The equipment for analysis is *Leco*, and before measurement the equipment is calibrated with reference materials. Surface carbon content is based on the chips from the first cut.

2.2.3. Surface Hardness

Surface hardness is measured by equipment *Indentec* by HRC 150kgf load (Hardness Rockwell C) at Getrag. Before measuring hardness on sample surface, the samples are polished manually with polishing paper in order to remove unknown surface contaminates such as oxides which could affect test results. The polishing depth is approximately less than 20 μm . Then each sample is tested three times and the distance from neighboring indentations is more than 2 mm to eliminate influences, see in Figure 4. Mean values are calculated by equipment automatically.

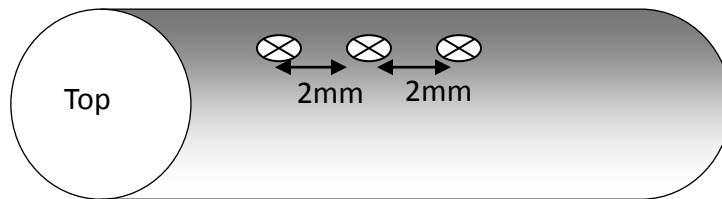


Figure 4 Surface hardness indentation positions

2.2.4. Core Hardness

Core hardness is measured by equipment *Matsuzawa VMT7* using *HV30* (Hardness Vickers 30 kg) at Getrag. For each sample, three indentations are made and then a mean value is calculated for each sample. The hardness is measured at depth of 6 mm from the surface and neighboring two indentations are approximately 120 degrees around the center of the sample rods, see in Figure 5.

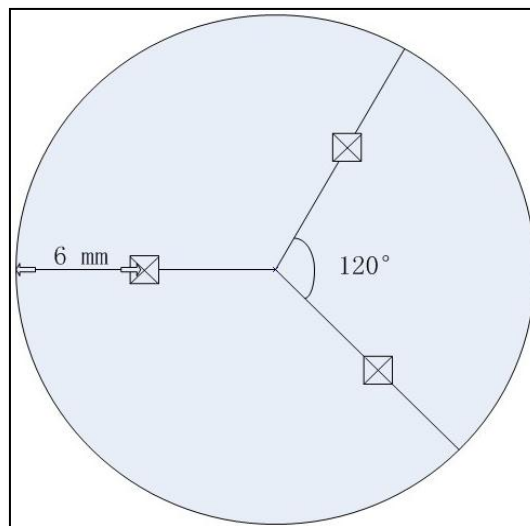


Figure 5 Position of each indentation on the sample for core hardness measurement

2.3. Process Capability Studies

2.3.1. Statistical Software Minitab

Statistical Minitab is kind of software for statistical analysis and quality improvement. In this project, Minitab version 16 is applied for implementation of Six Sigma Quality Tools and Analysis of Variance. The diagrams such as histograms, probability plots and box plots are plotted in software for better illustration and visualization of numeric data.

2.3.2. Standards (ISO TS 16949: 2002, CQI-9, AMS 2750D)

In this project, ISO TS 16949: 2002, CQI-9 and AMS 2750D are used to standardize process capability study. The standard describes the requirements for quality assurance of e.g. heat treatment processes and the equipment to be used at processes requiring controlled temperature, furnace atmosphere and heating time, etc. Some of the standards also define requirements for instrumentation checks and temperature uniformity survey tests.

CQI-9^[1] specifies the process requirements and is applied for continual improvement, emphasizing defect preventing, the reduction of variations and waste in the supply chain.

AMS 2750D^[2] (Aerospace Materials Specification) covers pyrometric requirement for thermal processing equipment used for heat treatment operations. It covers temperature sensors, instrumentation, thermal processing equipment and how to performance TUS (temperature uniformity survey). These are necessary to ensure that components are heat treated in accordance with the applicable procedures.

2.3.3. Process Capability Indices

Process capability is the ability of process to produce components that meet specification limits determined by e.g. customer's requirements. Capability indices, such as Cp, Cpk, Pp, Ppk and Cpm, estimate how capable the process is and compare the capability before and after improvement. For process capability studies, the process must meet two requirements. The process must be stable and the output data must follow a normal distribution.

Process capability index Cp measures how capable the process is to satisfy specification limits by using the "within subgroup variation" which analyzes the shifts and drifts within subgroup. Higher Cp value, more capable the process is. Many companies use 1.33 as benchmark value to determine whether the process is OK or not. If $1.33 < C_p < 1.67$, it means the current process is OK, and if $C_p > 1.67$ which indicates the process is quite good and no need for improvement. On the contrary, if

1.0<Cp<1.33, correction is needed for future improvement.

Process performance index Pp considers the “overall subgroup variation” of the process that takes into account of the shifts and drifts between subgroups, therefore Pp uses “standard deviation overall”. If calculating just Cp and Pp indices from process is insufficient because they compare the process spread with the specification limits without how far from the target, therefore, Cpk and Ppk are used.

Like index Cp, Cpk is using “standard deviation within”, which measures the distance of the process mean to the tolerances. Cpk equals to the lesser of CPL and CPU which estimates the distance of the process average to the lower and upper specification limits, respectively. Process performance index Ppk takes “overall” variance from process into account, which measures the distance of process average to the tolerance limits. Ppk equals to the lesser of PPU and PPL which is similar to CPL and CPU. 1.33 is used as benchmark value in most of cases. The drawback of Cpk and Ppk is that both of indices only consider one side of tolerance (USL/LSL) without the other (LSL/USL). Therefore, Taguchi index Cpm is introduced, which determines whether the process meets tolerances and is on target. The ideal Cpm value is of 2.0 right stay on the target, however, 1.33 is a common value for most companies. The formulas below represent how those indices are calculated in software Minitab.^[12]

$$Cp = \frac{(USL - LSL)}{(6 * \sigma_{Within})}$$

$$CPU = \frac{(USL - \mu)}{(3 * \sigma_{Within})}$$

$$CPL = \frac{(\mu - LSL)}{(3 * \sigma_{Within})}$$

$$Cpk = \text{minimum}\{CPU, CPL\}$$

$$Pp = \frac{(USL - LSL)}{6 * \sigma_{Overall}}$$

$$PPU = \frac{(USL - \mu)}{3 * \sigma_{Overall}}$$

$$PPL = \frac{(\mu - LSL)}{3 * \sigma_{Overall}}$$

$$Ppk = \text{minimum}\{PPU, PPL\}$$

$\hat{C}_{pm} = \frac{(USL - LSL)}{6 * \sqrt{\frac{\sum (x_i - T)^2}{(n - 1)}}}$	when LSL and USL are given, and T=m
$\hat{C}_{pm} = \frac{\min(T - LSL, USL - T)}{3 * \sqrt{\frac{\sum (x_i - T)^2}{(n - 1)}}}$	when LSL and USL are given, and T≠m
$\hat{C}_{pm} = \frac{(USL - T)}{3 * \sqrt{\frac{\sum (x_i - T)^2}{(n - 1)}}}$	when USL and T are given
$\hat{C}_{pm} = \frac{(T - LSL)}{3 * \sqrt{\frac{\sum (x_i - T)^2}{(n - 1)}}}$	when LSL and T are given

Where,

- T= Target
- LSL= Lower Specification Limit
- USL=Upper Specification Limit
- μ = Process Mean
- m= midpoint of USL and LSL
- StDev= standard deviation
- σ_{Within} = within subgroup process standard deviation
- σ_{Overall} =overall process standard deviation
- n = total number of observations
- “Within” standard deviation (σ_{Within}) can be estimated from control charts by $\frac{\bar{R}}{d_2}$.
- \bar{R} is average range R and $R = R_{\text{Max}} - R_{\text{Min}}$ (within subgroups).
- d_2 is a constant that varies with subgroup size.
- “Overall” standard deviation $\sigma_{\text{Overall}} = \sqrt{\sum_i^n \frac{(x_i - \bar{x})^2}{n-1}}$, where x_i is an observation and \bar{x} is the mean value of all observations, and n is the total amount of observations.

To compare the variation between “within” and “overall”, see in **Appendix A: Within- and Overall- subgroup Variation**.

2.4. Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) considers the variations from more than 3 levels of one single factor by comparing means to evaluate the significance. One-way ANOVA examines the equality of sample means when classification is by one variable.^[12] The factor which affects the responses or quality parameters refers to Track, Position, Upper/Lower level of the stacking tray (furnace), Fully/Empty loaded furnace condition and Inner/Outer part of the furnace. The responses which are described as component quality parameters e.g. surface hardness, core hardness, case depth and surface carbon content. The response is a result or consequence of the factor. For example, the influence of loading conditions on surface carbon content is included in this report. One-way ANOVA takes into account of one factor's influence on single response. However, in reality the response is affected by various factors in order to analyze more than one factor, multi-vari chart is applied in the report.

In Minitab, the sources of variations, the degree of freedom, the total sum of squares, the mean squares, F-tests and P-values are shown in software Minitab session window, see in Figure 6.

- Source - indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.
- DF - degrees of freedom from each source. If a factor has three levels, the degree of freedom is 2 ($n-1$). If you have a total of 30 observations, the degrees of freedom total is 29 ($n-1$).
- SS - sum of squares between groups (factor) and the sum of squares within groups (error)
- MS - mean squares are found by dividing the sum of squares by the degrees of freedom.
- F - calculate by dividing the factor MS by the error MS; You can compare this ratio against a critical F found in a table or you can use the p-value to determine whether a factor is significant.
- P - use to determine whether a factor is significant; Typically compare against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant.

Figure 6 Some Statistics in session window in Minitab [12]

All of these statistics are used to analyze whether the factor has significant influence on the response.

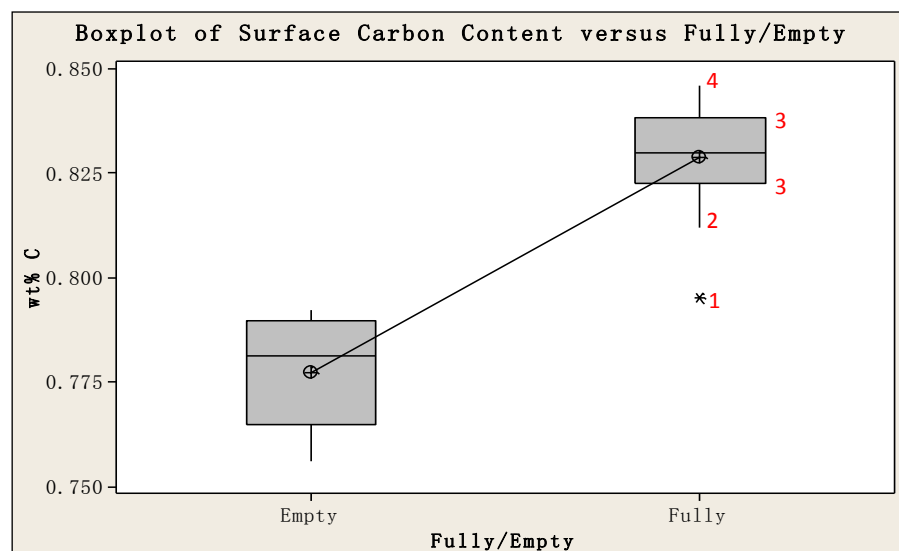
In One-way ANOVA, pooled standard deviation is used for showing all independent data when they are supposed to have a common standard deviation. The pooled standard deviation is the mean spread of all data with their group mean. The value is based on the weighting of larger groups because of its larger influence on the overall estimate.^[12]

Here introduce an example to study four groups from Software Minitab:

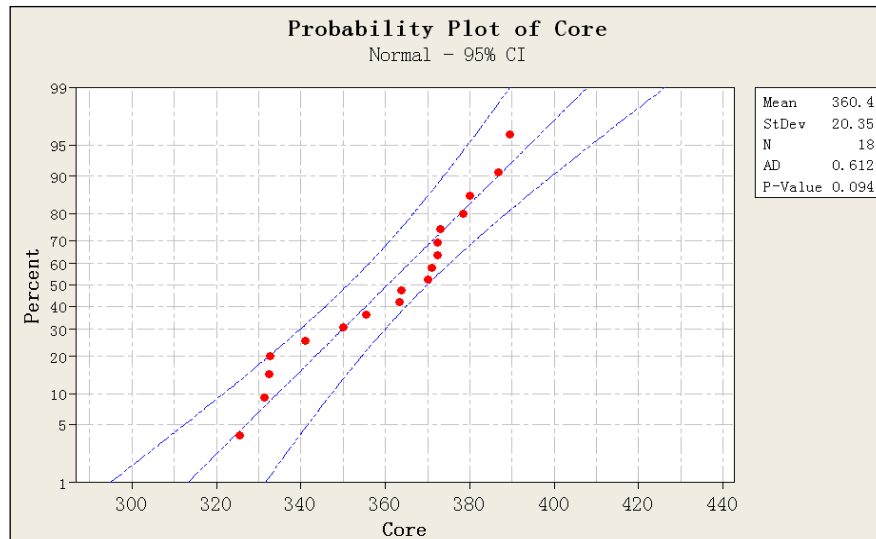
- Observations A (Mean=9.7, StDev=2.5 N=50)
- Observations B (Mean= 12.1, StDev=2.9 N=50)
- Observations C (Mean=14.5, StDev=3.2 N=50) and observations D (Mean=17.3, StDev=6.8 N=200).

The pooled standard deviation is 5.486 because it takes a weighted average which is closer to a larger group size. ^[12]

Except for statistical methods mentioned above, graphs such as box plots, probability plots and multi-vari charts are also used. Box plot is a rectangular box as showed in Figure 7 (a) used to summarize the distribution of the data by the position of three horizontal lines, height of the box and tail (whisker). The asterisk * 1 represents outliers that is beyond the lower straight line 2 (whisker) and upper straight line 4. Whisker lines (line 2 and 4) represent “the maximum data point within 1.5 times the box height from the bottom” or “the minimum data within 1.5 times heights from the top”. The length of whisker represents the scale of skewness. The three lines in the box from the bottom to the top are the third quartile line (Q3 line) which means 75% of the data are less than or equal to this value. Median line refers to the 50% of the data that are less than or equal to it, and the first quartile line (Q1 line) which means the 25% of data are less than or equal to this value. The box height equals to the distance from Q3 to Q1. If the median line is not centered in the rectangular box, the distribution is skewed. Larger of the box, higher the spread is.



(a) Box plot; [12]



b) Normal Probability plot; [12]

Figure 7 (a) Box plot; b) Probability plot [12]

Probability plot is a graph used to determine whether the data fit to a distribution or not. The middle straight line refers to the fitted distribution line and the curved lines represent 95% confidence intervals. P-value evaluates whether the distribution is normal or other distributions e.g. Weibull or Exponential, see in Figure 7 (b). P-value usually is chosen as 0.05. If the p-value from statistic is more than the level of significance ($\alpha=0.05$ or 0.1), it would lead to not rejecting the null hypothesis. In this project, level of significance values is always set as 0.05.

A hypothesis test is used to determine the validity of the statement that either equals to or non-equal to a desired value. Generally, there are two statements about hypothesis test. One is the null hypothesis H_0 which describes the statement such as hardness, case depth or surface carbon content is equal to a desired value. The other is the alternative hypothesis H_1 which states the parameters are not equal to in the null hypothesis. No rejecting the null hypothesis means the parameter is equal to a set value. Rejecting means the parameter either more than or less than the set value.

Multi-vari chart presents ANOVA data in an easy way to study possible interactions between factors and root causes for variations. In Minitab, the responses are chosen as surface hardness, core hardness, case hardening depth, surface carbon content and mean temperature values. Factor investigates the effects on the response variables. For instance, we need investigate factors that could affect hardness during the process. The following should be determined in the experiment:

Factor	Track	Position	Loading
A	1	2	Empty loaded
B	3	2	Empty loaded

Then, the influence of Track on hardness is shown in multi-vari chart.

3. Experimental - Results

3.1. Heat Treatment Furnaces and Experimental Setup

3.1.1. Furnace at Getrag

The furnace at Getrag All Wheels Drive AB was *LoI* with double tracks in the main heating chamber. The electrical heating elements were located in the roof and the bottom of each track. According to AMS 2750 D ^[2], the furnace class is FIVE which means the working temperature is within $910 \pm 14^\circ\text{C}$. The furnace was divided into three zones with feed rate at 13 min/position, however, there are no clear separations between the different zones. The first zone is heating zone. The second and third zones are carburizing and carburizing/diffusion zones, respectively. For carburizing zone and diffusion zones the temperature is 910°C with the carbon potential of 0.8 wt% C.

The measurement of quality parameters are derived from 9 specimens attached per track. Totally 18 dummy samples are attached on a fixture at different positions as shown in Figure 8. For samples on track 1, they are marked from 11 to 19. For samples on track 2, they are marked from 21 to 29. Note that both process capability studies and TUS were performed at Getrag in 2009, but only TUS was made in 2010. For temperature uniformity survey (TUS) in 2010, the furnace was tested one per track per day. The temperature was logged every five seconds by thermocouples (TCs) that located at different positions of the stacking tray, see in Figure 9.

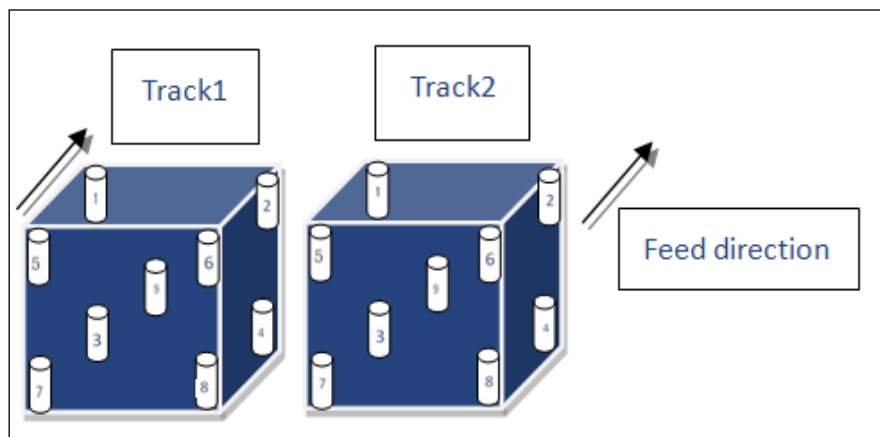


Figure 8 Samples attached on stacking trays at different positions (Getrag 2009)

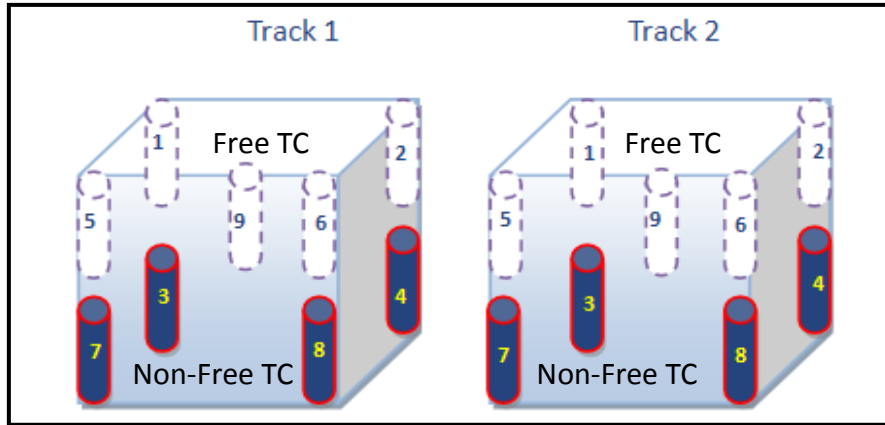


Figure 9 Positions of the TCs during TUS from track 1 and 2 (Getrag 2010)

Totally, there are nine thermocouples (TCs) per track which could be divided into two groups, Free and Non-free type. In upper level of the stacking tray, four TCs are located at each corner and TC 9 is attached in upper center of the stacking tray, which is used for logging the temperature in atmosphere of the furnace. At lower position, four samples are attached on the stacking tray with drilled holes (3 mm) in the center, which are prepared for TC probes (2 mm) to measure the temperature inside of samples.

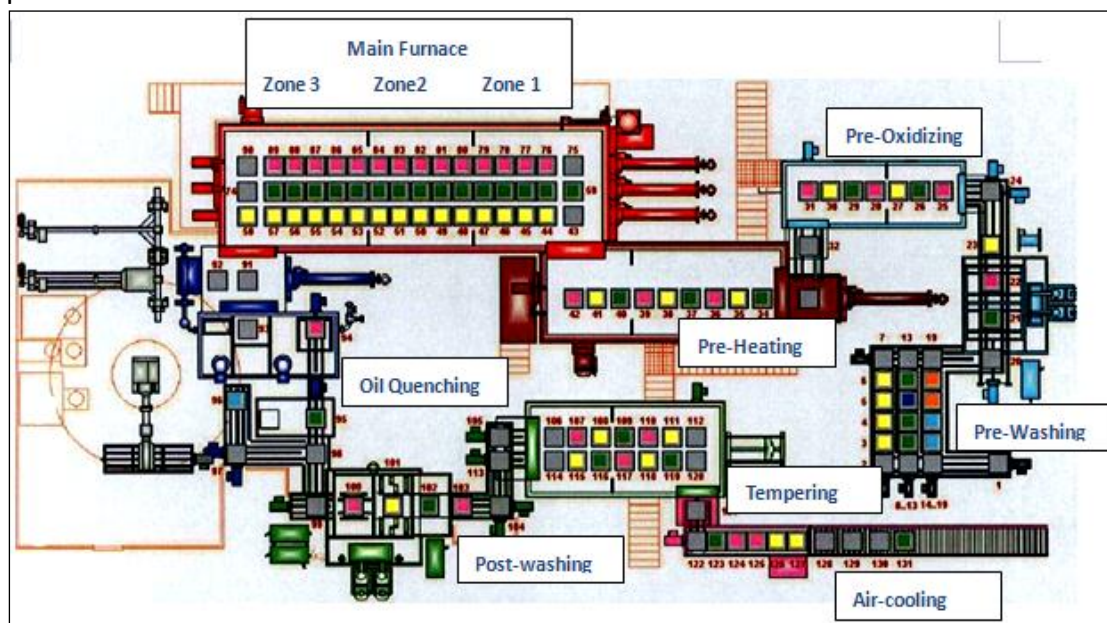
3.1.2. Furnace at Volvo CE

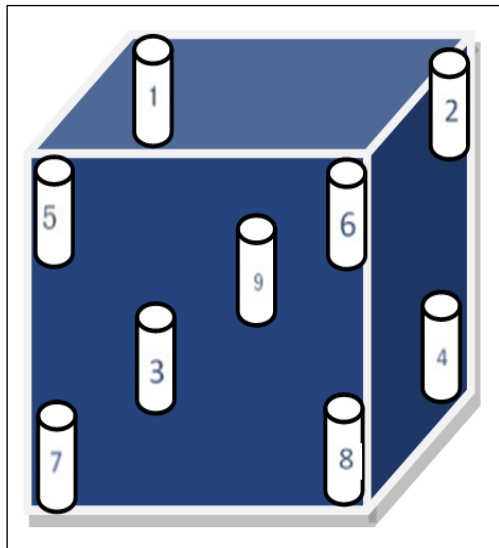
The type of the pusher furnace at Volvo CE is *Aichelin* which is a continuous furnace with three tracks parallel to each other in the main heating chamber. The electrical heating elements are located in the roof of the main furnace. The pusher in the furnace pushes the stacking trays automatically and continuously from one position to the next. There are three zones in the main working chamber. They are carburizing zone 1 & 2 and diffusion zone 3 with set working temperature of 925°C, 925°C and 860°C, respectively. However, there are not distinct separations between three zones. The sample material used for tests is V-2158 (Volvo standard hardness class 60). The samples are manufactured into cylinder shape with length of 120mm±0.5mm and diameter of 25±0.03mm.

The heat treatment process in VCE consists of various steps which are presented as follows; pre-washing at the temperature of 75 °C, pre-oxidizing at 400°C, pre-heating at 900°C at zone 1 and 925°C at zone 2, then all three tracks are moved into the main furnace, followed by oil quenching at 100°C, tempering at 160°C and finally cooling in air to room temperature. The studies only includes the carburizing and diffusion zones in the main furnace, thus pre-washing, pre-oxidizing, pre-heating, oil bath, post-washing and tempering are not considered in this report.

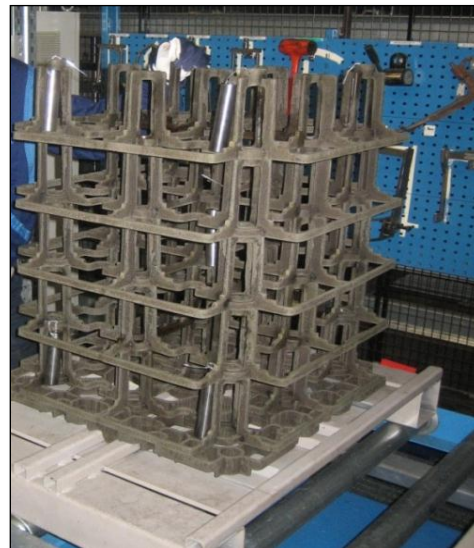
In VCE, methane (CH₄) gas is added in three zones as mentioned above, but only propane (C₃H₈) gas is added in carburizing zone one in order to keep carbon

potential at 0.82 wt% C.





a) Dummy samples on fixture



b) Dummy samples on-site

Figure 11 Fixture, samples and track lane (VCE 2010)

For temperature uniformity survey (TUS), track 1 and 3 were investigated in 2010. According to AMS 2750D ^[2], ten thermocouples are used per track which is slightly different from Getrag's measurement. Thermocouple (TC) 9 is fixed freely in the furnace atmosphere beside TC 8 in order to record the temperature of outer sample, see in Figure 12.

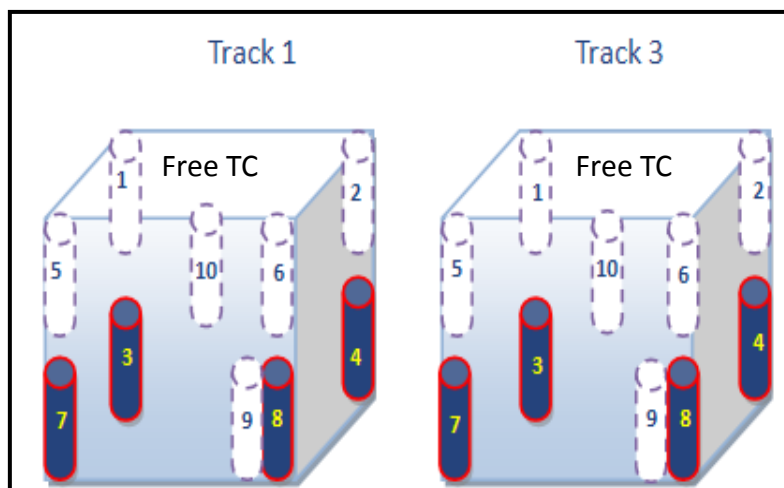


Figure 12 Thermocouples positions on stacking trays. For position 3, 4, 7 and 8, thermocouples were inserted within test samples (VCE 2010)

3.2. Case Hardening Depth (CHD)

3.2.1. Getrag All Wheels Drive AB

Heat treated samples from the Getrag's furnace were measured by three hardness profiles per sample at Getrag in 2009.

Case hardening depth is determined at the depth where hardness value is at HV 550. Measurement results for track 1 and track 2 are shown in Table 1 and 2 below. In order to better recognize the fact that the case depth from each position on each track, case depth cubes are shown in Figure 13.

Table 1 Measured case depth of track 1 [13]

Track	Position	Measurement 1 (mm)	Measurement 2 (mm)	Measurement 3 (mm)	Mean(mm)	Mean of CHD
1	1	0.80	0.79	0.78	0.79	-
1	2	0.82	0.82	0.82	0.82	-
1	3	0.79	0.80	0.83	0.81	-
1	4	0.80	0.80	0.81	0.80	-
1	5	0.79	0.78	0.79	0.79	-
1	6	0.78	0.77	-	0.79	-
1	7	0.77	0.77	0.77	0.77	-
1	8	0.79	0.80	0.78	0.79	-
1	9	0.78	0.79	0.80	0.79	-
						0.79

Table 2 Measured case depth of track 2 [13]

Track	Position	Measurement 1 (mm)	Measurement 2 (mm)	Measurement 3 (mm)	Mean(mm)	Mean of CHD
2	1	0.79	0.78	0.77	0.78	-
2	2	0.81	0.80	0.79	0.80	-
2	3	0.81	0.84	0.82	0.82	-
2	4	0.81	0.80	0.79	0.80	-
2	5	0.77	0.77	0.77	0.77	-
2	6	0.79	0.79	0.81	0.80	-
2	7	0.80	0.79	0.81	0.80	-
2	8	0.78	0.79	0.77	0.78	-
2	9	0.80	0.80	0.80	0.80	-
						0.79

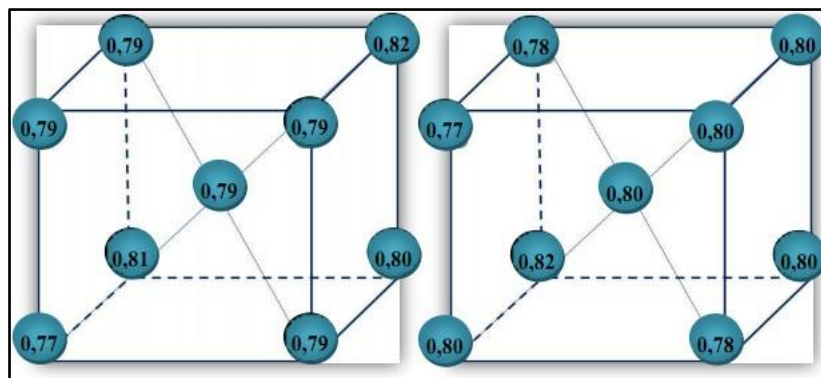


Figure 13 Case depth cube of (Left) track 1; (Right) track 2 [13]

The target value is set at 0.8 mm with tolerance limits $\pm 0.1\text{mm}$, which gives USL=0.9 mm and LSL= 0.7 mm. The recommended minimum sample size for normality test is 15, and if the sample size is less than 15, the result from the normality test can be questionable. Since track 1 and 2 are tested under the same condition (heated at the same time), combine both data and analyze them together. Before combination, a 2-sample t-test should be made to prove the validity.

A 2-sample t-test is made to examine whether or not there is a significant difference between the two groups of data. After the tests, p-value is 0.950 (which is more than level of significance $\alpha=0.05$), which means that there is no significant difference between the mean values for each track, thus analyzing them together is possible.

Before capability indices calculation, case hardening depth data are investigated to examine whether the data are normally distributed or not. The results are shown in the Table 3 which turns out to have a p-value higher than 0.05, and thus normally distributed (95% confidence interval and $\alpha=5\%$).

Table 3 Normality test of the case depths for track 1, track 2 and track 1&2[13]

Track	Sample N	Distribution	P-value	Mean(mm)	StDev
1	9	Normal	0.630	0.794	0.013
2	9	Normal	0.151	0.794	0.016
1&2	18	Normal	0.840	0.794	0.014

Table 4 Capability analyses of the case depth for track 1, track 2 and track 1&2[13]

Track	Sample N	Pp	Ppk	Cpm	Target	USL	LSL
1	9	2.48	2.34	2.28	0.8	0.9	0.7
2	9	2.01	1.97	1.94	0.8	0.9	0.7
1&2	18	2.33	2.20	2.15	0.8	0.9	0.7

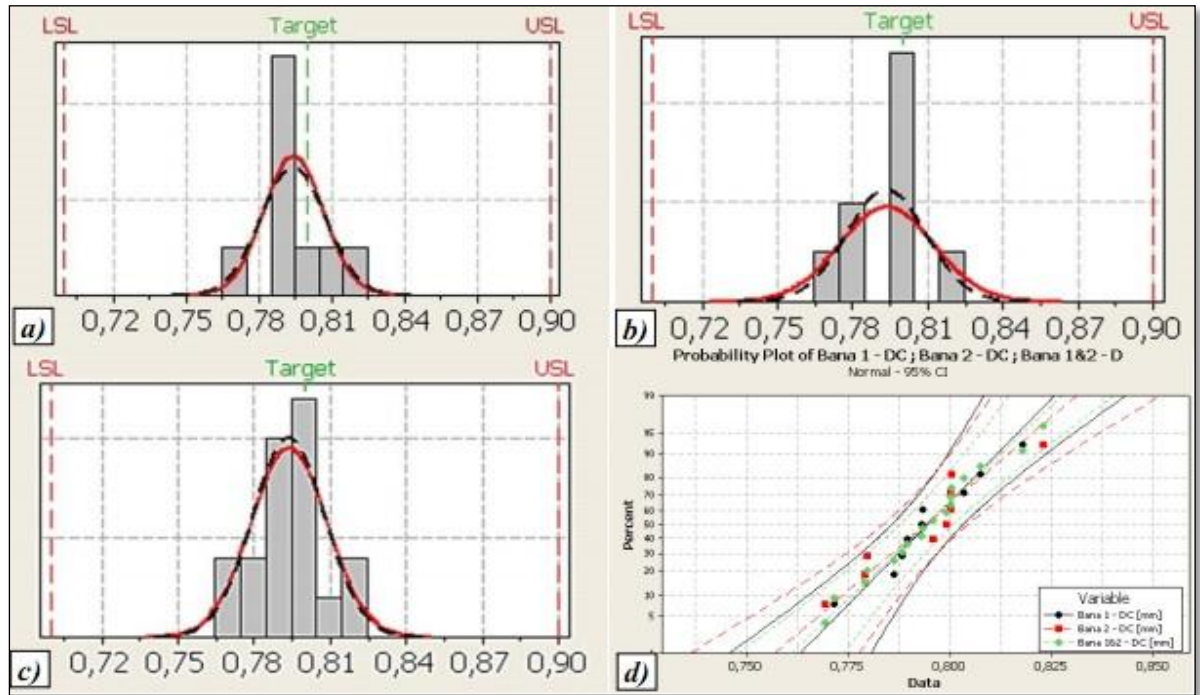


Figure 14 Capability histograms for case depth a) track 1; b) track 2; c) track 1&2; d) normal probability plot of track 1, track 2 and track 1&2 [13]

The analysis of Pp, Ppk and Cpm shows that the capability of the furnace is good and is performed within specification limits, see in Table 4 and Figure 14. For track 1, track 2 and track 1&2, they all achieve high PP values which mean that the process is capable of meeting with tolerances. Ppk and Cpm values indicate that the case depth is well-centered on the target. Track 2 shows the highest Pp value with wider spread but lowest Ppk and Cpm values if compared to other cases. This could be due to the number of specimens are too few to obtain sufficiently good results but there might be other causes, and therefore it is important to examine and compare with the other parameters such as surface hardness, core hardness and surface carbon content from the tests.

3.2.2. Volvo Construction Equipment AB

After heat treatment, case hardening depth (CHD) was estimated from one hardness profile (HV1) per sample at laboratory of Getrag in 2010. The measurement results are presented in Table 5 below. For capability study, the target value is 0.95 mm with the upper and lower specification limits at 1.10 mm and 0.80mm, respectively.

Table 5 Case depth of a) Track 1; b) Track 2; c) Track 3 (VCE 2010)

a) Track 1

Track	Position	Case Depth (mm)	Mean(mm)
1	1	1.13	-
1	2	1.15	-
1	3	1.16	-
1	4	1.05	-
1	5	1.14	-
1	6	1.13	-
1	7	1.02	-
1	8	1.10	-
1	9	1.16	1.12

c) Track 3

Track	Position	Case Depth (mm)	Mean(mm)
3	1	1.14	-
3	2	1.16	-
3	3	1.10	-
3	4	1.14	-
3	5	1.14	-
3	6	1.19	-
3	7	1.09	-
3	8	1.08	-
3	9	1.16	1.13

b) Track 2

Track	Position	Case Depth (mm)	Mean(mm)
2	1	1.15	-
2	2	1.13	-
2	3	1.14	-
2	4	1.16	-
2	5	1.17	-
2	6	1.18	-
2	7	1.17	-
2	8	1.18	-
2	9	1.20	1.16

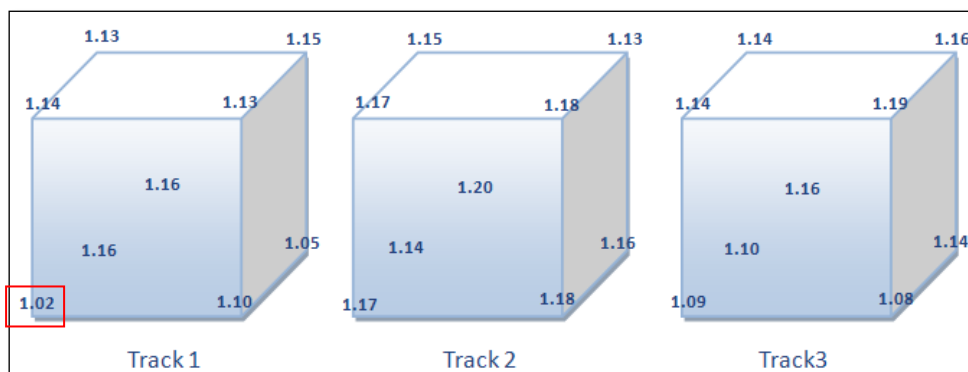


Figure 15 Cubes of case hardening depth at each position on each track (VCE 2010)

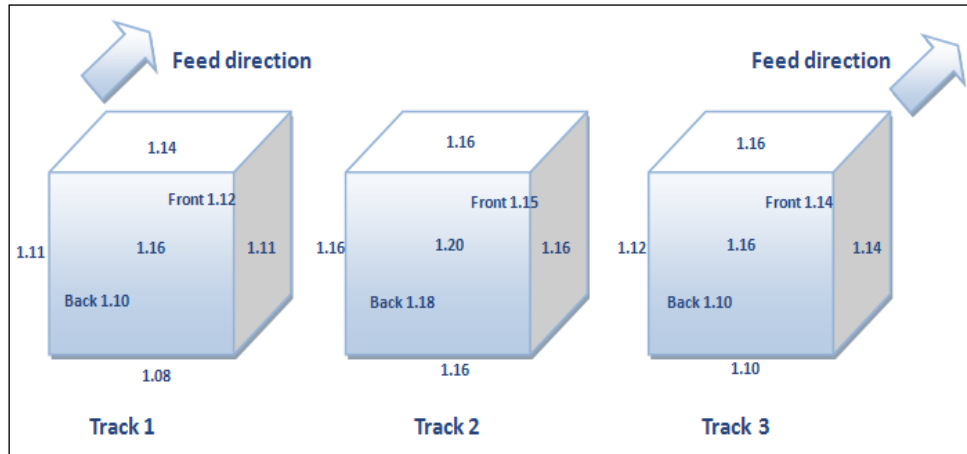


Figure 16 Mean case hardening depth on cubic faces (VCE 2010)

Track 1 and track 3 have relative similar CHD mean values at 1.12 mm and 1.13mm, respectively. Track 2 shows the highest CHD mean at 1.16 mm of three tracks. Position 7 on Track 1 indicates the least case depth at 1.02 mm as illustrated in Figure 15. CHD mean cubes are displayed in Figure 16 and the result turns out to be that the upper positions have deeper case depth than the lower positions. The result also shows the right and left side case depth from track 2 is the same but a little higher than that of Track 1- Right and Track 3-Left.

2-sample t-tests are made to obtain p-values to determine whether or not the difference significantly between two samples and one-way ANOVA is made to check out the significant difference among three tracks. The p-value for track 1 and track 2 is 0.022 which is lower than 95% of confidence interval with alpha equals to 0.05. The p-value for track 1 and 3 is 0.402 higher than the value of 0.05, and therefore there is no significant difference between mean CHD of two tracks. The p-value for track 2 and 3 is 0.047 which means the difference is significant that indicate not to allow merging them. The p-value from one-way ANOVA test is 0.025. Only track 1 and track 3 could be combined and analyzed as a one sample group. After combination, normality test is made to examine whether or not the data follow normal distributions. If they are, then capability indices can be obtained and valid. If not, other methods should be used for analysis. Normality test results are shown in Table 6 below.

Table 6 Normality test of track 1, track 2, track 3 and track 1&3 (VCE 2010)

Track	Sample N	Distribution	P-value	Mean(mm)	StDev
1	9	Normal	0.062	1.116	0.050
2	9	Normal	0.883	1.164	0.022
3	9	Normal	0.346	1.133	0.036
1&2	18	-	-	-	-
1&3	18	Normal	0.052	1.124	0.043
2&3	18	-	-	-	-
1,2,3	27	-	-	-	-

Table 7 Capability analyses of track 1, track 2, track 3 and track 1&3 (VCE 2010)

Track	No. of Samples	Pp	Ppk	Cpm	Target	USL	LSL
1	9	1.00	-0.10	0.27	0.95	1.10	0.80
2	9	2.29	-0.98	0.22	0.95	1.10	0.80
3	9	1.37	-0.31	0.25	0.95	1.10	0.80
1 & 3	18	1.16	-0.19	0.27	0.95	1.10	0.80

In Table 7 above, all cases present low Ppk and Cpm values which mean the process is not centered but outside specification limits. Track 1 and track 3 have low Pp values at 1.00 and 1.37 which indicate possible improvement for both tracks. On track 2 Pp value is high at 2.29 which exceeds good value of 1.67. If compared capability histograms and normal probability plots in Figure 17 and 18, conclusions could be drawn that the process is close to the upper specification limit USL (upper specification limit).

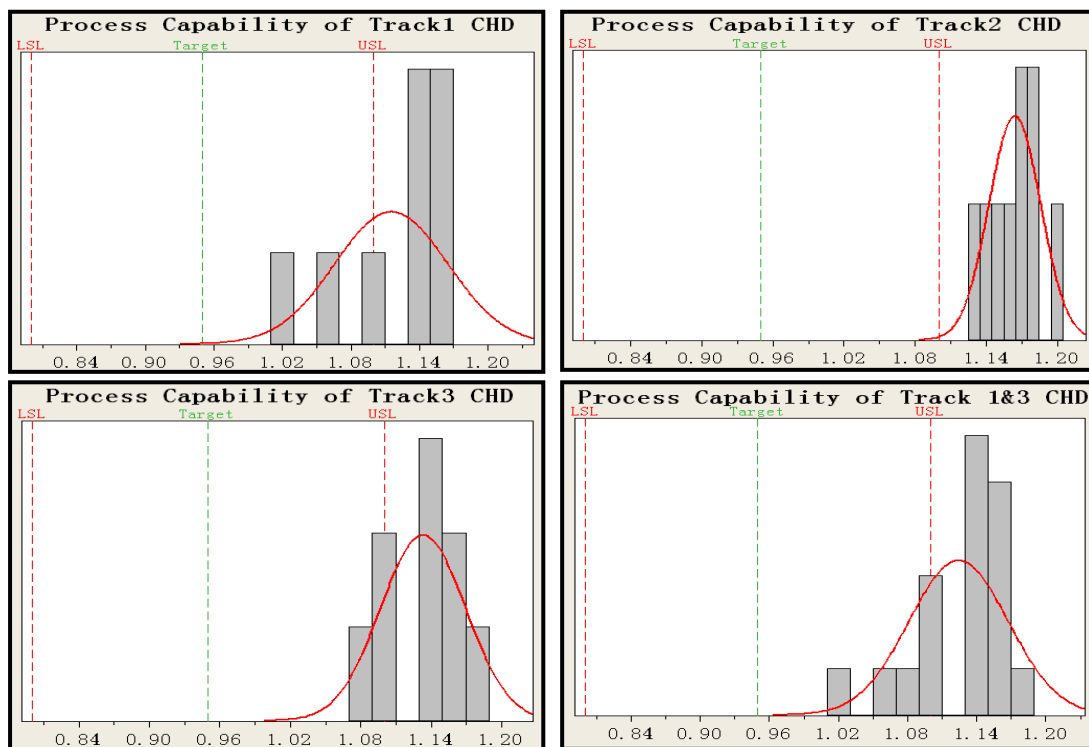


Figure 17 Capability histograms of track 1, track 2, track3 and track 1&3 (VCE 2010) [12]

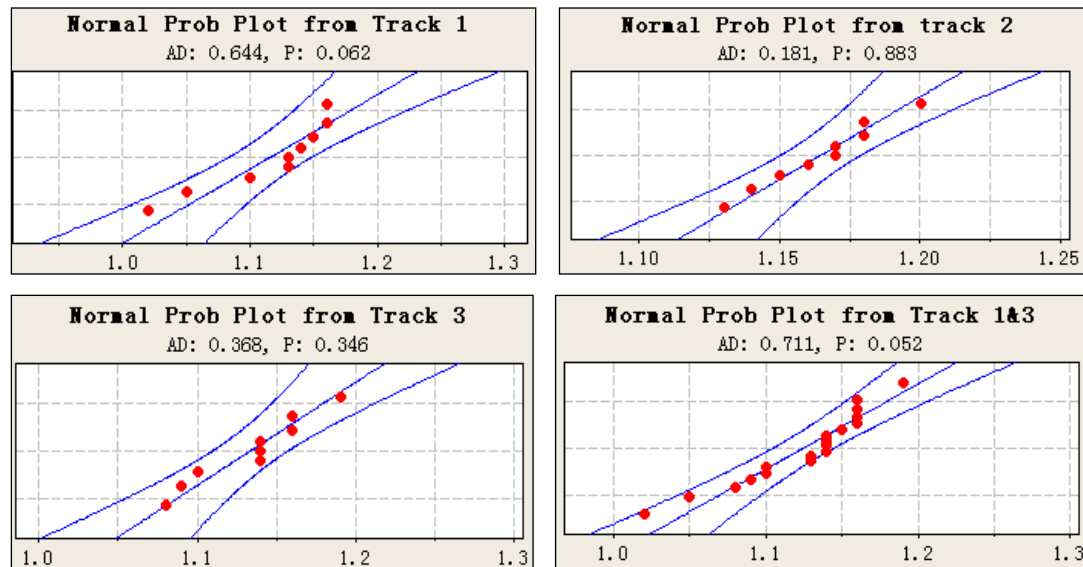


Figure 18 Normal probability plots from track 1, track 2, track 3 and track 1&3 (VCE 2010) [12]

In normal probability plots, the central blue line is the fitted normal distribution line, and the points are the measured values versus the percentage of values in the sample that are less than or equal to it. From Figure 18, spreads and distribution can be compared among track 1, track 2, track 3 and track 1&3. In normal probability plots, AD values refer to Anderson-Darling statistics which should be as low as possible, and the p-value should be more than the level of significance with alpha equals to 0.05. If so, the distribution is normal, otherwise either transforming the data to follow normal distribution or finding the possible best fitting to a non-normal distribution to make a strictly correct statistical analysis.

To investigate cause of variance, one-way ANOVA is applied for different factors such as Track, Position, Upper/Lower positions and Fully/Empty loading condition of the furnace.

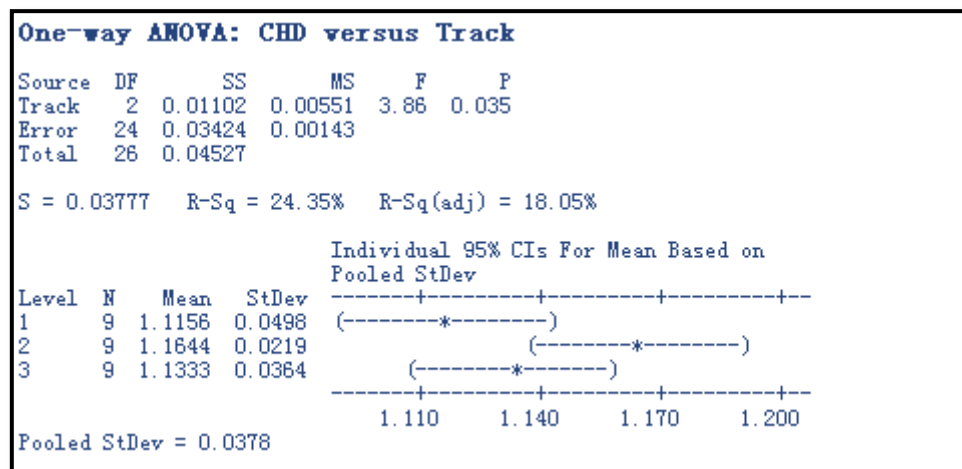


Figure 19 One-way ANOVA: CHD versus Track (VCE 2010) [12]

If CHD is set as the response value and Track as factor, then a p-value is obtained. In Figure 19, the p-value is 0.035 for “Track” factor which means that there is a significant difference among three tracks’ CHD mean (chosen the level of significance $\alpha=0.05$).

Grouping Information Using Tukey Method			
Track	N	Mean	Grouping
2	9	1.18444	A
3	9	1.13333	A B
1	9	1.11556	B

Means that do not share a letter are significantly different.

Figure 20 Grouping information (VCE 2010) [12]

In Figure 20, grouping information shows track 2 and track 3 are in the same group, track 1 and 3 are in the other same group. There is no evidence to prove that track 1 and 2 are in the same group. It means track 1 and track 3 can be merged and analyzed together.

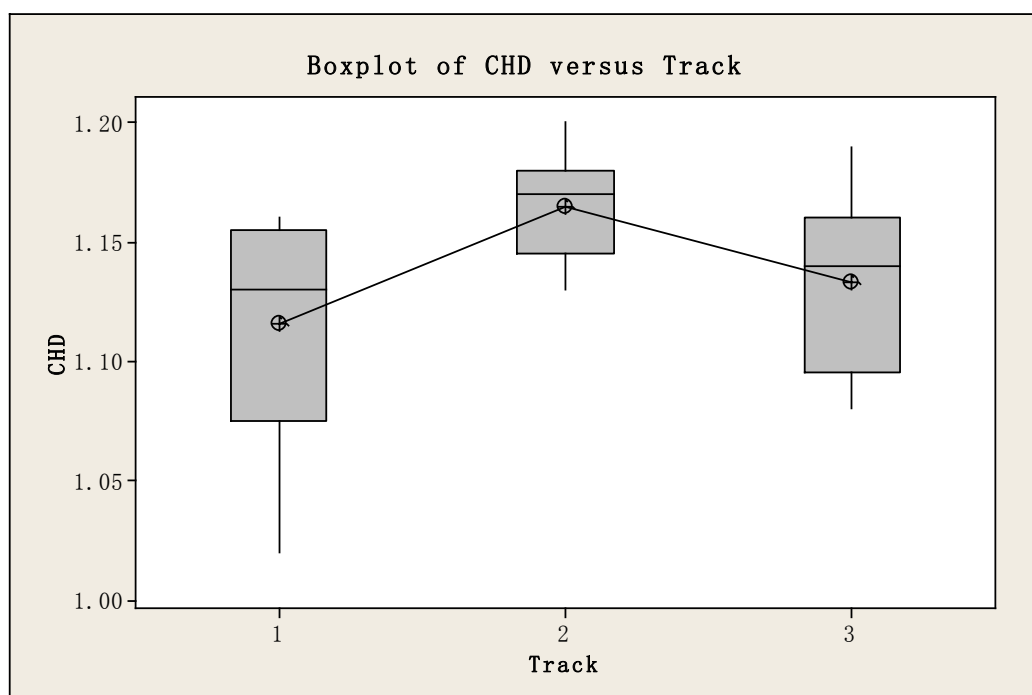


Figure 21 Box plot of CHD versus Track (VCE 2010) [12]

The box plot in Figure 21 indicates that track 1 has the widest spread because the height of the box is the largest of the three. The variation on track 2 is small as shown in the height of the box. All boxes have mean values higher than their medians, which indicate the data are positively skewed.

To investigate the influence of Position on the response of CHD, one-way ANOVA is performed in Minitab. The summary and box plot are presented below.

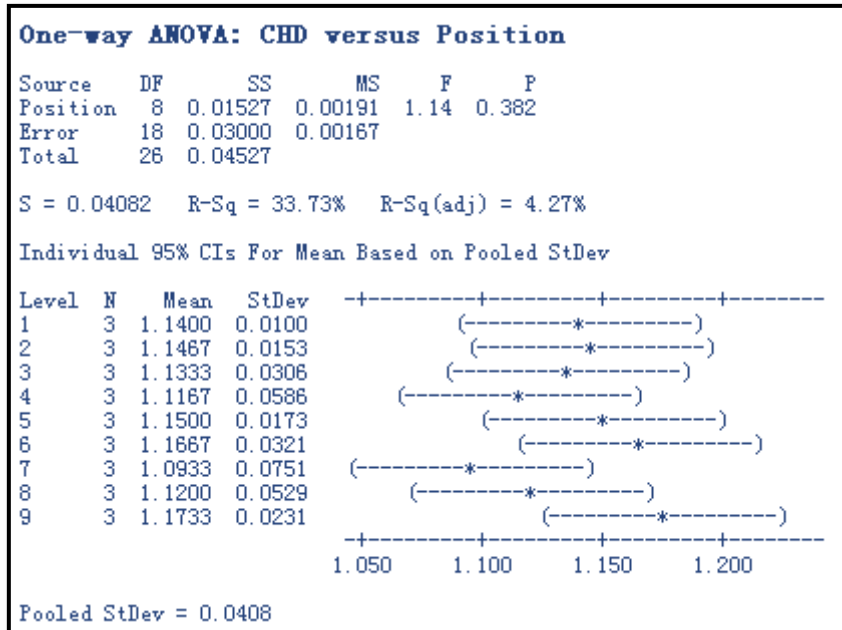


Figure 22 One-way ANOVA: CHD versus Position (VCE 2010) [12]

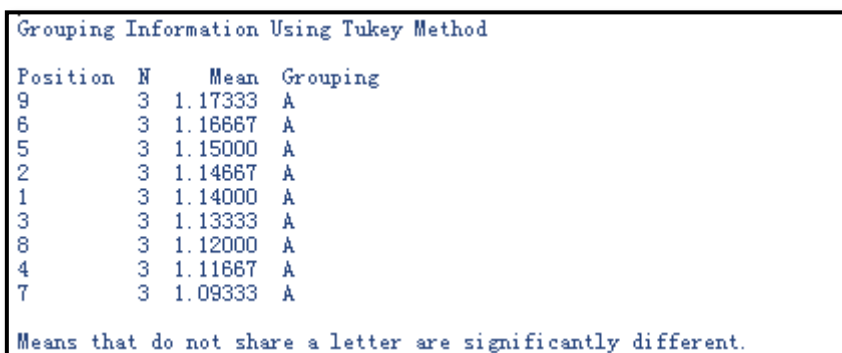


Figure 23 The grouping information (VCE 2010) [12]

The p-value in Figure 22 is 0.382 which means there is no significant difference among all positions from all tracks. Position 9 has the highest CHD, while position 7 presents the lowest mean value. All positions within the same group, which means the mean value share a letter that are not significantly different.

The influence of Upper/Lower positions in the furnace is studied. One-way ANOVA is made with U/L as a factor. "U" means the upper positions of the furnace which consists of four positions per track. "L" refers to the lower positions in the furnace which consists of four values from each track. "Center" is position 9.

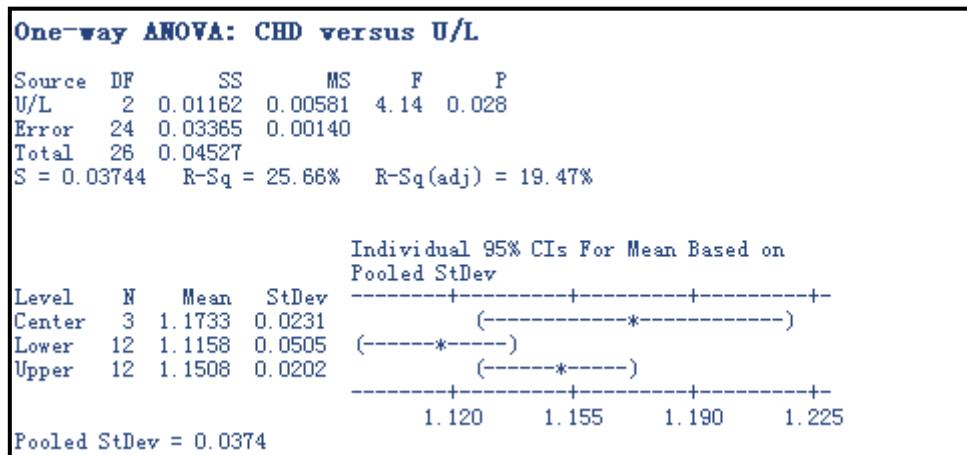


Figure 24 One-way ANOVA: CHD versus Upper/ Lower positions of furnace (VCE 2010) [12]

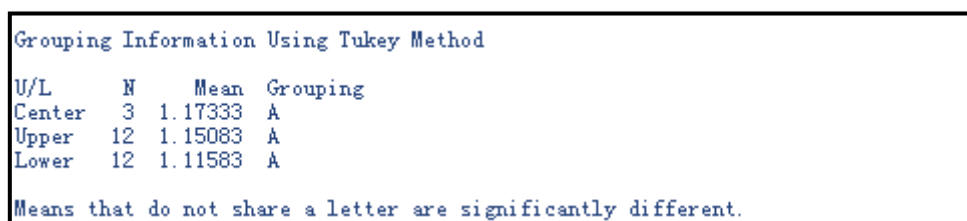


Figure 25 The grouping information (VCE 2010) [12]

The p-value is 0.028 which is lower than significant level of 0.05 in Figure 24. The difference is significant for CHD between the upper and lower positions in the furnace. Grouping information reveals all positions, upper, lower and central belong to the same group. Means that do not share a letter are significantly different. Box plot is shown in Figure 26.

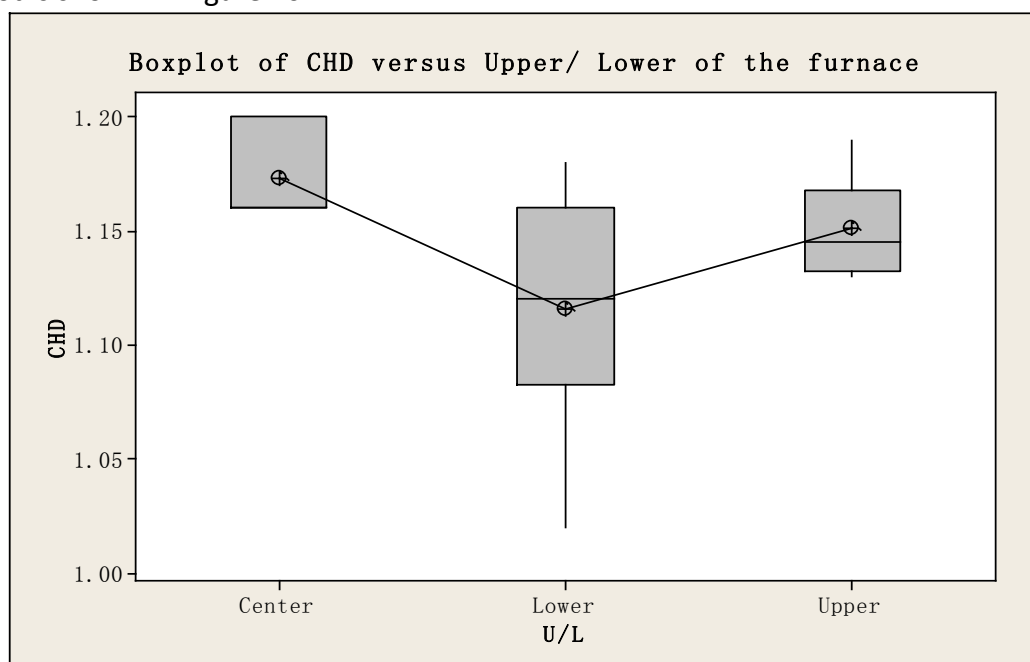


Figure 26 Box plot of CHD versus Upper/Lower positions of the furnace (VCE 2010) [12]

The Center of each track has the highest mean value of all positions but the box doesn't have the upper and lower whiskers due to low amount of data (just 3 values). The Upper positions have the smallest box size which means the lowest deviation. In box plot above, the Lower positions reveal a long lower whisker and the Upper positions present positive skewness.

To investigate the influence of factor "Fully/Empty" loading condition in the furnace on the response CHD, one way-ANVOA is conducted. "F" means the first test which involves "Fully loaded track 1 and track 3". "E" is empty loaded track that is derived from only track 2 which is just loaded with dummy samples (see in Section 3.1.2 Furnace at Volvo CE).

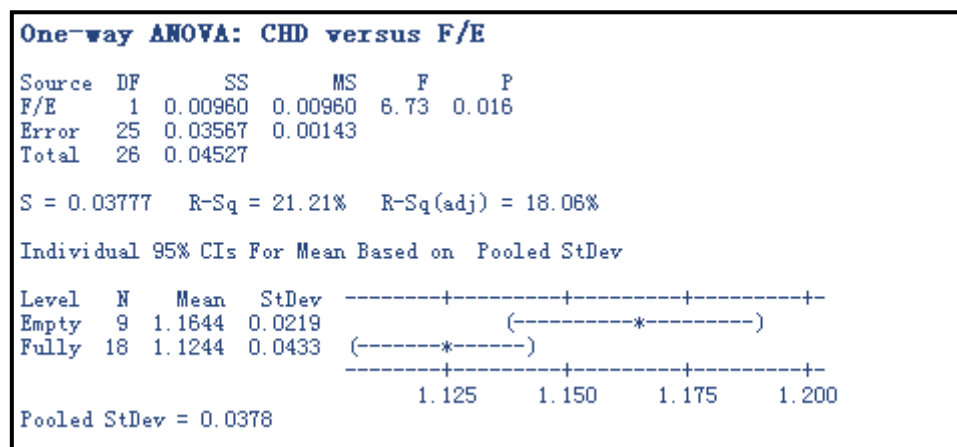


Figure 27 One-way ANOVA: CHD versus Fully/Empty loaded track (VCE 2010) [12]

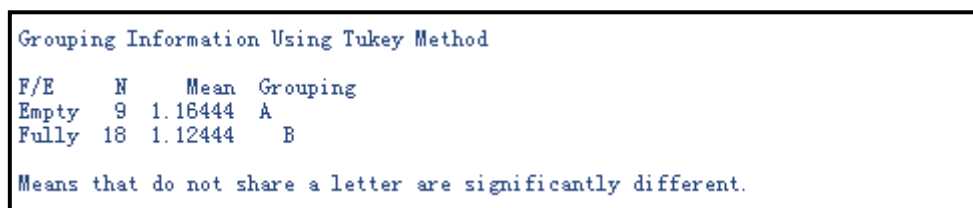


Figure 28 The group information (VCE 2010) [12]

The p-value from one-way ANOVA (CHD vs. Fully/Empty loading conditions) is $0.016 < 0.05$ in Figure 27, which means that the difference is significant between fully loaded and empty loaded track. Empty loaded track presents a high mean CHD value and spread, while fully loaded track obtained low mean CHD value but high standard deviation. Grouping information in Figure 28 explains that two cases belong to two different groups, which means that they do not share a letter are significantly different.

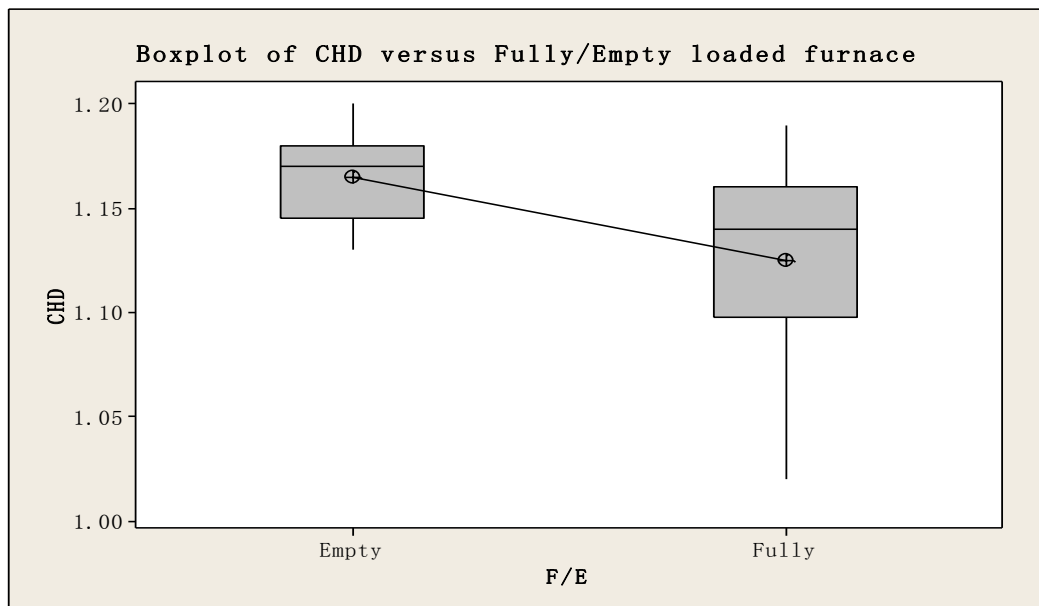


Figure29 Box plot of CHD versus Fully/Empty loaded track (VCE 2010) [12]

In Figure 29, fully loaded track shows a negative skewness with a long lower whisker. In order to investigate multiple factors' influence on the response, multi-vari Charts are plotted in Figure 30 - 32. Multi-vari chart takes into account two factors such as "Track - Position", "Track - Upper/Lower", "Track - Fully/Empty", "Position-Upper/Lower", "Position - Fully/Empty" and "Upper/Lower - Fully/Empty". (Note: if more than 40% of the cells in Minitab sheet are missing, no chart is generated).

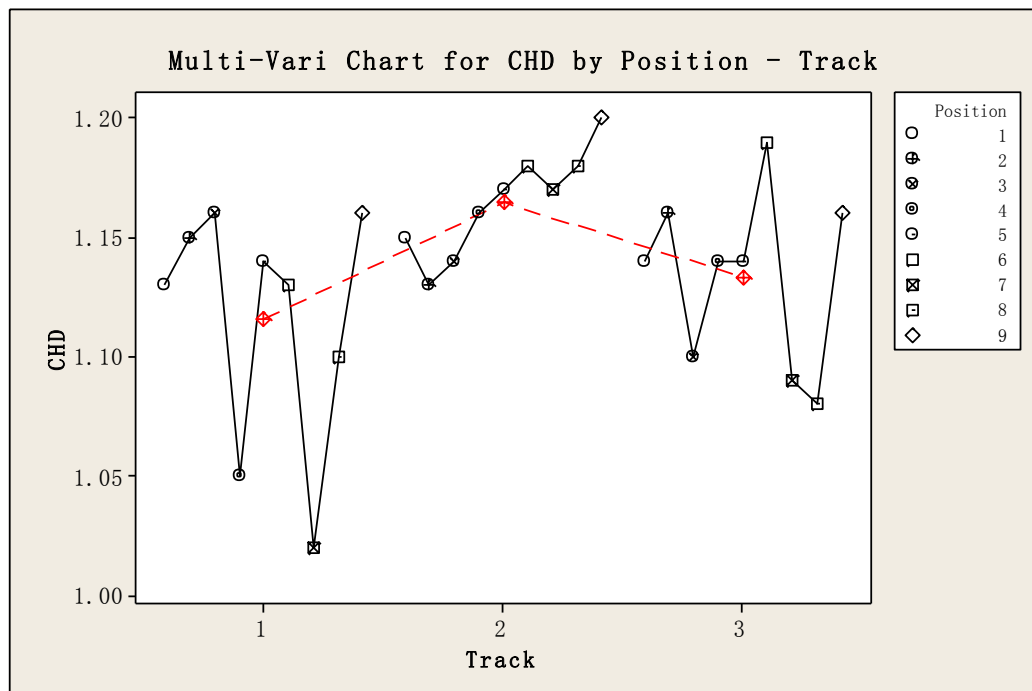


Figure 30 Multi-Vari Chart for CHD by Position - Track (VCE 2010) [12]

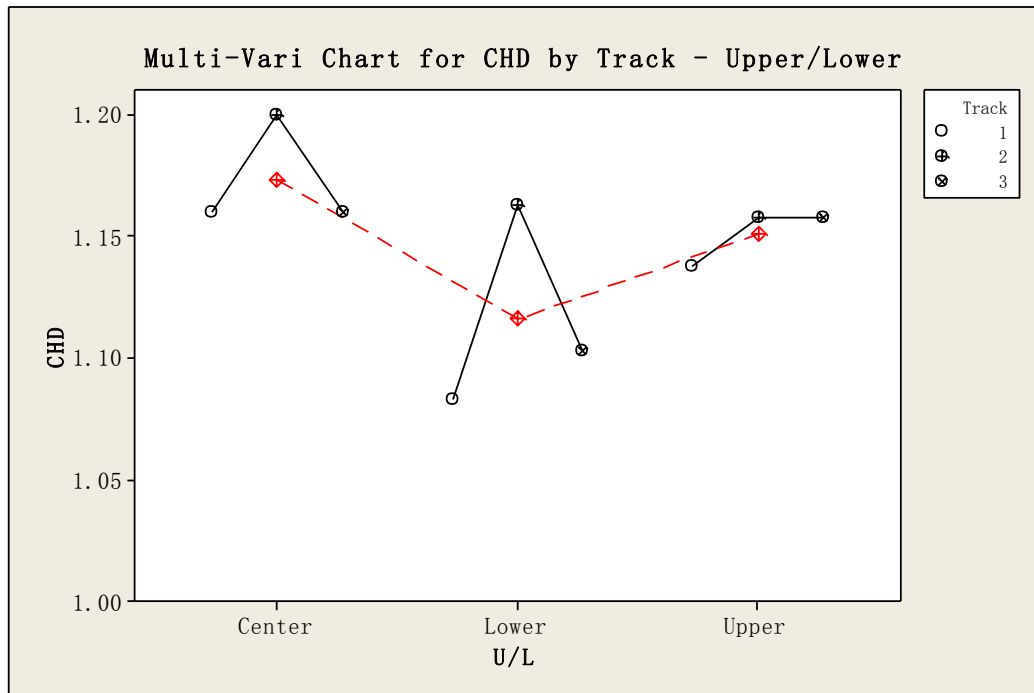


Figure 31 Multi-Vari Chart for CHD by Track – Upper/Lower part of furnace (VCE 2010) [12]

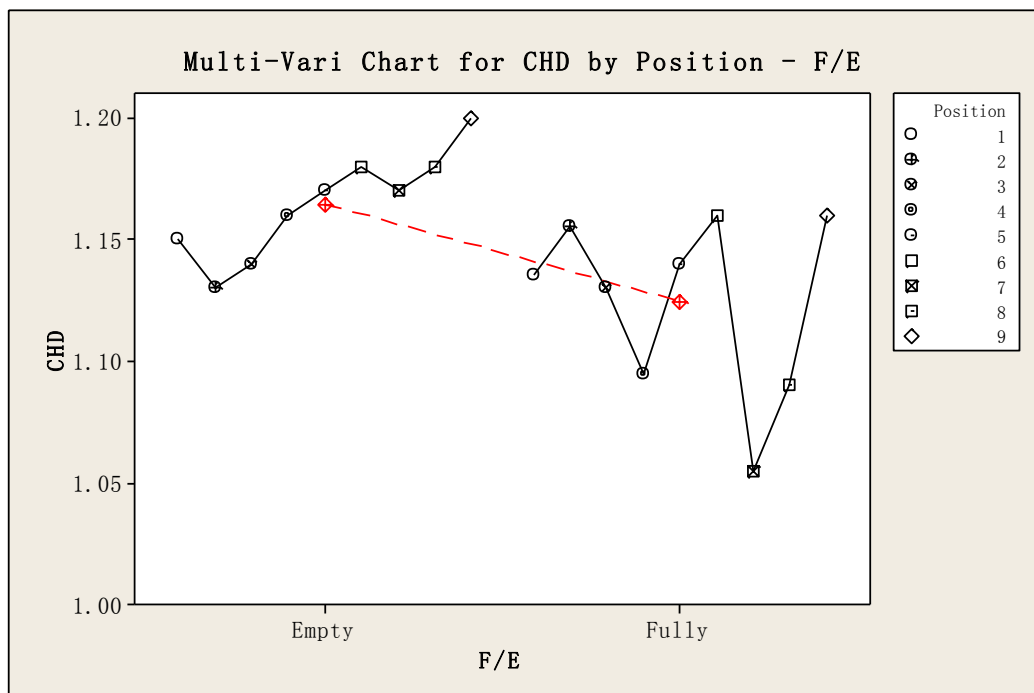


Figure 32 Multi-Vari Chart for CHD by Position – Fully/Empty loaded track (VCE 2010) [12]

In Figure 30, track 2 shows an increasing trend of CHD. For track 1 and 3, CHD fluctuates around 1.12 mm. Although track 1 and 3 are operated under the same conditions, still track 3 has higher CHD mean than track 1 in both the upper and lower positions of the furnace, see in Figure 31. Figure 32 shows the difference between fully/empty loaded track among positions. Note that for the case of empty

loaded track, the mean from track 2 includes 9 observations, for fully loaded track there are totally 18 observations included in the mean value.

When concluding the CHD results in VCE, the factors of Track, Upper/Lower and Fully/Empty loaded track have significant influences on case depths, and position 7 in all three tracks should be paid special attention in further capability studies. Note that CHD values are collected from one hardness profile in this project. It's recommended to make three profiles to form CHD mean values. Also note that a warning happened at the first test which results in higher carbon potential on track 1 and 3. Higher carbon potential in the furnace means high carbon content which not only influences the results of surface carbon content on dummy sample, but also case depth is affected. That is why capability indices are relatively low and Ppk indices are negative. For process capability studies, these results should also be compared with other parameters such as surface hardness and surface carbon content.

3.3. Surface Hardness

3.3.1. Getrag All Wheels Drive AB

Surface hardness was measured by HRA (Hardness Rockwell A, load 60kg) at Getrag in 2009. Three indentations were made on each sample surface. Mean values were recorded automatically by the equipment, see in Table 7. Mean cubes are presented in Figure 33. The lower (LSL) and upper (USL) tolerance is 81.5 and 82.5 HRA with the target value of 82.0 HRA. A two-sample t-test shows that there is no a significant difference ($p\text{-value} = 0.136 > \alpha = 0.05$) between the two tracks, and thus combine two tracks and analyze them together as one group. The results from track 1, track 2 and track 1&2 are normally distributed, and thus capability indices can be determined, see in Table 8 and 9 below.

Table 8 Mean surface hardness (HRA) from track 1 and track 2 (Getrag 2009) [13]

Track	Position	Hardness	Track	Position	Hardness
1	1	82.20	2	1	82.50
1	2	82.50	2	2	82.50
1	3	81.80	2	3	82.50
1	4	82.00	2	4	82.30
1	5	82.30	2	5	82.40
1	6	82.60	2	6	82.50
1	7	82.20	2	7	82.20
1	8	82.00	2	8	82.00
1	9	82.00	2	9	82.20

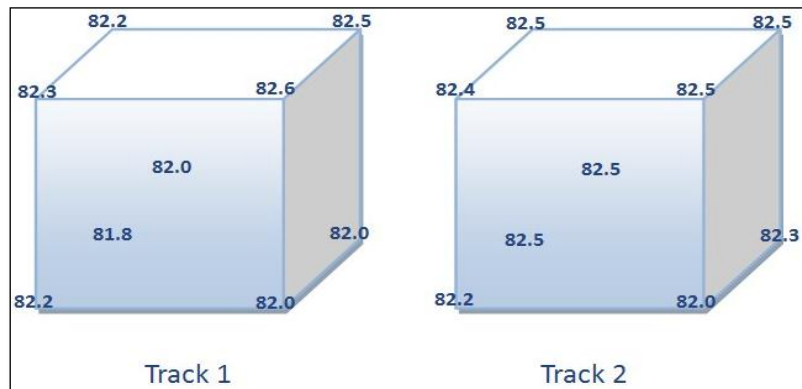


Figure 33 Mean Surface hardness (HRA) for each position (Getrag 2009) [13]

Table 9 Normality test of the surface hardness for track 1, 2 and 1&2 (Getrag 2009) [13]

Track	Number of Samples	Distribution	P-value	Mean	StDev
1	9	Normal	0.511	82.178	0.259
2	9	Normal	0.077	82.344	0.181
1 & 2	18	Normal	0.089	82.261	0.233

Table 10 Capability analyses of the mean surface hardness for track 1, 2 and 1&2 (Getrag 2009)
[13]

Track	Number of Samples	Distribution	Pp	Ppk	Cpm	StDev	Target	USL	LSL
1	9	Normal	0.64	0.42	0.52	0.259	82.00	82.50	81.50
2	9	Normal	0.92	0.29	0.41	0.181	82.00	82.50	81.50
1 & 2	18	Normal	0.72	0.34	0.34	0.233	82.00	82.50	81.50

In Table 10 Pp, Cpm and Ppk are in the range from 0.34 to 0.92 which are considered low if compared with benchmark value of 1.33. Track 1 shows a slightly lower hardness but with wider distribution. Track 2 shows a slightly higher hardness but with a lower spread. Track 1 also shows a higher Cpm value which means that the data mean is slightly closer to the target than track 2. The capability indices show the improvement for the process is needed, however, the size of the data set should be also considered. The centering of process would not generate a higher Pp value, but Ppk and Cpm values would improve to some extent. For a higher Pp value, either reducing spread or increasing tolerance range is required. ^[13]

3.3.2. Volvo Construction Equipment AB

Surface hardness was measured from three indentations by HRC 150kg load (Hardness Rockwell C) at Getrag in 2010. Three measurement values are collected and mean values are calculated by equipment automatically, see in Table 11 below. The mean surface hardness on the fixture at each position can be obtained from Figure 34 below.

Table 11 Surface hardness (HRC) of each sample (VCE 2010)

Track	Position	Surface Hardness (HRC)	Mean
1	1	62.26	62.32
1	2	62.36	
1	3	62.26	
1	4	62.26	
1	5	62.63	
1	6	62.23	
1	7	62.43	
1	8	61.93	
1	9	62.50	

Track	Position	Surface Hardness (HRC)	Mean
3	1	62.16	62.26
3	2	62.43	
3	3	62.23	
3	4	62.00	
3	5	62.50	
3	6	62.30	
3	7	62.23	
3	8	62.10	
3	9	62.40	

Track	Position	Surface Hardness (HRC)	Mean
2	1	62.16	62.17
2	2	62.40	
2	3	62.30	
2	4	61.93	
2	5	62.30	
2	6	62.20	
2	7	62.20	
2	8	61.86	
2	9	62.20	

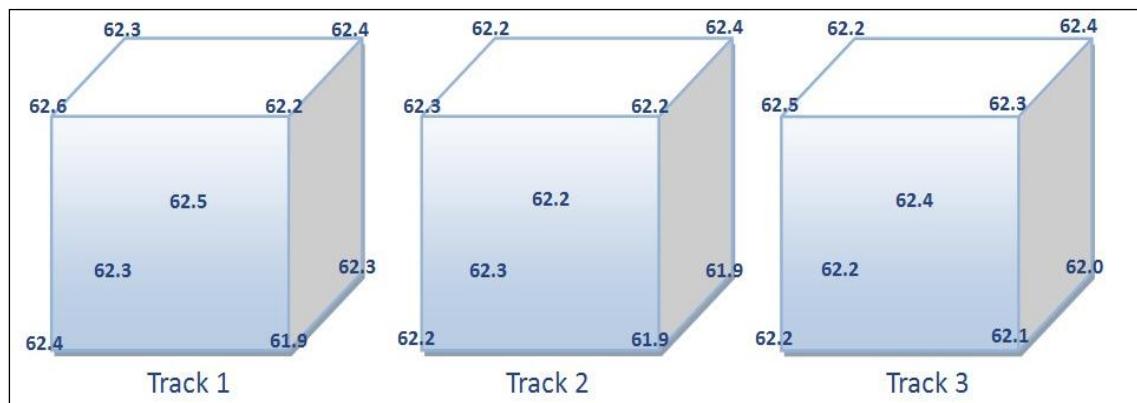


Figure 34 Mean surface hardness (HRC) cubes (VCE 2010)

The mean surface hardness cubes at each position is shown in Figure 34 and mean value of each cubic face is calculated from four corners which is shown in Figure 35 below.

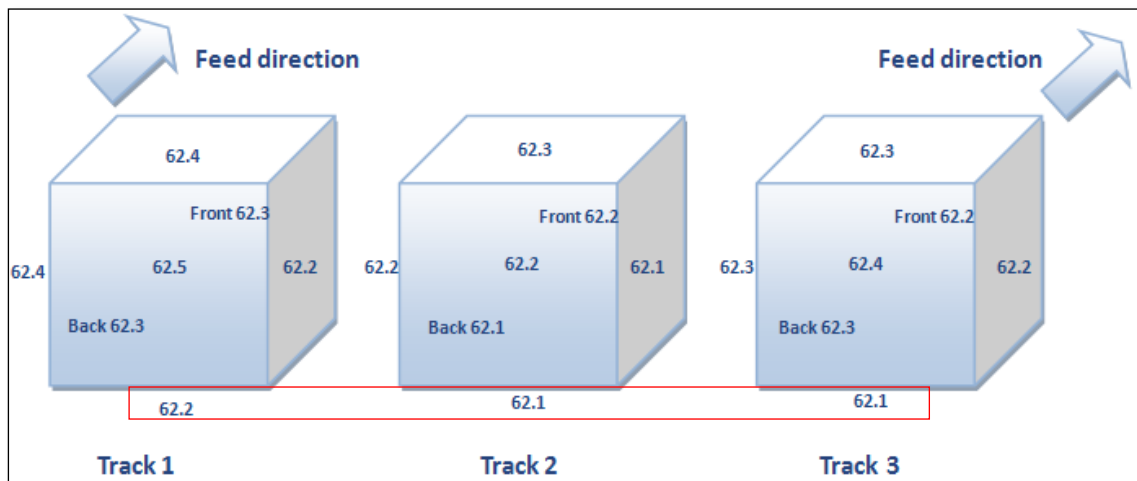


Figure 35 Mean surface hardness of each face (VCE 2010)

The top regions in all three tracks show slightly higher mean surface hardness than that of the bottom regions', and the left side of each track have slightly higher mean values than that of right side as well. The central regions in track 1 and track 3 have the highest mean values than other regions within the same track.

For further study, statistical software Minitab is used. The target value is 61.5 HRC with the upper (USL) and lower (LSL) tolerance at 58 HRC and 63 HRC, respectively. 2-sample t-tests are made between track 1 & 2, track 1 & 3, and track 2 & 3 in order to check out whether there is or not a large p-value. After 2-sample t-tests, p-values are obtained for 0.169, 0.705 and 0.508 for track 1, 2 and 3 all of which are larger than a 95% two-sided confidence interval (level of significance, $\alpha=0.05$) and which mean the difference is not significant, thus combine two tracks into one group and analyze as one. When comparing more than two samples, one-way ANOVA is applied. The result of one-way ANOVA shows differences among the means are not significant with p-value 0.280 higher than the value of 0.05, therefore, analyzing all three tracks together is possible. However, normality couldn't be reliably when checked with small samples, cautions should be paid when interpreting the results. Normality test and statistical summary of track 1, track 2, track 3, track 1&2, track 1&3, track 2&3 and track 1&2&3, see in Table 12 below.

Table 12 Normality test of track 1, track 2, track 3, track 1&2, track 1&3, track 2&3 and track 1,2,3 (VCE 2010)

Track	Number of Samples	Distribution	P-value	Mean	StDev
1	9	Normal	0.373	62.32	0.198
2	9	Normal	0.124	62.17	0.058
3	9	Normal	0.925	62.26	0.163
1 & 2	18	Normal	0.169	62.25	0.196
1 & 3	18	Normal	0.705	62.29	0.178
2 & 3	18	Normal	0.508	62.22	0.170
1,2,3	27	Normal	0.348	62.25	0.182

All distributions in Table 12 are normally distributed, therefore capability analyses of the mean surface hardness can be performed. The results of analyses are presented in Table 13 below.

Table 13 Capability analyses of the mean surface hardness for all cases (VCE 2010)

Track	Sample N	Pp	Ppk	Cpm	Target	LSL	USL
1	9	4.21	1.15	0.56	61.50	58.00	63.00
2	9	4.78	1.58	0.68	61.50	58.00	63.00
3	9	5.11	1.51	0.61	61.50	58.00	63.00
1&2	18	4.26	1.29	0.63	61.50	58.00	63.00
2&3	18	4.90	1.54	0.66	61.50	58.00	63.00
1&3	18	4.67	1.33	0.60	61.50	58.00	63.00
1&2&3	27	4.57	1.37	0.64	61.50	58.00	63.00

In Table 13, all indices show high Pp but relatively low Ppk values, which refers to the process is very capable of meeting specification limits. Track 1 has the highest mean surface hardness value and the widest spread but lowest Pp value at 4.21. Track 1 is very capable of but relative low Ppk value at 1.15 which means off-centering. Track 2 shows the best Ppk and Cpm values, which means the best within specifications and close to the target. (Also see in Discussion).

Taguchi index Cpm measures whether or not current process meets specifications and is on target, taking into account of the data's deviation from the target value rather than the spread from the process mean.^[13] In Table 13 above, all Cpm values are low at the range of 0.56 to 0.68, which means all positions are far shift to the USL side. The combination results reveal that track 2&3 has the highest Pp value with the lowest mean surface hardness and the narrowest spread (0.170). Track 1 and Track 3 are pushed into the main furnace at the same temperature and with the same carbon potential, capability indices should be relatively similar, however, the results are different. From the capability indices, conclusion could be drawn that track 3 is more capable than track 1, but the influence from sample material and measurement should also be considered. Also note that a warning occurred at track 1 and 3 due to low pressure in the furnace. It results in low carbon potential in the carburizing zone 2 but high carbon potential at the end of the diffusion zone 3. However, the influence of the lack of gas is not investigated in this case.

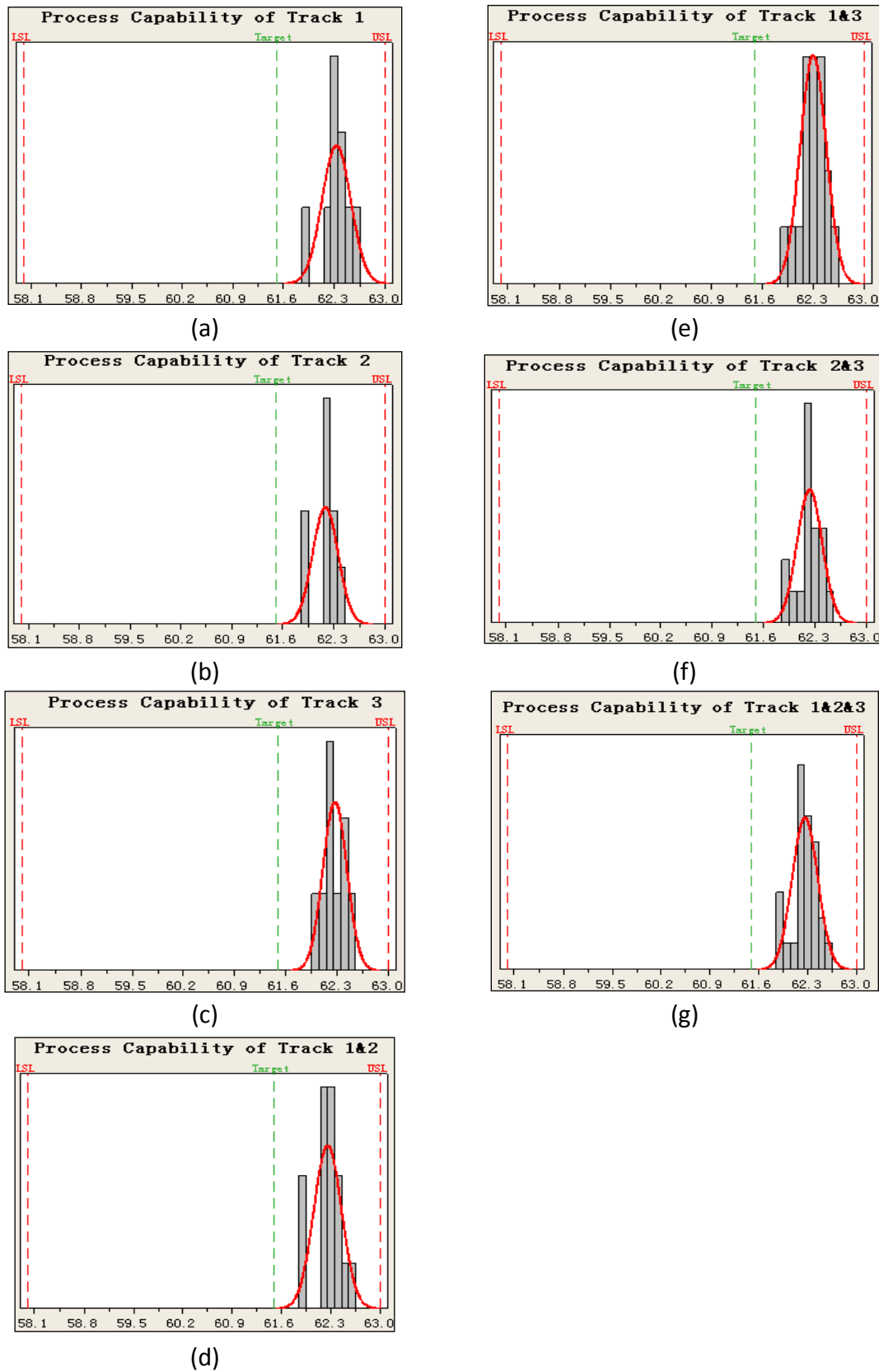


Figure 36 Capability Histograms of mean surface hardness from a) Track 1; b) Track 2; c) Track 3; d) Track 1&2; e) Track 1&3; f) Track 2&3; g) Track 1,2,3 (VCE 2010) [12]

The histograms for mean surface hardness of Track 1 and 3 are shown in Figure 36.

Track 1 and 3 have almost the same spread, while Track 2 has the smallest spread which means that the hardness values are more centered to the process mean. All distributions are rightward shift which mean the process means are approach to the USL rather than the target.

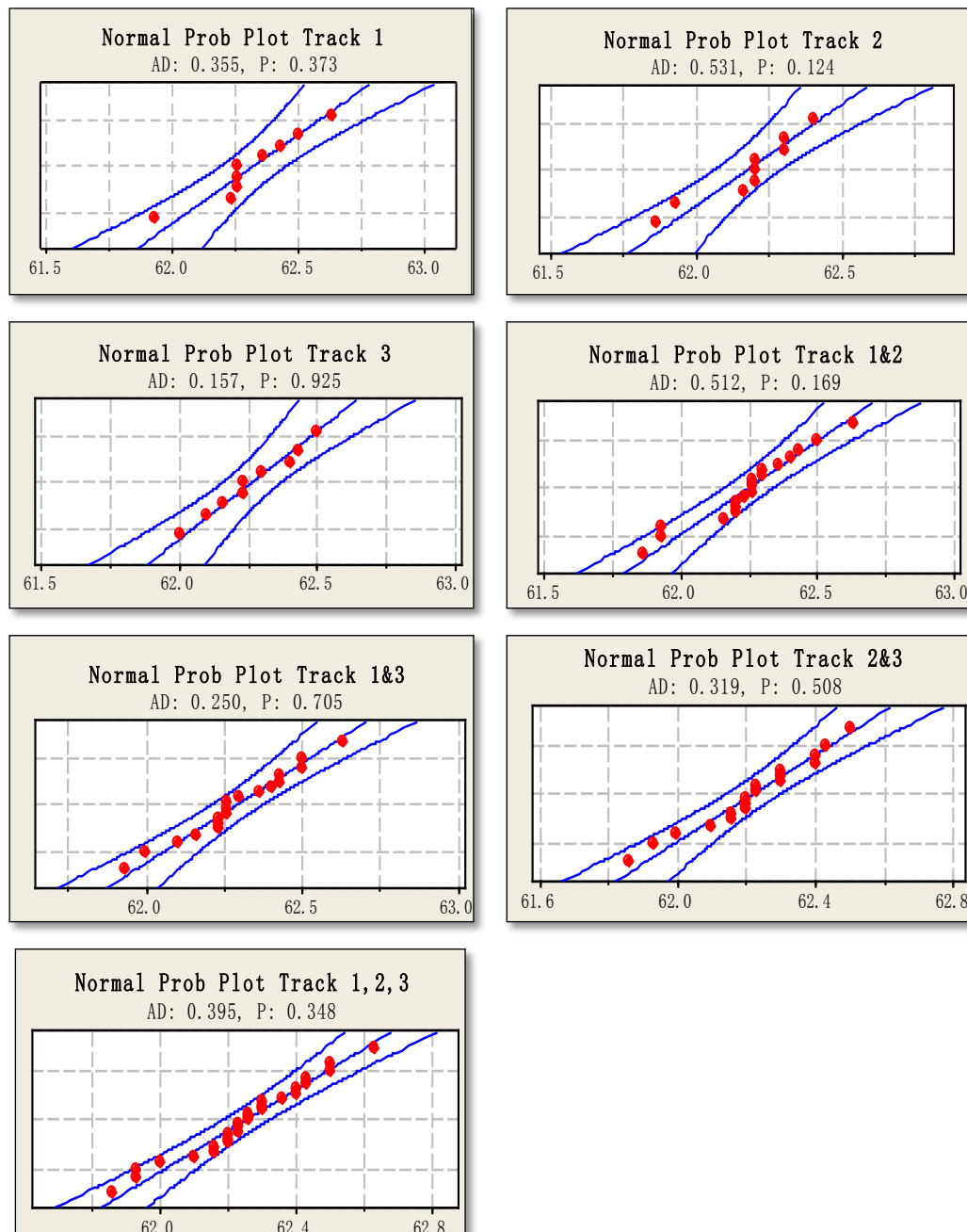


Figure 37 Normal Probability Plots from Track 1 to Track 1, 2, 3 (VCE 2010) [12]

Normal probability plots are shown in Figure 37 for all cases. Note that all probability plots are approximately along the straight central fitted lines and with similar slopes, which in return explains that the standard deviations for all cases are about the same.

One-way ANOVA and multi-vari charts are made to identify the relationships between response and factors. The responses are mean surface hardness. Factors are Tracks, Positions, Upper/Lower positions and Full/Empty loaded condition. The interactions between response and factors are shown in Figure 38 to 46 below.

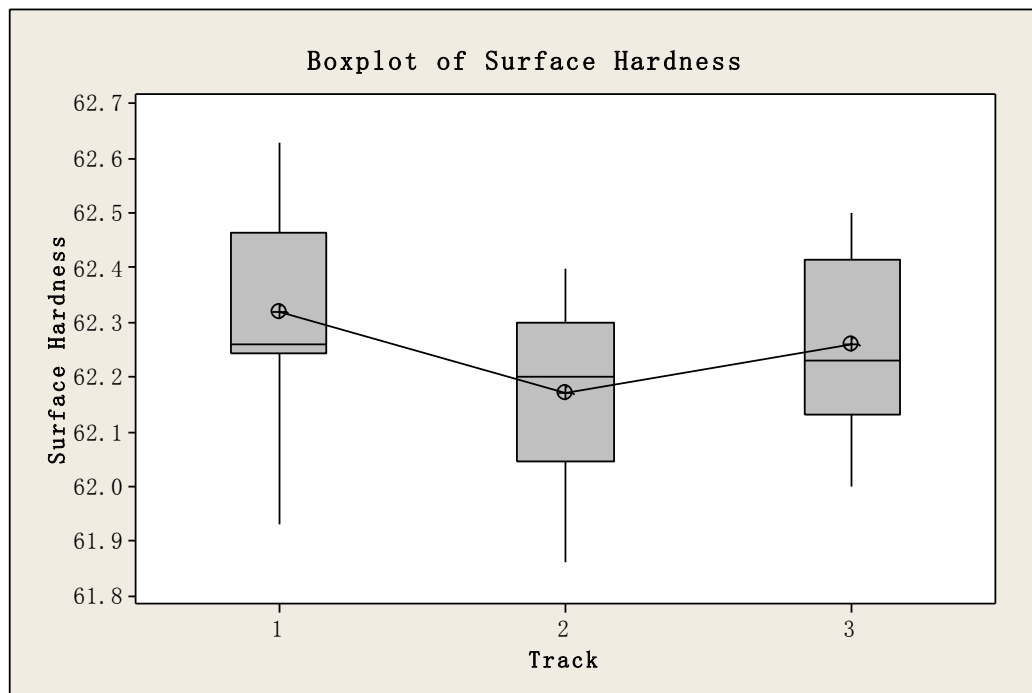


Figure 38 Box plot of surface hardness HRC vs. track [12]

In the box plot above, both track 1 and 2 show long lower whiskers, which mean negative skewness. The height of boxes is the same which refer to the same spread.

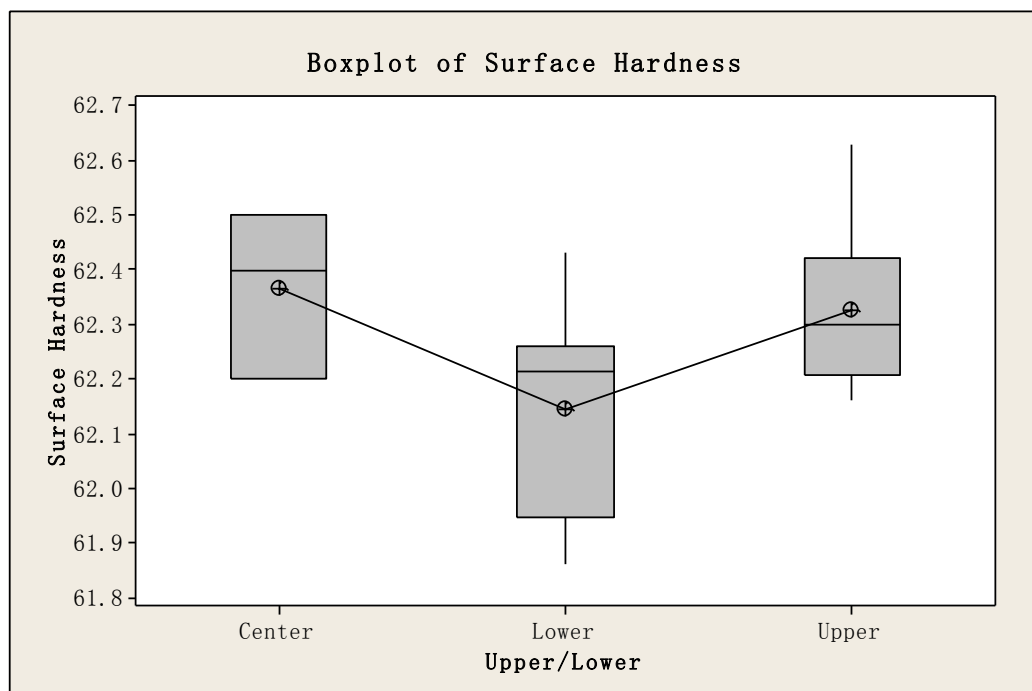


Figure 39 Box plot of surface hardness vs. Upper/Lower part of furnace (VCE 2010) [12]

The box plots in Figure 39 show surface hardness versus Upper/Lower positions of furnace. Both the lower and upper positions show long upper whiskers, which mean positive skewness. Note that the upper position has a small box height, in other word, a small spread. The median line in upper part box shows least skewness.

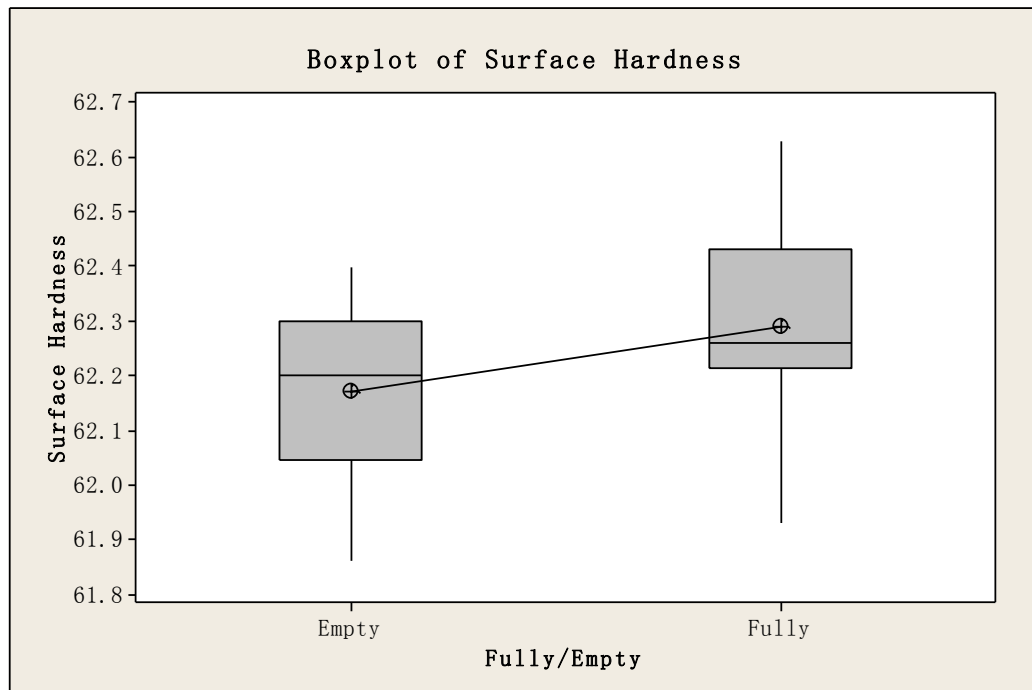


Figure 40 Box plot of surface hardness vs. Fully/Empty loaded track (VCE 2010) [12]

The box plots in Figure 40 above illustrate the influence of Fully/Empty loaded track on surface hardness. Note that at the first test the furnace was fully loaded with components on track 1, 2 and 3. The test samples were loaded on track 1 and 3. At the second test track 1 and 3 were loaded in the same way as in the first test. The test samples were loaded on track 2 with empty trays in front and behind. “Empty” refers to the second test, while “Fully” stands for the first test. The result shows that on empty loaded track is better than fully loaded track as the median line is better centered and with shorter whiskers. For the case of fully loaded track, the distribution is negative skewed, which means a tendency of lower surface hardness. The analyses above take single factor into account to estimate whether or not it has severe influences on surface hardness, however, in reality interactions are always complicated related to each other. To investigate the interactions between factors, multi-vari chart is used for analysis. The response is surface hardness and the factors are Track, Position, Upper/Lower and Fully/Empty loading conditions.

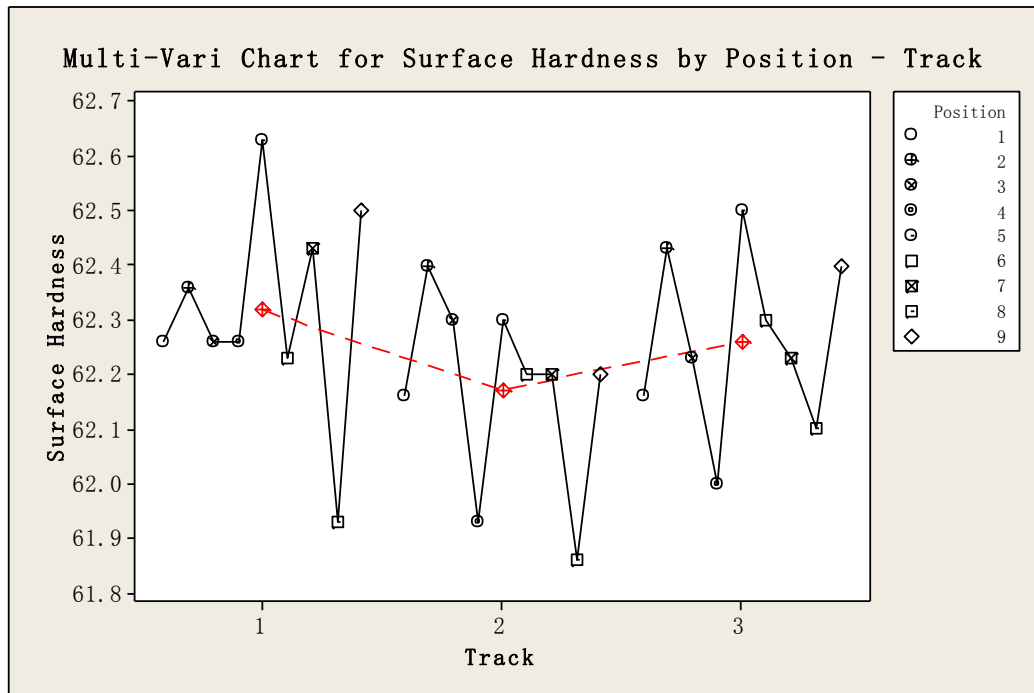


Figure 41 Multi-Vari Chart for surface hardness by Position- Track (VCE 2010) [12]

In Figure 41, “Track” and “Position” are factors and surface hardness is the response. Mean surface hardness for track 1 and 3 are almost the same but the mean of track 2 is slightly lower. Positions 5 and 6 have highest and lowest mean values on track 1, respectively. Track 2 position has the highest and lowest values at positions 2 and 8. Positions 4 and 5 on track 3 show the highest and lowest values see in Figure 42 below.

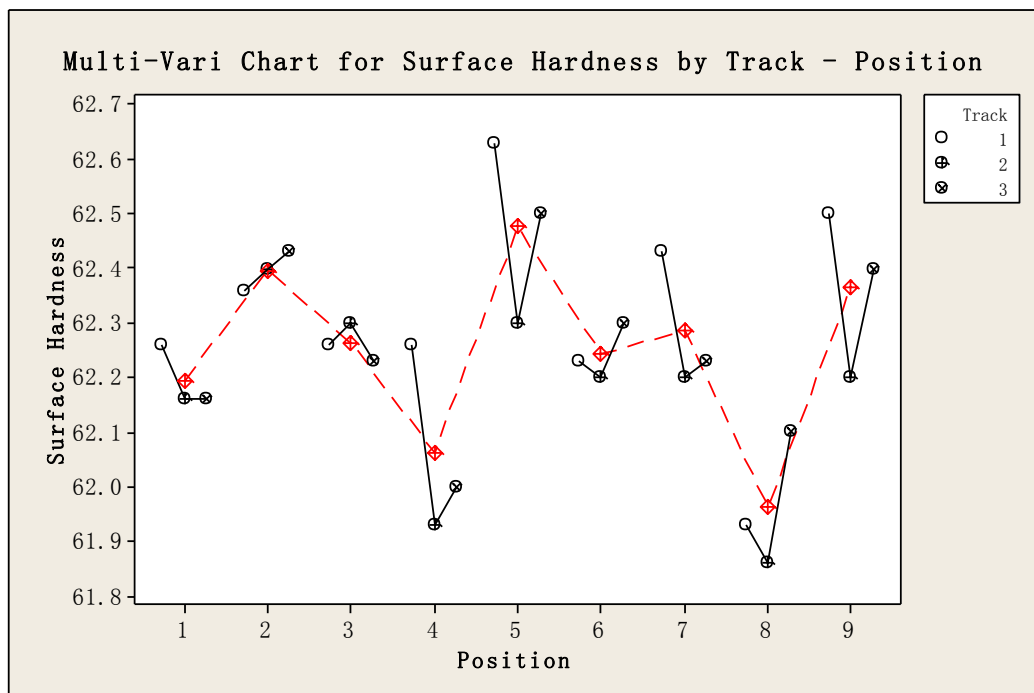


Figure 42 Multi-Vari Chart for Surface Hardness by Track-Position (VCE 2010) [12]

In Figure 43, the factors are “Track” and “Position” and the response is mean surface hardness. All three tracks show lower positions give low surface hardness.

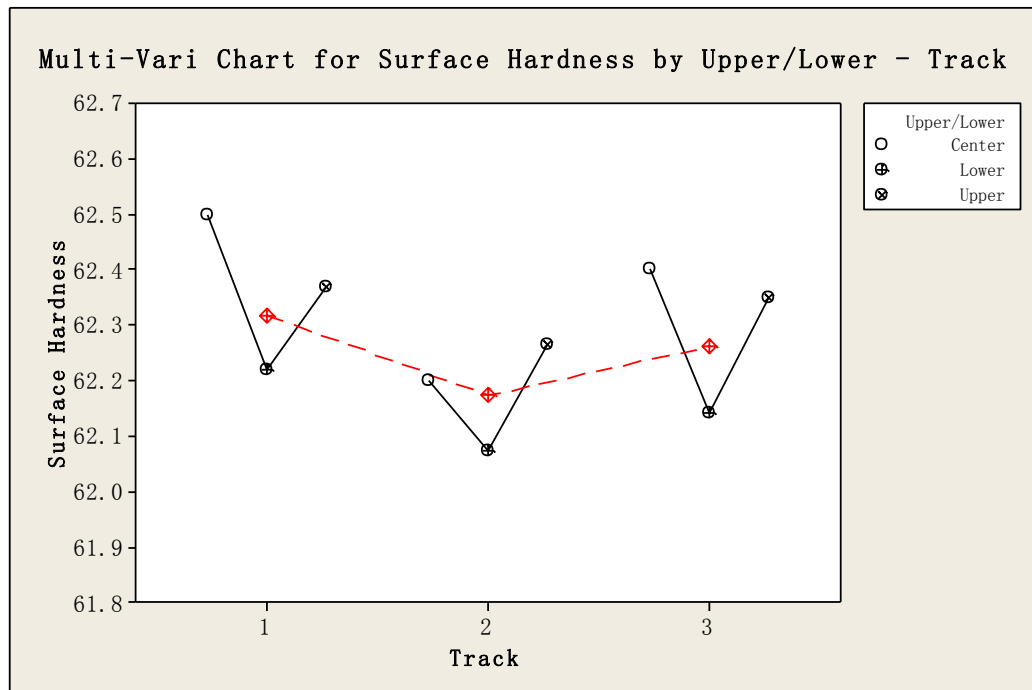


Figure 43 Multi-Vari Chart for surface Hardness by Upper/Lower-Track (VCE 2010) [12]

In Figure 44, the factors are “Fully/Empty loading condition” and “Position” and keep the response the same. The mean surface hardness values vary from positions, and position 4 and 8 show rather low mean values. In most cases, fully loaded track gives higher hardness value than that of an empty furnace.

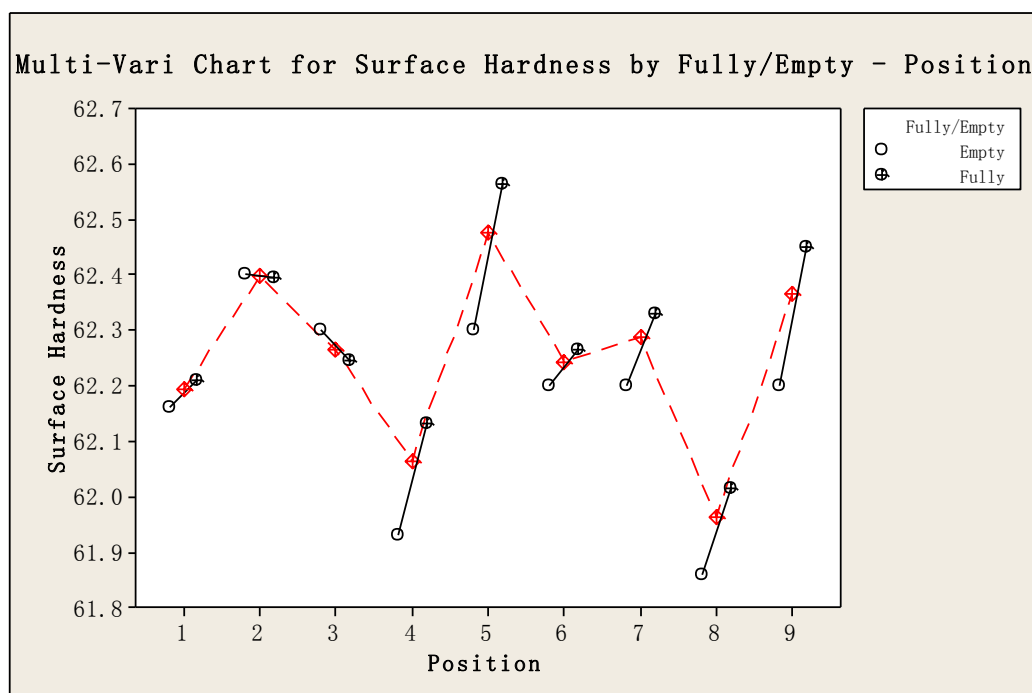


Figure 44 Multi-Vari Chart for Surface Hardness by fully/empty loaded – position (VCE 2010) [12]

The interactions between factors “Fully/Empty” loading conditions and “Upper/Lower” positions in furnace on the response of mean surface hardness is shown in Figure 45 is obtained.

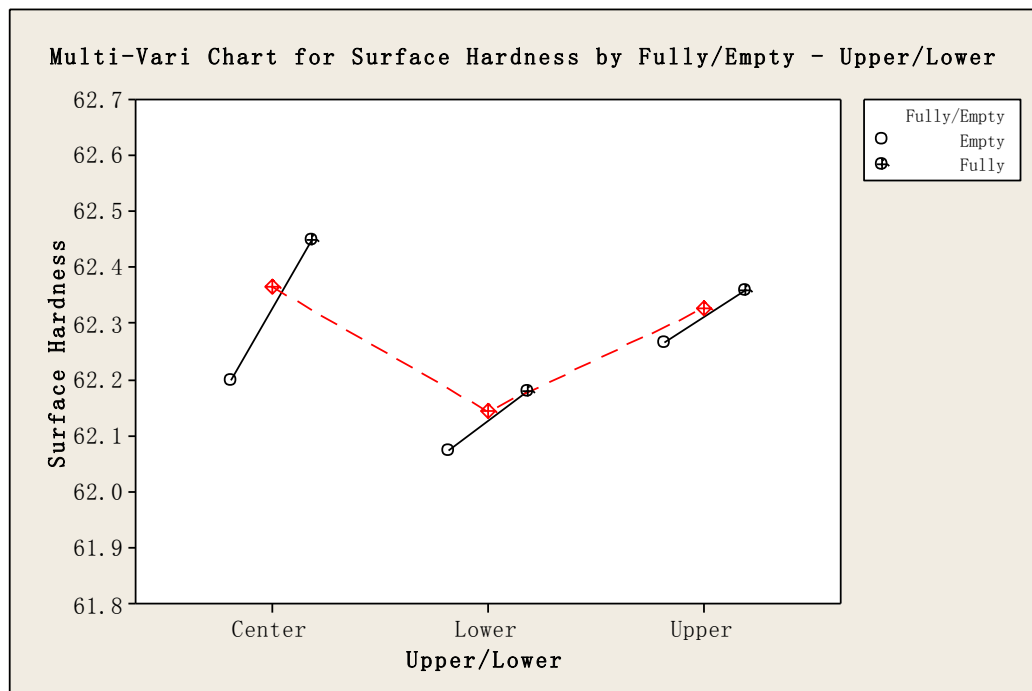


Figure 45 Multi-Vari Chart for Surface Hardness by Fully/Empty– Upper/Lower (VCE 2010) [12]

In Figure 45, lower positions in fully/empty loaded track shows low mean surface hardness. The mean value for upper and center part are similar, however, the center is calculated from three samples from three tracks.

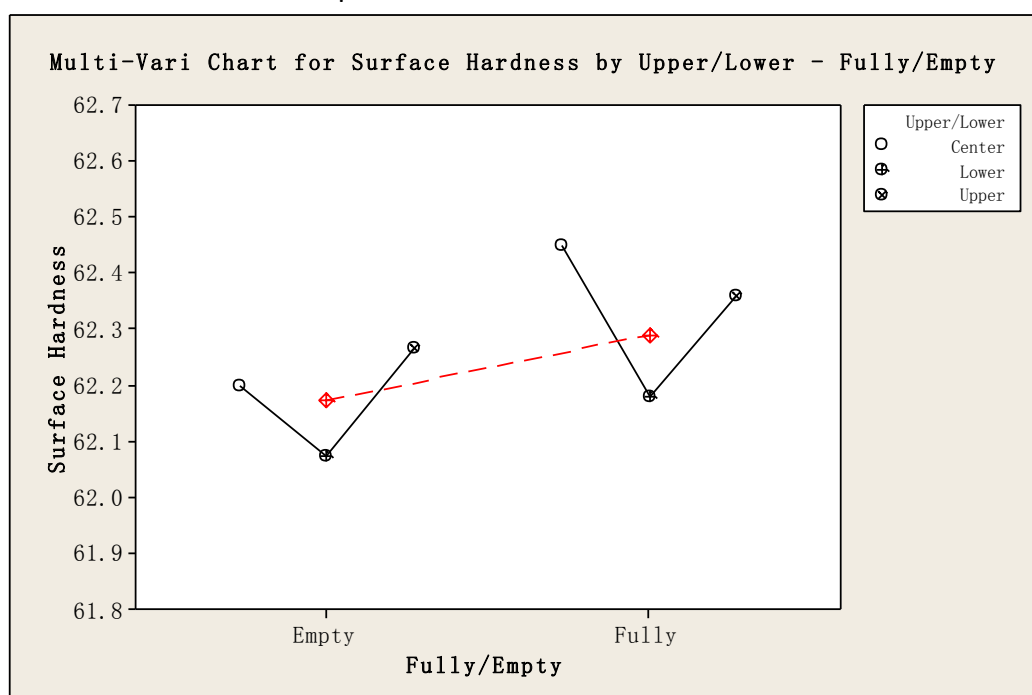


Figure 46 Multi-Vari Chart for surface hardness by Upper/Lower – Full/Empty: VCE 2010 [12]

To investigate the influences of factors “Upper/Lower” positions of furnace and “Fully/Empty” loading conditions of the furnace on the response of mean surface hardness, multi-chart is as shown in Figure 46.

In Figure 46, the lower positions on both Fully and Empty loaded track show low surface hardness values. Fully loaded track shows higher mean value than that of empty loaded track. Note that Figure 45 and 46 show both factors as Fully/Empty and Upper/Lower, however, each of them provides extra information about the process, e.g. Figure 45 shows the mean value of Upper, Lower and Center positions of the stacking tray. Figure 46 shows the mean values for Fully and Empty loaded track. Also note that “Fully loaded track” refers to track 1 and 3 which are tested on the first day when a warning occurred and there are possible disturbances.

Summary of capability study for surface hardness at VCE in 2010, Fully loaded furnace (day 1) achieves higher surface hardness. Lower positions of the three tracks give lower surface hardness. For capability studies, track 3 shows better capability indices than track 1. Position 4 and 8 on track 1 and 3 should be paid special attention in future process capability studies and during production. For process capability studies, these results should also be compared with other parameters e.g. case depth and surface carbon content.

3.4. Core Hardness

3.4.1. Getrag All Wheels Drive AB

The core hardness was measured using 30 kg Vickers at Getrag in 2009. For each sample, three indentations were made and then average was calculated. The hardness was measured approximately 6.5 mm from the center of rod samples since there were signs of segregations in the center of the test rods. Although the hardness was measured at a distance from center, still there were large spread of results, see in Table 14 and Figure 47. The difference within sample is negligible compared with the differences between different samples. This is probably due to a combination of segregations and variations in quenching. Because large spread that exists between the samples which results in non-normal distributions, thus it is impossible to make capability analysis from this aspect.

Table 14 Core hardness of each sample and their mean values (Getrag 2009) [13]

Track	Position	Measurement 1	Measurement 2	Measurement 3	Mean	StDev	Range
1	1	333	334	331	332	1.5275	3
1	2	377	373	367	372	5.0332	10
1	3	366	343	341	350	13.8924	25
1	4	394	394	372	387	12.7017	22
1	5	367	369	374	370	3.6056	7
1	6	369	368	380	372	6.6583	12
1	7	329	327	320	325	4.7258	9
1	8	387	387	394	389	4.0415	7
1	9	378	373	389	380	8.1854	16
					364	6.7079	12
Track	Position	Measurement 1	Measurement 2	Measurement 3	Mean	StDev	Range
2	1	334	330	333	332	2.0817	4
2	2	370	372	371	371	1.0000	2
2	3	376	379	364	373	7.9373	15
2	4	357	363	371	364	7.0238	14
2	5	330	332	332	331	1.1547	2
2	6	361	365	340	355	13.4288	25
2	7	375	372	388	378	8.5049	16
2	8	338	341	344	341	3.0000	6
2	9	363	366	361	363	2.5166	5
					356	5.1831	10

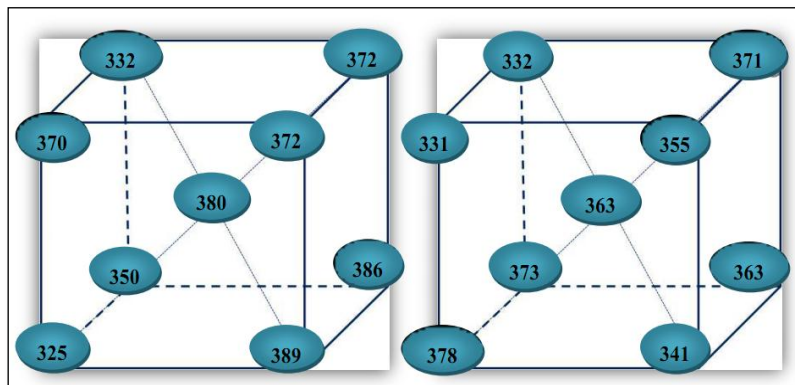


Figure 47 Mean core hardness on fixture (Left) Track 1; (Right) Track 2 (Getrag 2009) [13]

3.4.2. Volvo Construction Equipment AB

Samples from VCE furnace were measured at Getrag in 2010. The results of core hardness measurement for different samples are shown in Table 15 below.

Table 15 Core hardness of each sample and their mean value (VCE 2010) [12]

Track	Position	Measurement 1	Measurement 2	Measurement 3	Mean	StDev	Range
1	1	361	355	362	359	3.7859	7
1	2	360	359	360	360	0.5774	1
1	3	399	385	404	396	9.8489	19
1	4	397	404	410	404	6.5064	13
1	5	399	403	400	401	2.0817	4
1	6	375	400	382	386	12.8970	25
1	7	378	387	395	387	8.5049	17
1	8	374	378	366	373	6.1101	12
1	9	362	351	355	356	5.5678	11
					380	6.2089	12
Track	Position	Measurement 1	Measurement 2	Measurement 3	Mean	StDev	Range
2	1	412	399	405	405	6.5064	13
2	2	385	396	385	389	6.3509	11
2	3	400	387	392	393	6.5574	13
2	4	407	364	379	383	21.8251	43
2	5	401	387	395	394	7.0238	14
2	6	398	404	410	404	6.0000	12
2	7	423	415	410	414	6.5574	13
2	8	380	371	374	375	4.5826	9
2	9	359	391	353	368	20.4287	38
					392	9.5369	18
Track	Position	Measurement 1	Measurement 2	Measurement 3	Mean	StDev	Range
3	1	378	368	397	381	14.7309	29
3	2	365	356	371	364	7.5498	15
3	3	404	402	407	404	2.5166	5
3	4	389	391	404	395	8.1445	15
3	5	405	395	401	400	5.0332	10
3	6	400	387	399	395	7.2342	13
3	7	371	364	404	380	21.3620	40
3	8	368	376	371	372	4.0415	8
3	9	397	393	395	395	2.0000	4
					387	8.0681	15

Core hardness of the samples from three tracks varies from each other to a large extent. This is probably because of different microstructures e.g. bainite and martensite in the sample material. Besides, core hardness within the same track is also not the same, therefore process capability would not be studied in this case, but microstructures are studied instead for comparison.

It is generally thought that steels are homogenous, however, they are not in reality. Chemical composition varies from the surface to the core within the same sample. This is called segregations. For illustration of segregations in the test samples, see in Figure 48 (a) to (b) below.

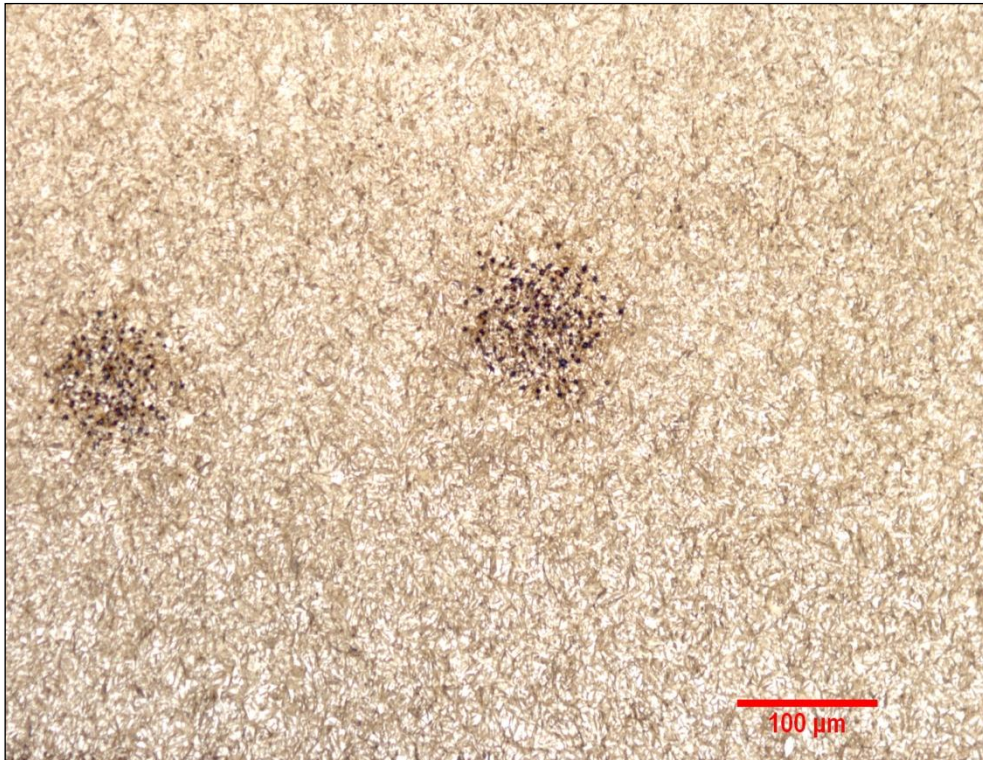


Figure 48 (a)

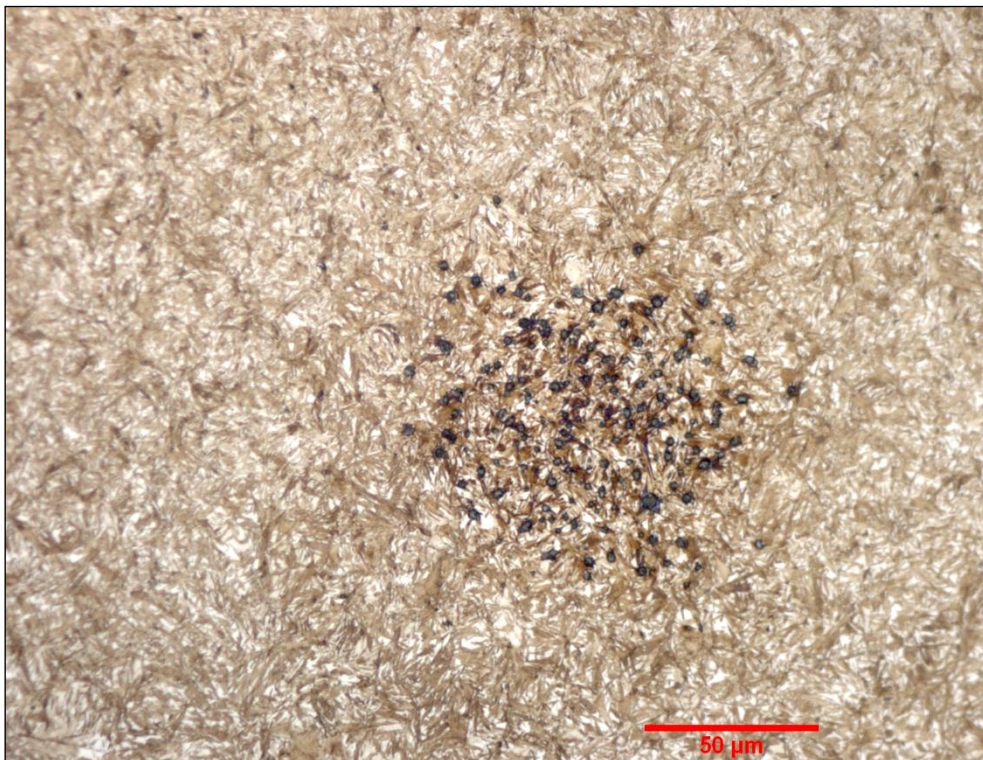


Figure 48 (b)

Figure 48 Segregation in case of sample 17, etched in 2% nital.

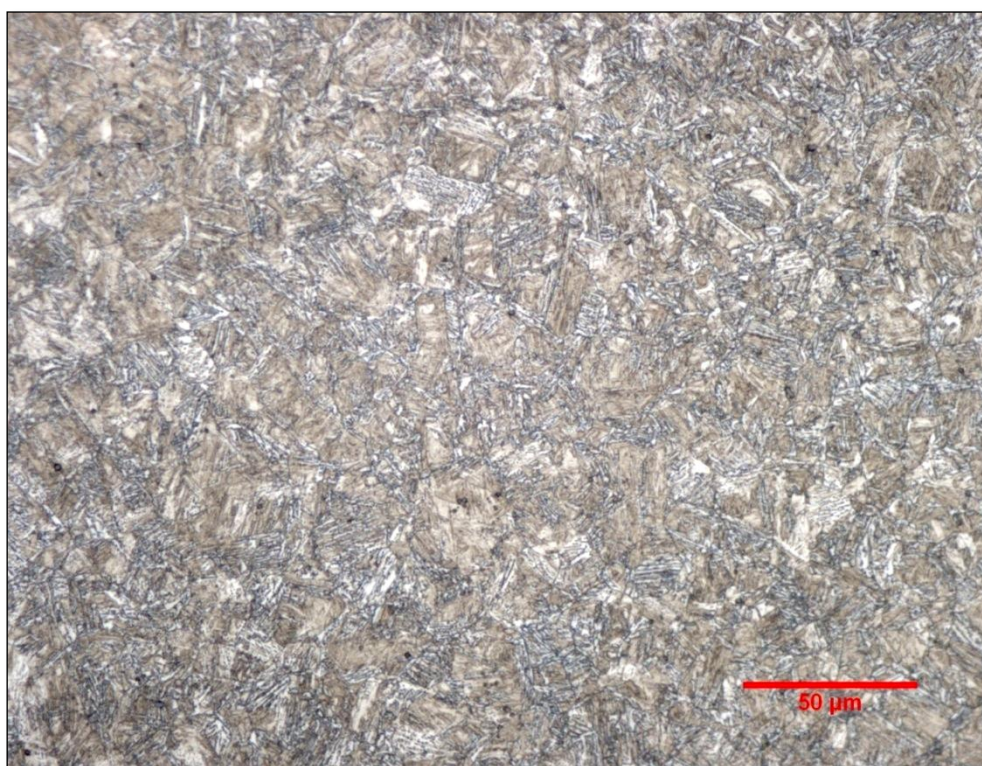
(a) 200 X ; (b) 1000X (VCE 2010)

The nominal chemical composition of sample material V-2158 can be seen from Table 16 below.

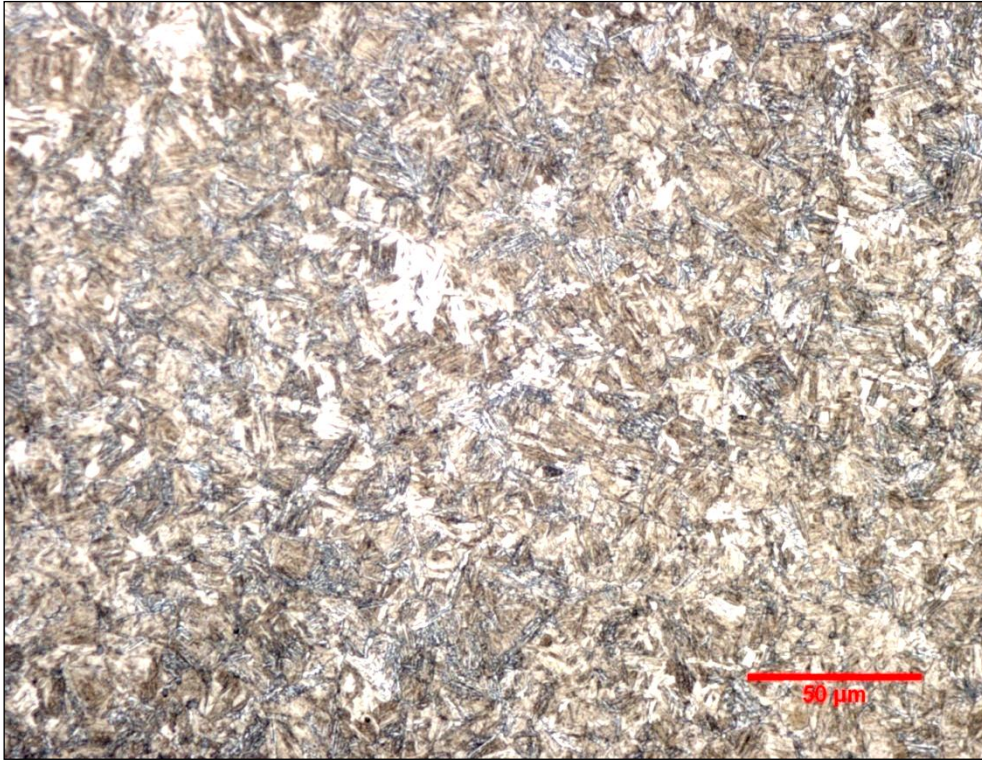
Table 16 Nominal chemical composition of V-2158 [14]

%	C	Si	Mn	P	S	Cr	V	Al	Mo
Min %	0.150	0.150	0.090	-	0.040	0.900	-	-	-
Max %	0.180	0.400	1.400	0.035	0.060	1.400	0.010	0.030	0.010

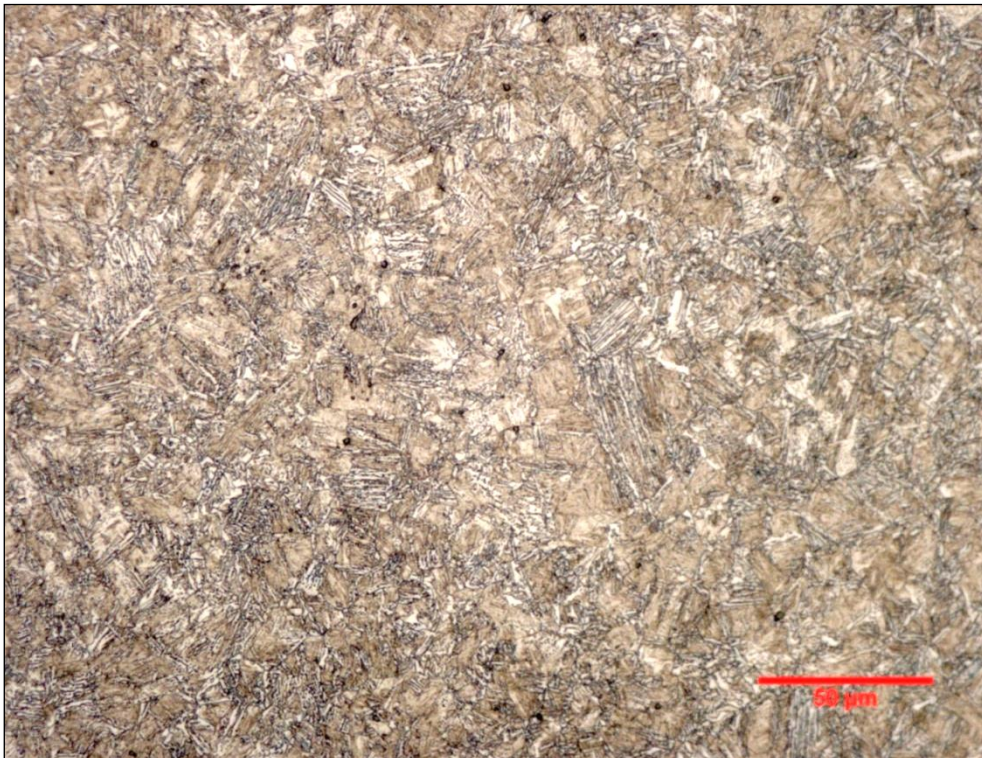
The microstructure has a strong influence on hardness, for example, the martensite is the hardest microstructure compared with retained austenite and bainite. The variations in microstructure probably results from segregations and different cooling rate (quenching speed).^[8] According to Geoffrey (1999), within a certain range of cooling rates, the alloy-rich areas have transformed to either martensite or bainite, while the areas which contain less alloys have the transformation from austenite to martensite and bainite with increasing amounts of pearlite and ferrite with the lower cooling rates.^[8] Segregation affects the hardness especially if it leads to local concentrations of pearlite or bainite in martensitic matrix. Figures 49(a)-(g) shows the core regions of each position from each track.



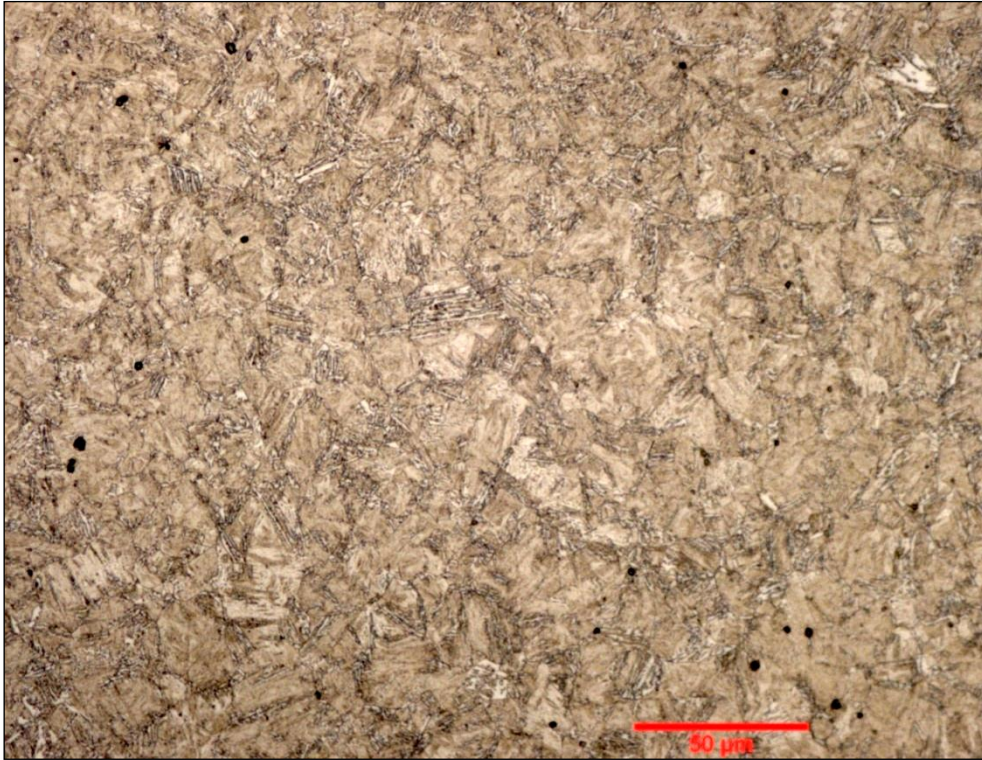
(a) Sample 11, core region (359 HV), etched in 2% nital, 500 X



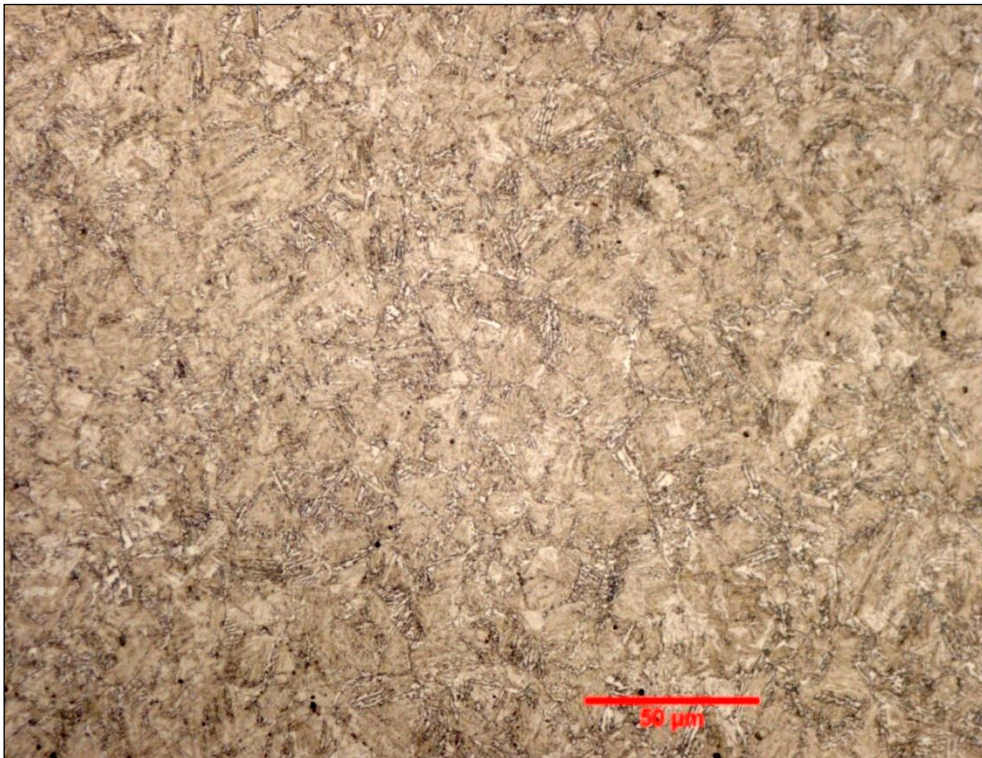
(b) Sample 14, core region (404 HV), etched in 2% nital, 500 X



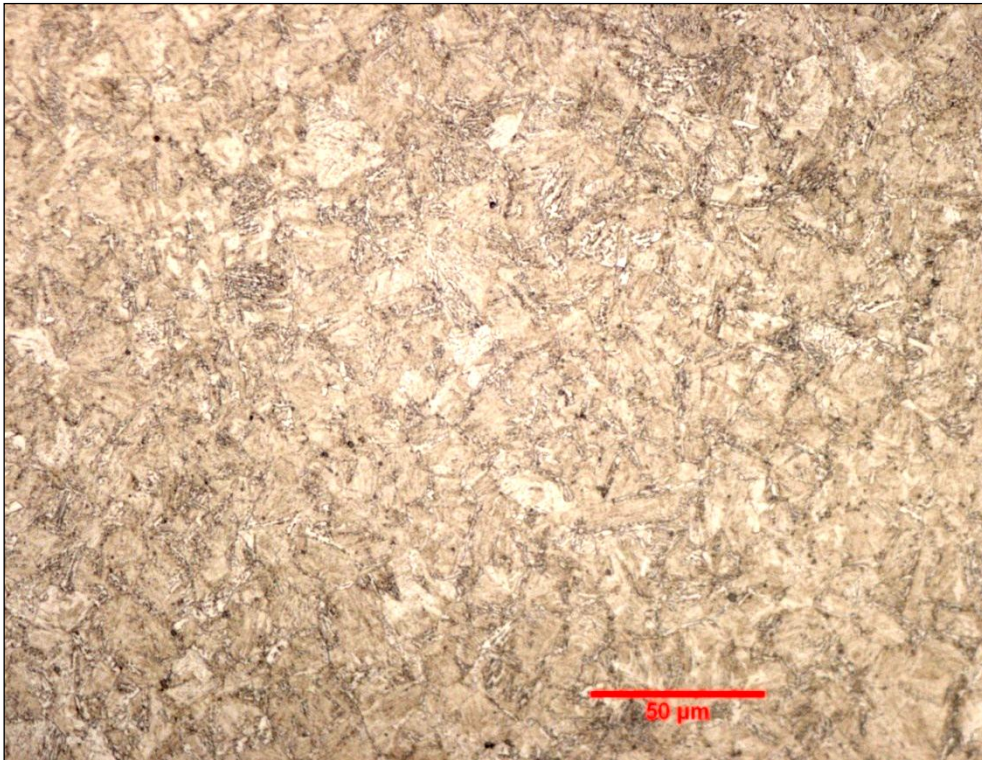
(c) Sample 19, core region (356 HV), etched in 2% nital 500 X



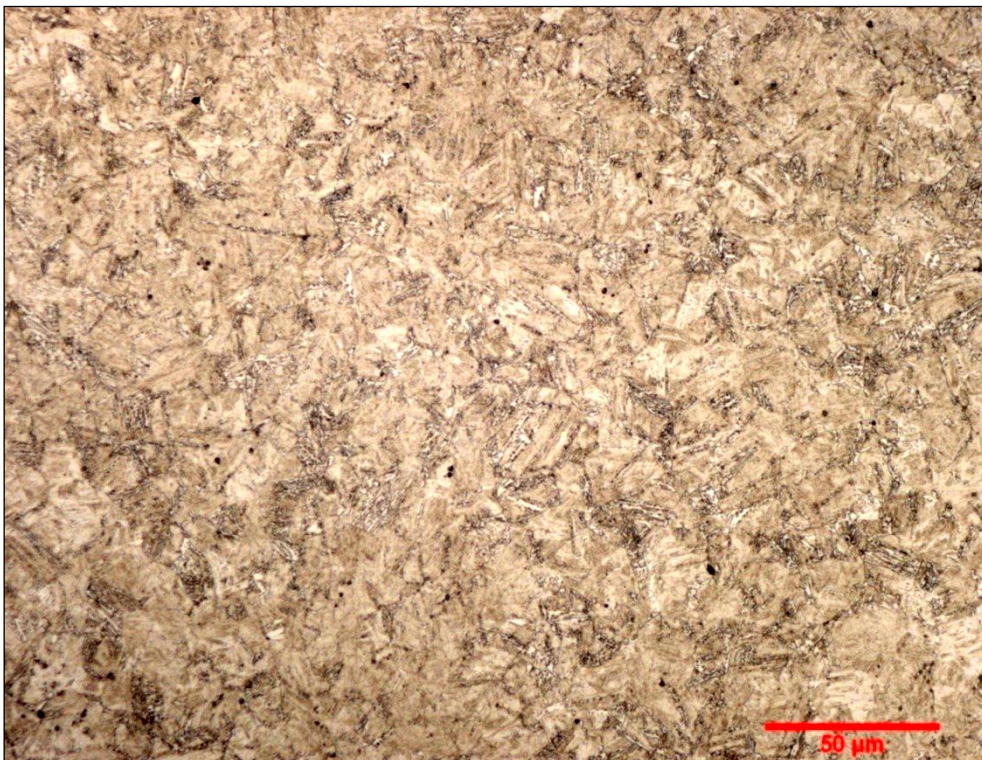
(d) Sample 21, core region (405 HV), etched in 2 % nital, 500 X



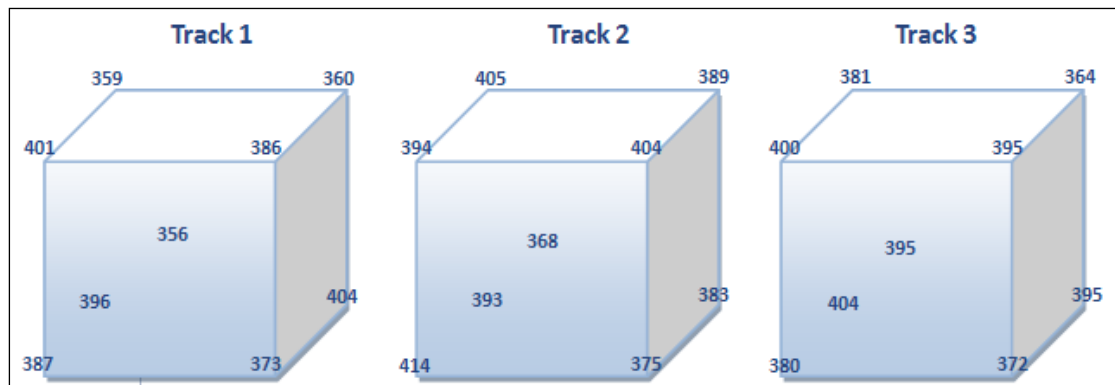
(e) Sample 28, core region (375 HV), etched in 2%, 500 X



(f) Sample 36, core region (414 HV), etched in 2% nital, 500 X



(g) Sample 39, core region (395 HV), etched in 2 % nital, 500 X.



(h) Mean core hardness

Figure 48 (a) Sample 11; (b) Sample 14; (c) Sample 19; (d) Sample 21; (e) Sample 28; (f) Sample 36; (g) Sample 39; (h) Mean core hardness

Note that the chemical composition for raw material is not studied in this project, no CCT diagrams are made to identify the amount of microstructure e.g. 40 % martensite. All graphs shown above are just for comparison of different core hardness mean values.

To investigate the influence of factors on the responses, box plots and multi-vari charts are made. In Figure 50, the response is core hardness and the factor is Track.

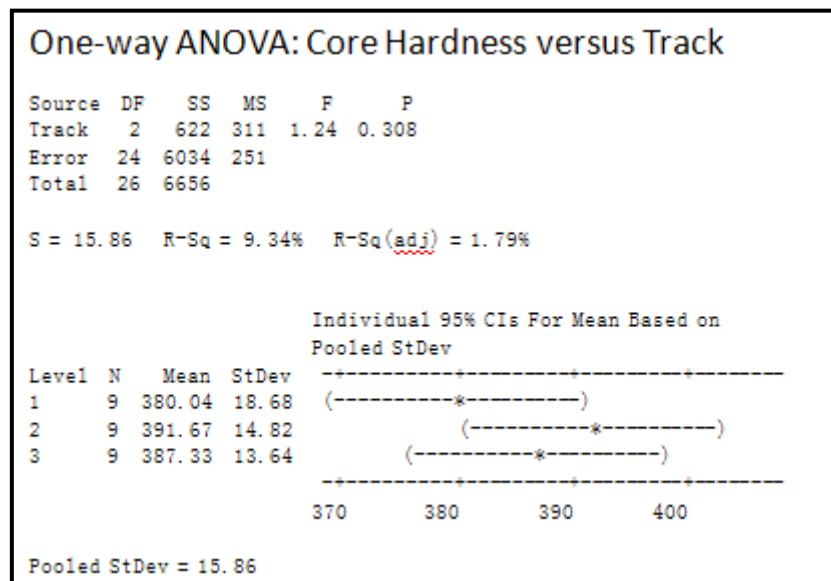


Figure 50 One-way ANOVA: Core hardness versus Track (VCE 2010) [12]

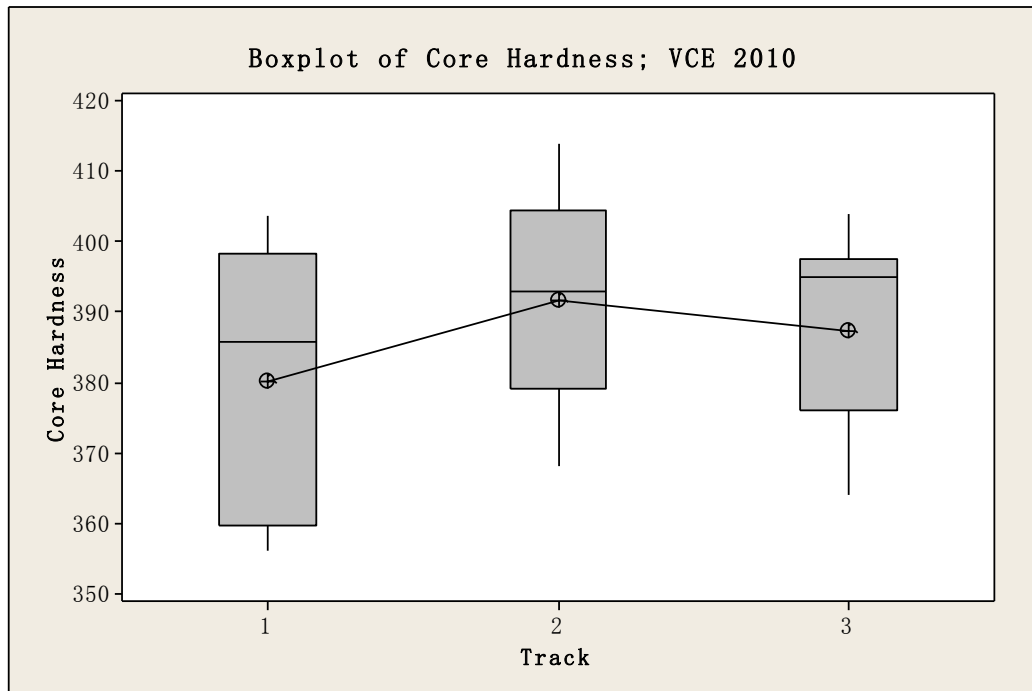


Figure 51 Box plot of Core Hardness (VCE 2010) [12]

The p-value obtained in Figure 49 is 0.308 which means there is no significant difference between different tracks. The individual 95% CI (confidence interval) for mean based on pooled standard deviation shows track 1 has lower core hardness. Box plot in Figure 51 indicates that from track 1 to track 3 the variability is reducing due to the trend of smaller box height.

If the factor is Position and the response is Core Hardness, one-way ANOVA is made, see in Figure 52.

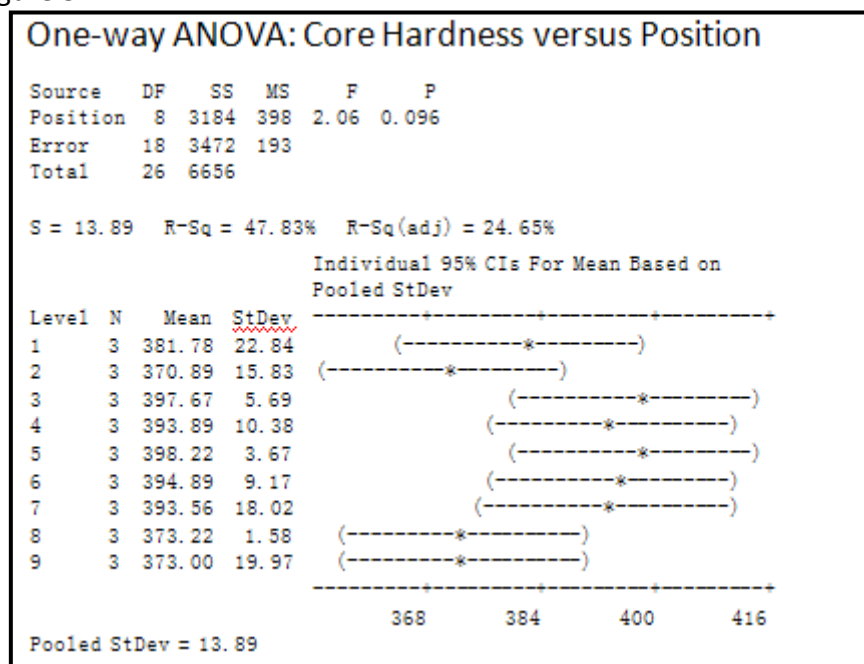


Figure 52 One-way ANOVA: Core Hardness versus Position (VCE 2010) [12]

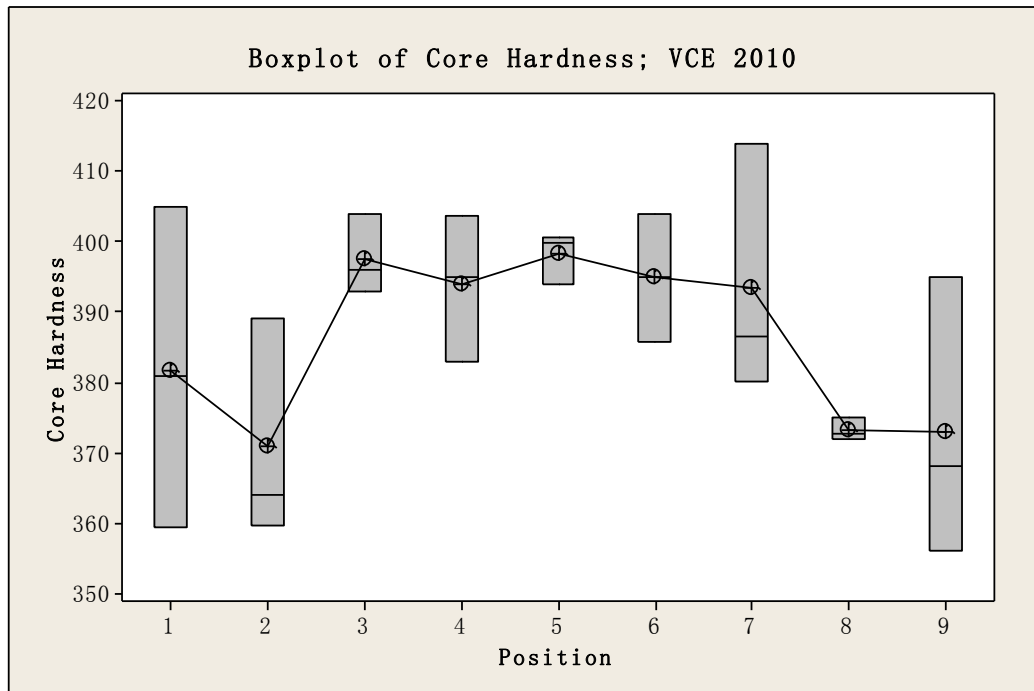


Figure 53 Box plot of core hardness (VCE 2010) [12]

The p-value in Figure 52 is 0.096, higher than 0.05 which means there is no significant difference among the mean values of core hardness. Note that position 1, 2, 8 and 9 present lower means than the rest of the positions. Position 3, 4, 5, 6 and 7 shows relatively similar mean values, see in the box plot above.

The influence of factor Upper/Lower on Core Hardness is shown in Figure 54 below.

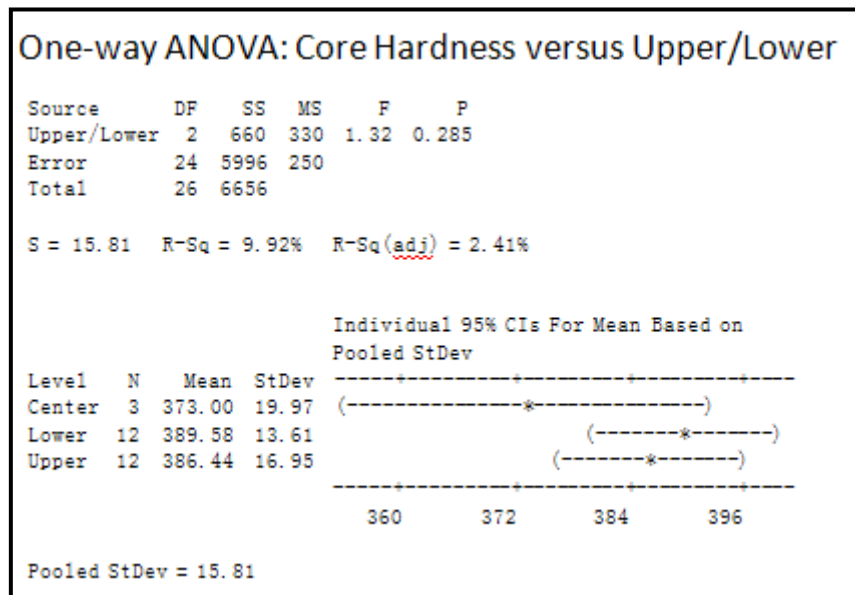


Figure 54 One-way ANOVA: Core Hardness versus Upper/Lower (VCE 2010) [12]

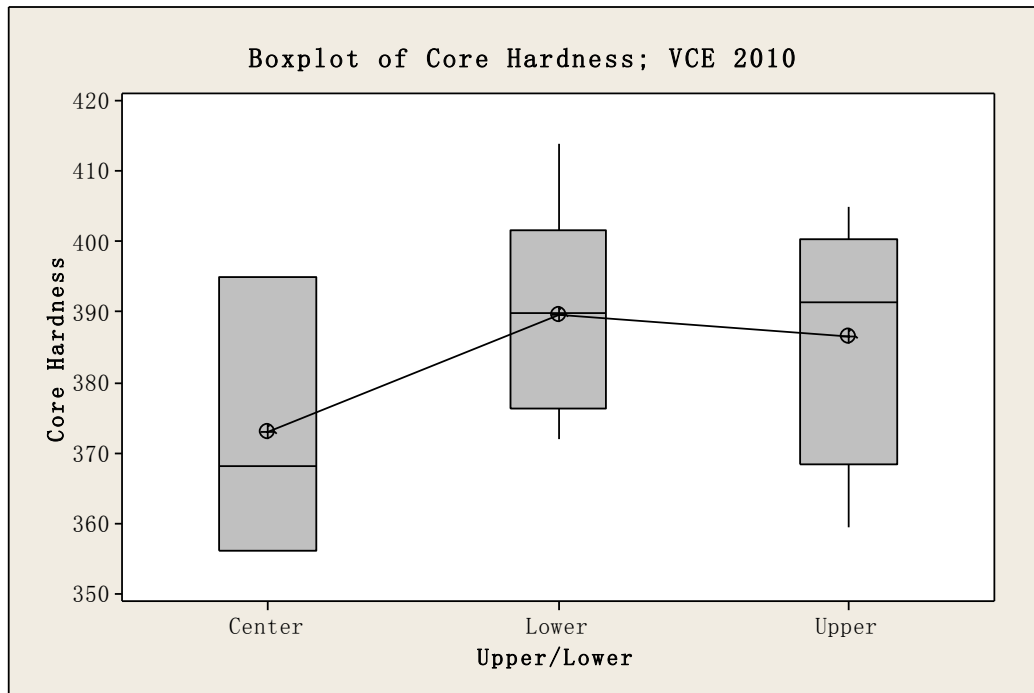


Figure 55 Box plot of core hardness (VCE 2010) [12]

The p-value in Figure 54 is 0.285 which is larger than set the level of significance (0.05). This means that the difference between the upper and lower positions of the furnace is not significant. The box plots from upper positions show wider spread than lower positions see in Figure 55 above. The box plot for Center doesn't have the upper and lower whiskers due to small amount of data.

The influence of Fully/Empty loading conditions on core hardness using one-way ANOVA test is illustrated in Figure 56 below.

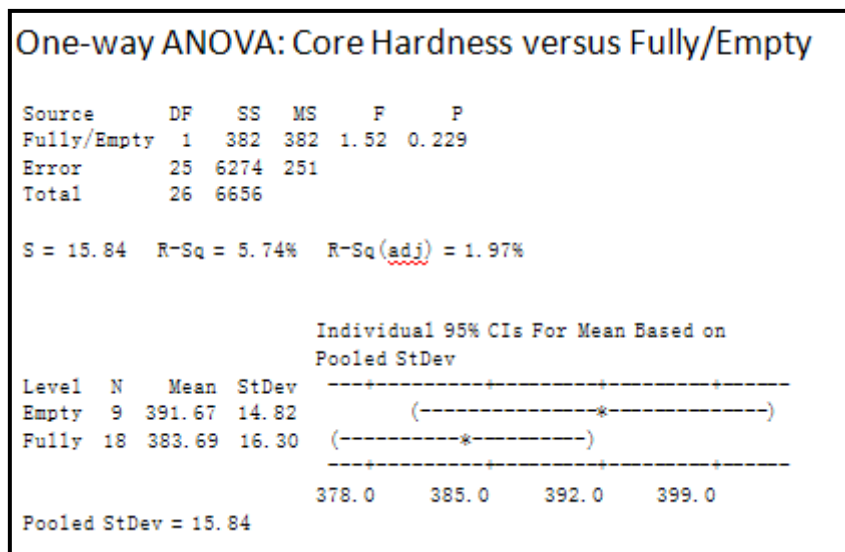


Figure 56 One-way ANOVA: core hardness versus fully/empty loaded track (VCE 2010) [12]

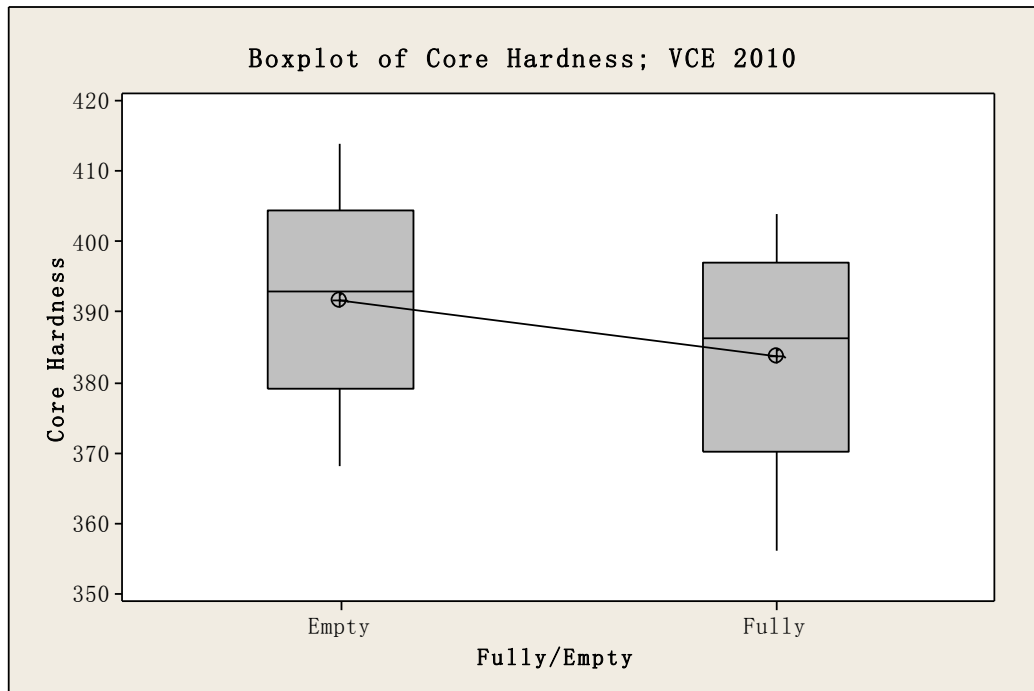


Figure 57 Box plot of core hardness (VCE 2010) [12]

In Figure 57, the p-value from one-way ANOVA test shows that there is no significant difference, however, fully loaded track shows slightly lower core hardness than that of empty loaded track. The box plot in Figure 56 displays that fully loaded track has a little wider spread as the height of the box was larger than empty furnace. To study two factors' interactions, multi-vari charts are plotted in software. These factors are Track, Position, Upper/Lower and Fully/Empty. The response is mean core hardness.

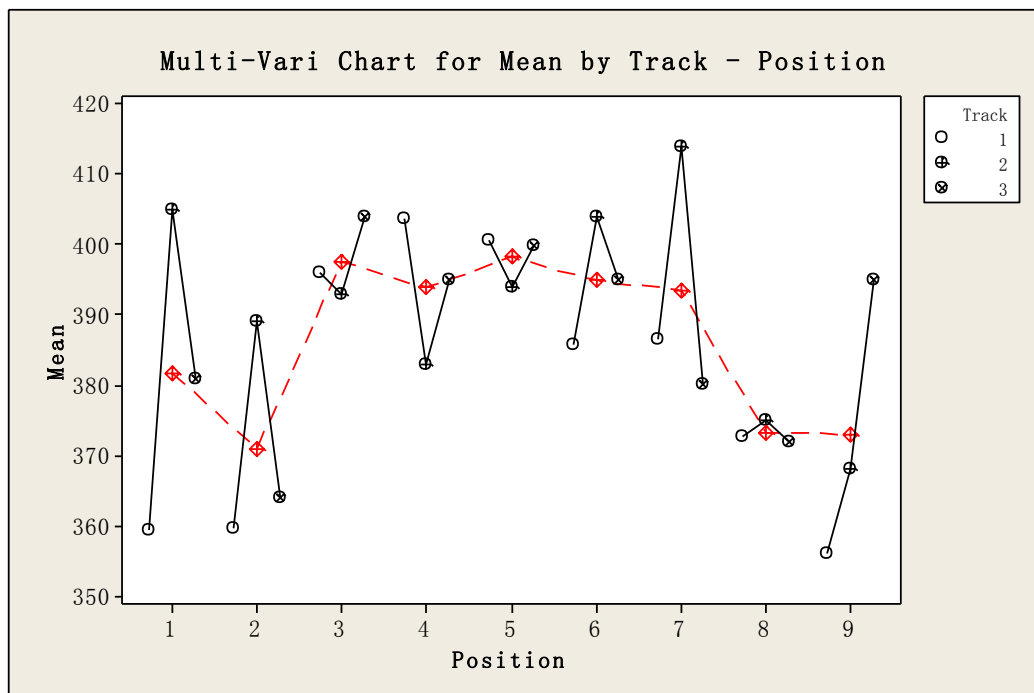


Figure 58 Multi-vari chart for mean core hardness by Track – Position (VCE 2010) [12]

The multi-vari chart above shows that track 2 differs a lot from track 1 and 3, which

might be due to track 2 is tested on the second day which is empty loaded track, and track 1 and 3 might be disturbed by the warning on the first day as well.

In order to investigate interaction of Track and Upper/ Lower level of the furnace, multi-vari chart is shown in Figure 59 below.

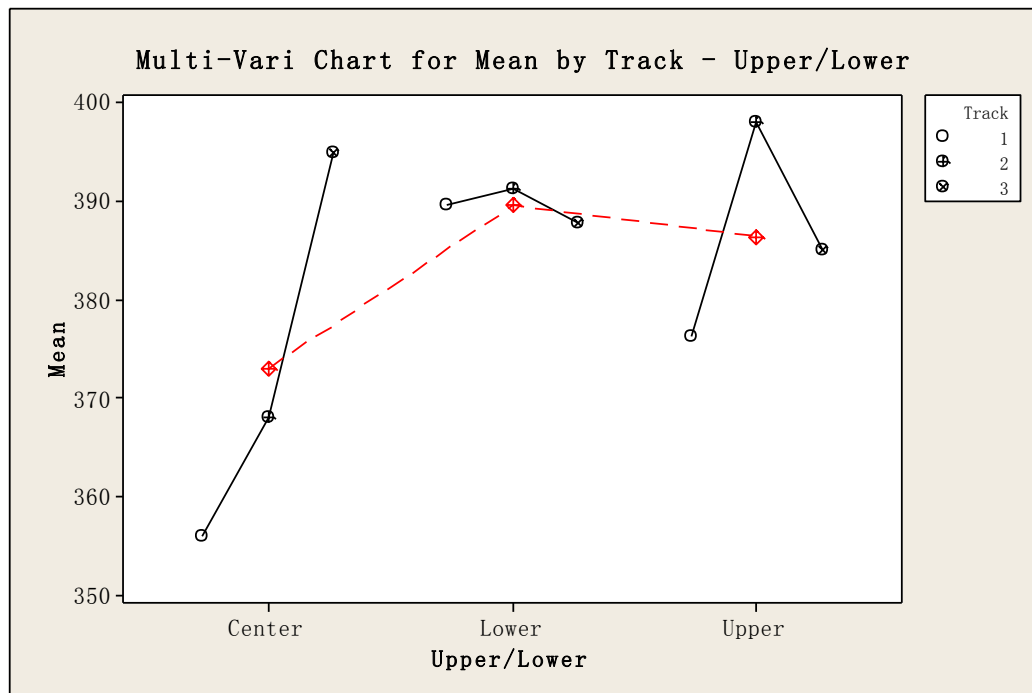


Figure 59 Multi-vari chart for mean core hardness by Track – Upper/Lower (VCE 2010) [12]

Note that Center is calculated from three values from all three tracks, while the Upper and Lower are calculated from 12 values from all tracks. The lower part has higher core hardness value than that of upper and center. It is impossible to plot multi-vari chart by Track – Fully/Empty and Position – Upper/ Lower due to more than 40% cells is missing in Minitab data sheet, thus no charts are made about these two factors. Multi-vari chart about factors as position and fully/empty is shown in Figure 60 below.

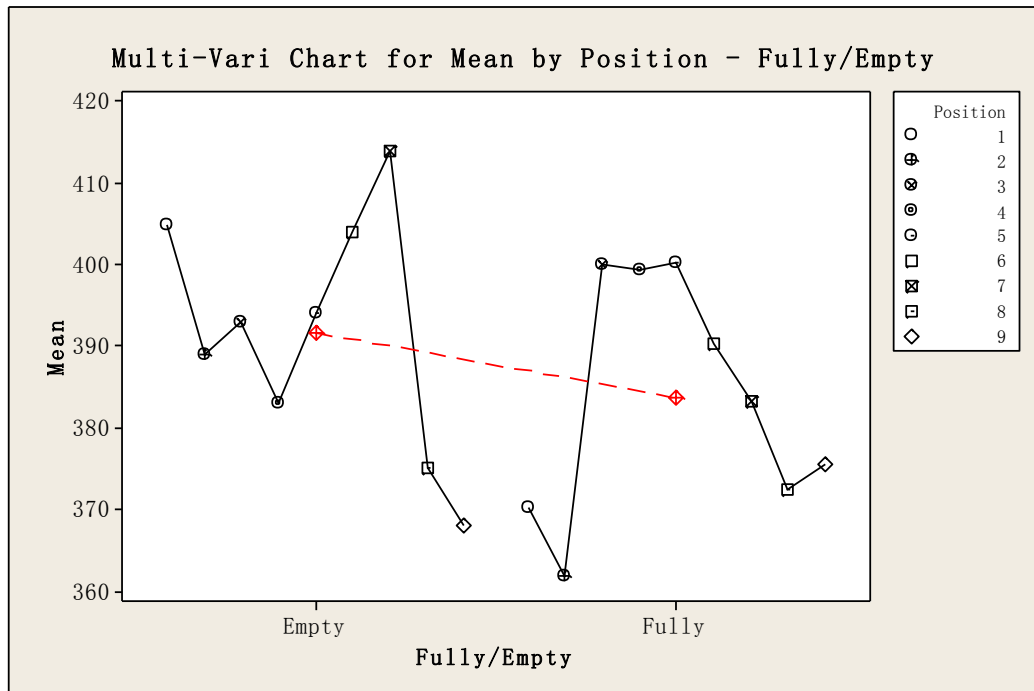


Figure 60 Multi-vari chart for means by Position – Fully/ Empty (VCE 2010) [12]

In Figure 60 above, fully loaded track shows lower core hardness than that of empty loaded track, which is measured from track 2, however, the difference is very small.

To study the interaction of Upper/Lower and Fully/Empty on core hardness, multi-vari chart is shown in Figure 61.

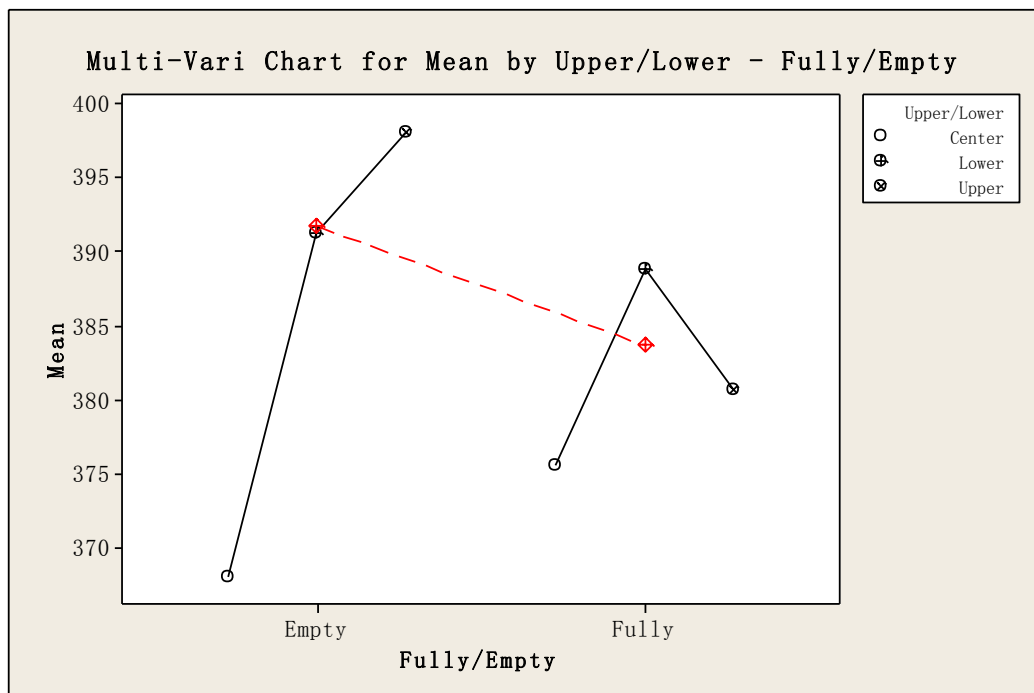


Figure 61 Multi-vari chart for Mean by Upper/Lower – Fully/Empty (VCE 2010) [12]

From Figure 61 above the conclusion could be made that the upper position of

empty loaded track has higher core hardness, while the center shows low core value which is 30 HV lower than upper parts. The central parts on all three tracks show low core hardness and empty furnace give a wide spread.

Summary of capability study for core hardness at VCE in 2010, all factors show high p-values but core hardness varies from position to position and from track to track. One possible reason is due to the amount of martensite and bainite in the core which has influence results, however, production disturbance on the first day and different testing conditions could also affect results.

3.5. Surface Carbon Content

3.5.1. Getrag All Wheels Drive AB

Surface carbon content and carbon profiles were determined with *Leco* equipment at Getrag in 2009. Surface carbon content is measured from a layer thickness of 0.15 mm, see in Table 17 below. The target for surface carbon content is 0.8 wt % C, with LSL at 0.7 wt% C and USL at 0.9 wt% C.

Table 17 Surface carbon content from track 1 and track 2 (Getrag 2009) [13]

Track	Position	wt % C	P-value	Mean	StDev
1	1	0.83	0.207	0.842	0.027
1	2	0.81	-	-	-
1	3	0.89	-	-	-
1	4	0.86	-	-	-
1	5	0.81	-	-	-
1	6	0.83	-	-	-
1	7	0.86	-	-	-
1	8	0.86	-	-	-
1	9	0.83	-	-	-

Track	Position	wt % C	P-value	Mean	StDev
2	1	0.83	0.459	0.852	0.024
2	2	0.86	-	-	-
2	3	0.86	-	-	-
2	4	0.89	-	-	-
2	5	0.82	-	-	-
2	6	0.84	-	-	-
2	7	0.83	-	-	-
2	8	0.88	-	-	-
2	9	0.86	-	-	-

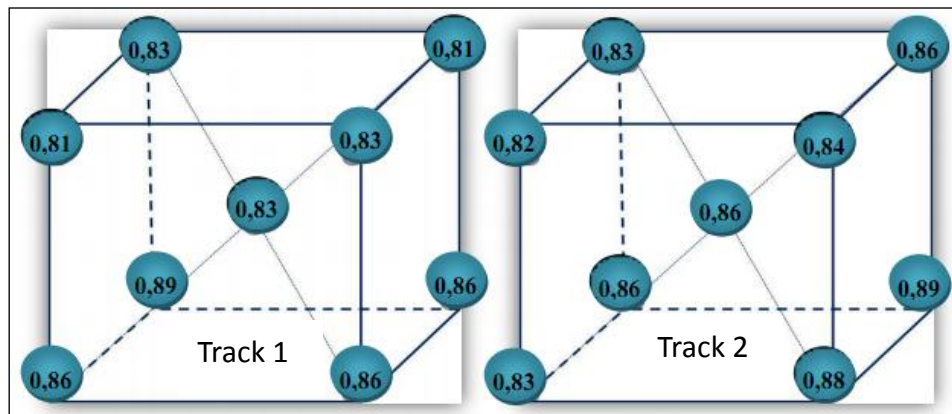


Figure 62 Surface carbon content of each position from track 1 and 2 (Getrag 2009) [13]

Figure 62 shows a difference between Upper and Lower positions of the surface carbon content. For further study of differences, the stacking trays are divided into two parts, that is, the Upper and Lower half. 2-sample t-tests are made to check out whether there is a significant difference or not between two tracks. The p-value is 0.416 which is higher than the level of significance with $\alpha=0.05$, which means that there is no significant difference between two tracks, and thus it is possible to analyze them as one group. For track 1, track 2, track 1&2, Upper and Lower cases, surface carbon content are normally distributed, therefore capability indices could be obtained, see in Table 18 below.

Table 18 Normality test of Track 1, 2 and 1 & 2, Upper and Lower positions (Getrag 2009) [13]

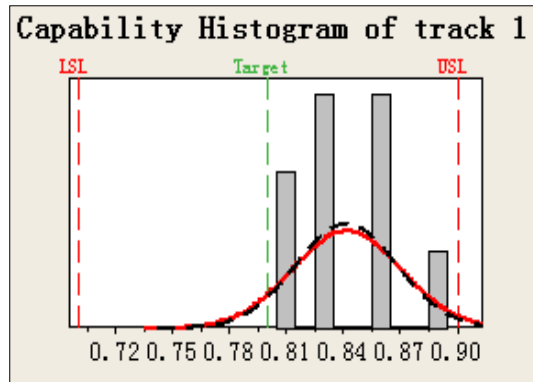
Track	P-value	StDev	Mean	Distribution
1	0.207	0.027	0.842	Normal
2	0.459	0.024	0.852	Normal
1 & 2	0.065	0.025	0.847	Normal
Upper	0.140	0.018	0.832	Normal
Lower	0.056	0.021	0.862	Normal

The mean value in Table 18 shows that the lower part has a higher mean value than upper part, and track 2 has a higher mean than track 1. Capability indices are obtained from Minitab, see in Table 19 below.

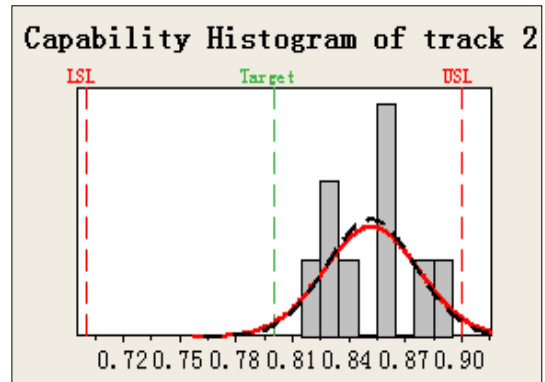
Table 19 Capability indices of track 1, track 2, track 1&2, upper and lower positions (Getrag 2009)

Track	Sample N	Pp	Ppk	Cpm	Target	LSL	USL
1	9	1.24	0.72	0.64	0.8	0.7	0.9
2	9	1.40	0.67	0.55	0.8	0.7	0.9
1 & 2	18	1.32	0.70	0.61	0.8	0.7	0.9
Upper	10	1.90	1.29	0.88	0.8	0.7	0.9
Lower	10	1.59	0.60	0.49	0.8	0.7	0.9

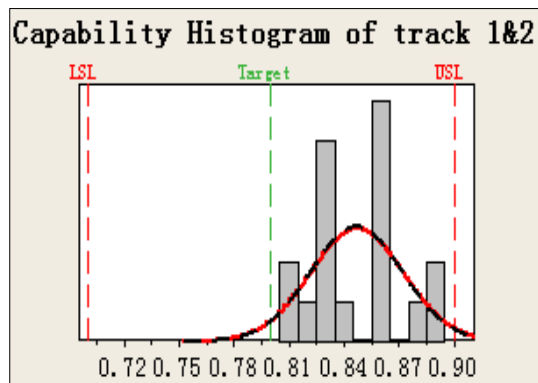
Pp values in Table 19 for all cases are OK but correction is needed for track 1 to achieve higher performance index. The upper part has the highest Pp which indicates that the carbon potential is well controlled at upper half of furnace. For track 1 and 2, the former has lower Pp value but higher Ppk value which means the process is better centered. The lower positions of the furnace shows low Ppk and Cpm values, which means the process is off-centered even worse.



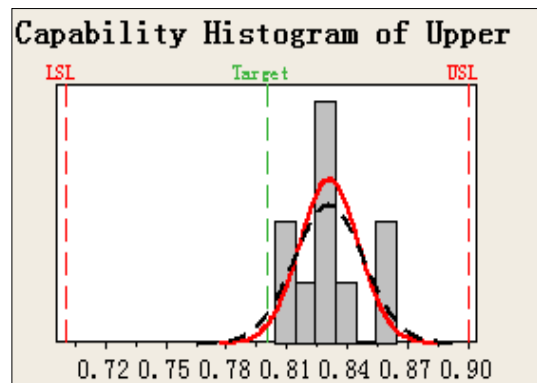
a)



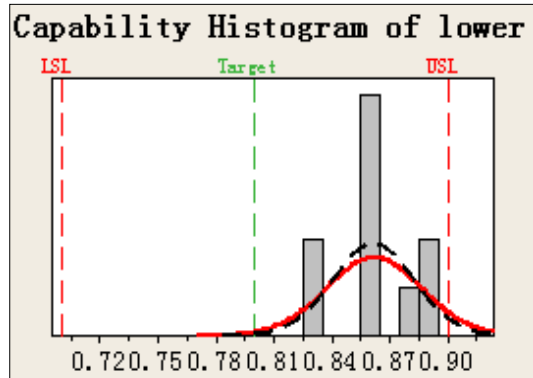
b)



c)



d)



e)

Figure 63 Capability Histogram of a) Track 1; b) Track 2; c) Track 1&2; d) Upper part; e) Lower part.
Getrag 2009 [12]

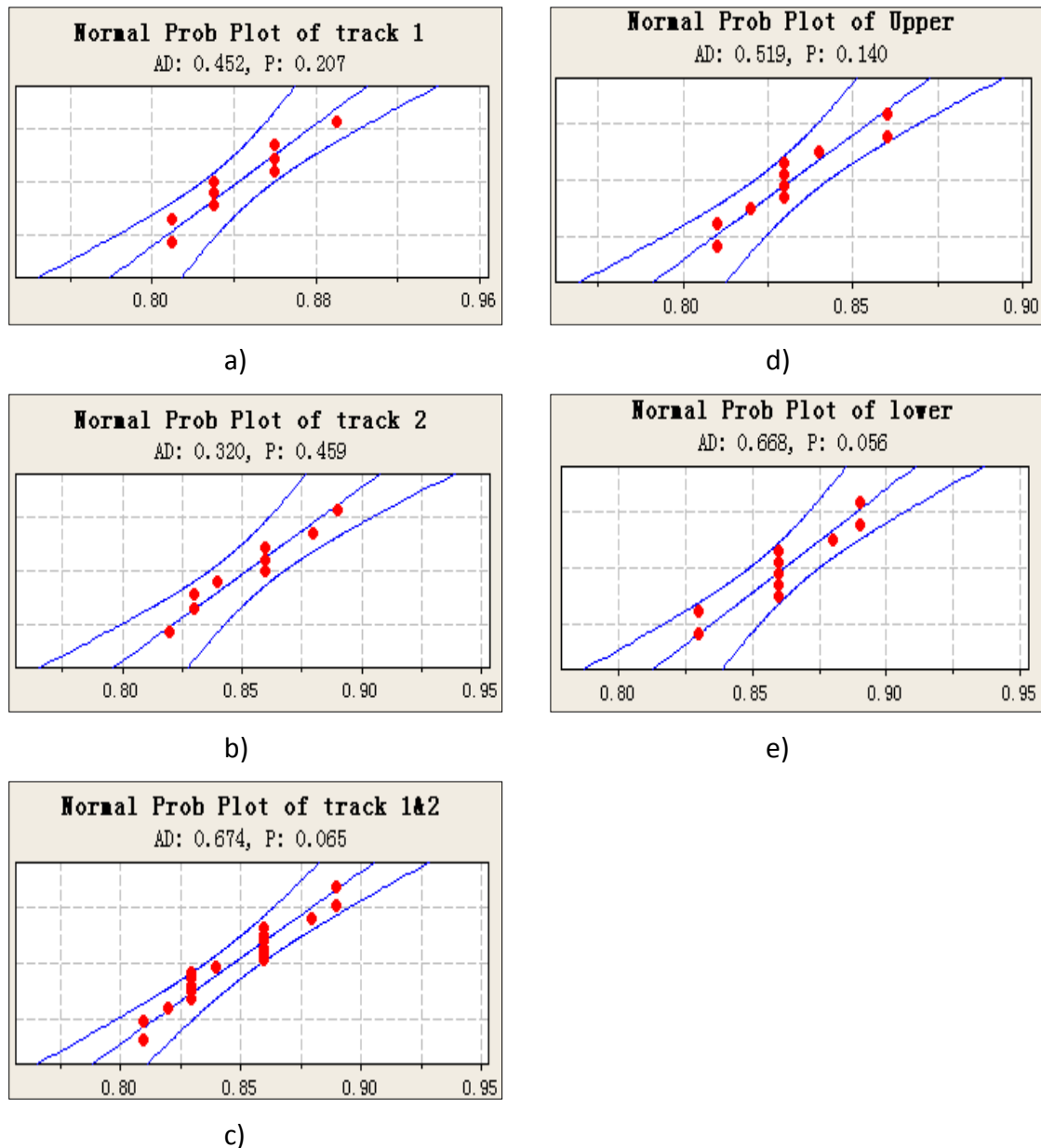


Figure 64 Normal Probability Plot of a) Track 1; b) track 2; c) Track 1&2; d) Upper; e) Lower.
Getrag 2009 [12]

In Figure 63, the spread is wide in relation to the tolerance limits, and all processes are not centered with low Ppk and Cpm which means that there is potential to make improvement by controlling the carbon atmosphere in the furnace for higher capability indices. One suggestion is to improve the gas circulations in the furnace.

3.5.2. Volvo Construction Equipment AB

Surface carbon content of the samples from VCE was determined with *Leco* equipment at Getrag in 2010. The result for each case is shown in Table 20. The target value is 0.80 wt% C with LSL and USL are 0.70 and 0.90 wt% C, respectively.

Table 20 Surface carbon content from track 1, 2 and 3 (VCE 2010)

Track	Position	Carbon Content %	P-value	Mean	StDev
1	1	0.84	0.122	0.829	0.015
1	2	0.83	-	-	-
1	3	0.85	-	-	-
1	4	0.84	-	-	-
1	5	0.83	-	-	-
1	6	0.80	-	-	-
1	7	0.83	-	-	-
1	8	0.84	-	-	-
1	9	0.83	-	-	-

Track	Position	Carbon Content %	P-value	Mean	StDev
2	1	0.78	0.231	0.777	0.014
2	2	0.79	-	-	-
2	3	0.79	-	-	-
2	4	0.79	-	-	-
2	5	0.76	-	-	-
2	6	0.77	-	-	-
2	7	0.77	-	-	-
2	8	0.76	-	-	-
2	9	0.79	-	-	-

Track	Position	Carbon Content %	P-value	Mean	StDev
3	1	0.82	0.731	0.828	0.010
3	2	0.83	-	-	-
3	3	0.84	-	-	-
3	4	0.83	-	-	-
3	5	0.82	-	-	-
3	6	0.81	-	-	-
3	7	0.82	-	-	-
3	8	0.84	-	-	-
3	9	0.84	-	-	-

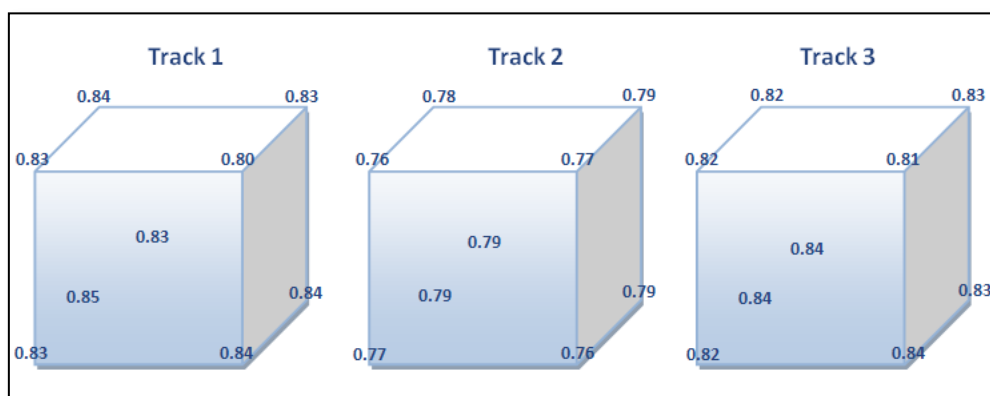


Figure 64 Surface carbon content cubes (VCE 2010)

In Table 20 and Figure 65, it is shown that track 1 and 3 have higher mean surface carbon content than that of track 2. The mean value for track 1 and 3 are slightly different (0.001 wt% C) from each other which is neglectable. 2-sample t-tests are made in Minitab, and the p-values for track 1&2 and track 2&3 are even lower than

expected value of 0.05 which means the significance difference exists. For the case of track 1&3, the p-value is 0.831 which means there is no significant difference between mean values of tracks 1 and 3, thus it is possible to analyze them together. The normality test results are shown in Table 21 below. Because all of them have the p-values higher than 0.05, therefore capability indices can be evaluated to analyze the process. Pp, Ppk and Cpm are shown in Table 22.

Table 21 Normality tests of track 1, track 2, track 3 and track 1&3 (VCE 2010)

Track	Sample N	P-Value	Mean	StDev	Distttribution
1	9	0.122	0.829	0.015	Normal
2	9	0.231	0.777	0.014	Normal
3	9	0.731	0.828	0.010	Normal
1&3	18	0.478	0.829	0.013	Normal

Table 22 Capability analyses of track 1, track 2, track 3 and track 1, 2, 3 (VCE 2010)

Track	Sample N	Pp	Ppk	Cpm	Target	LSL	USL
1	9	2.21	1.56	0.96	0.80% C	0.70% C	0.9% C
2	9	2.43	1.87	1.20	0.80% C	0.70% C	0.9% C
3	9	3.15	2.27	1.05	0.80% C	0.70% C	0.9% C
1&3	18	2.63	1.88	1.04	0.80% C	0.70% C	0.9% C

For capability indices in Table 22, track 3 shows the highest Pp value at 3.15 which means the furnace is really good. Besides, Ppk and Cpm are higher than the other two tracks. For the first test, track 1 and 3 were put in the furnace at the same time with the same temperature and carbon potential, however, track 1 shows less Pp, Ppk and Cpm than that from track 3, which means track 3 is more capable of meeting specifications than track 1. The combination result of track 1 and 3 shows that the first capability study has good Pp and Ppk value but low Cpm value, which refers to the process is not centered within specification range. The Figure 66 indicates that the furnace can be divided into two parts, where Upper positions has slightly lower carbon content, and Lower part shows higher carbon content.

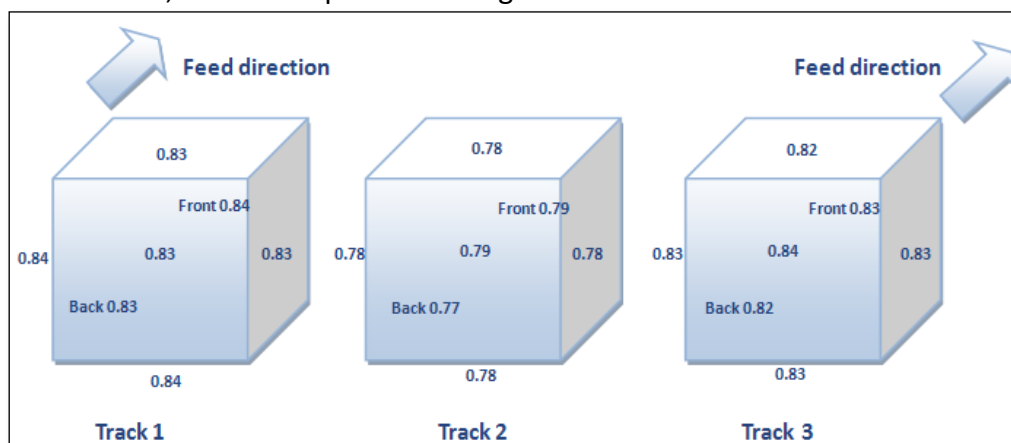


Figure 66 Mean surface carbon content of each cubic face (VCE 2010)

Lower positions of the track give a little higher surface carbon content than Upper positions, with the difference of 0.015 wt% C for track 1, 0.003wt %C for track 2 and 0.013 wt% C for track 3. Further analyses of the spread and distributions are shown in Figure 67 and 68 below.

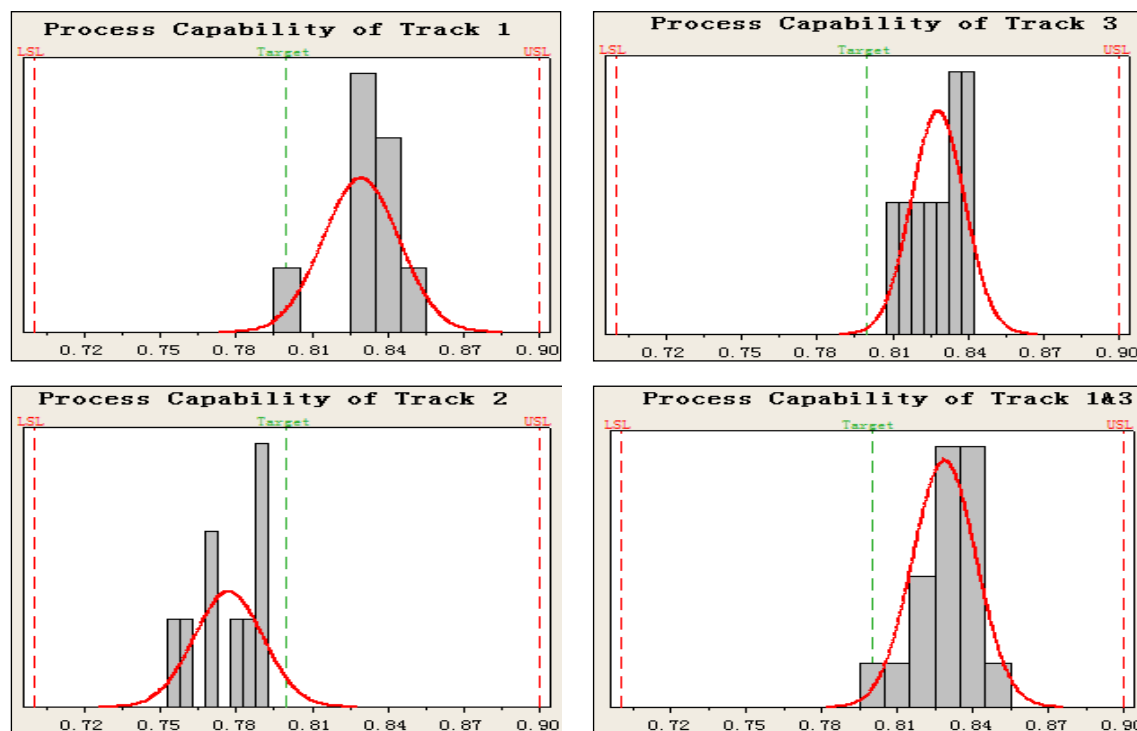


Figure 67 Histogram of track 1, track 2, track 3 and track 1&3 (VCE 2010) [12]

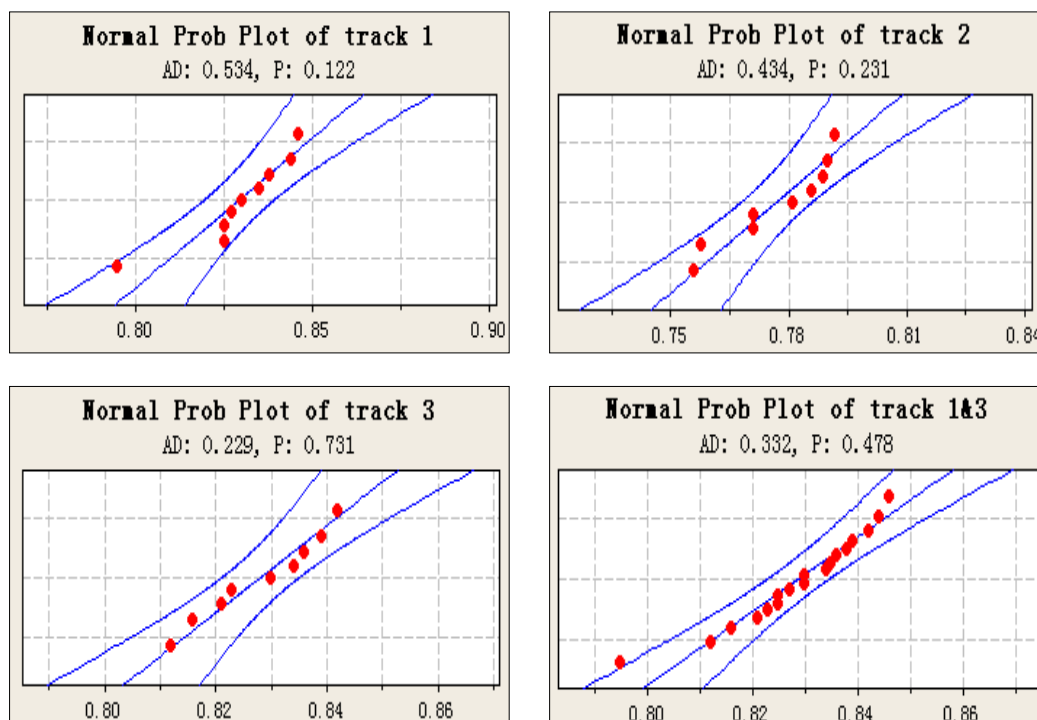


Figure 68 Normal Probability Plot of track 1, track 2, track 3 and track 1&3 (VCE 2010)

In Figure 67 the mean values of surface carbon content from Track 1 and 3 are located to the USL which means the process means are larger than the target, while the mean value from Track 2 is shift leftwards of the target. Note that the measure result of Position 3 on Track 1 is larger than 0.85 wt % C, which can have influence on mean and spread, see in Table 20 and Figure 68. In order to investigate factors such as Track, Position, Upper/Lower part and Fully/Empty loaded track, one-way ANOVA and multi-vari charts are made.

The influence of factor of Track on the response of Surface Carbon Content is shown in Figure 69.

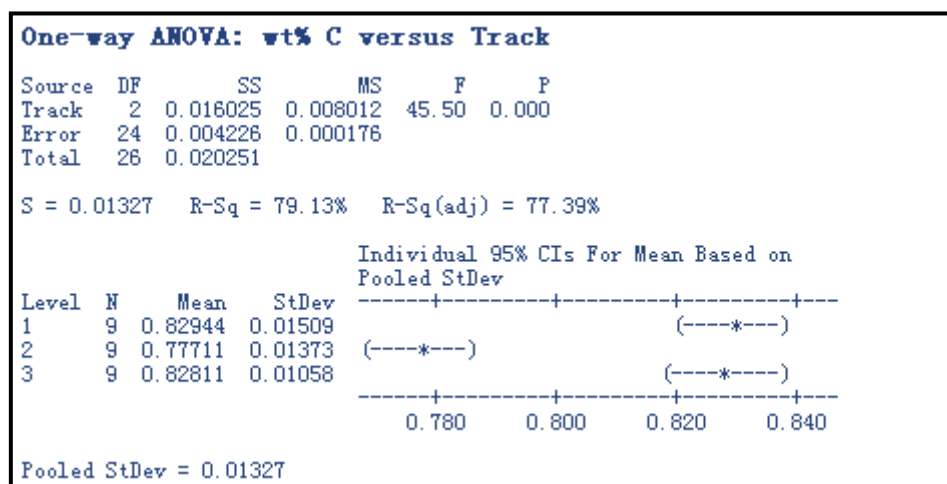


Figure 69 One-way ANOVA: Surface carbon content versus Track (VCE 2010) [12]

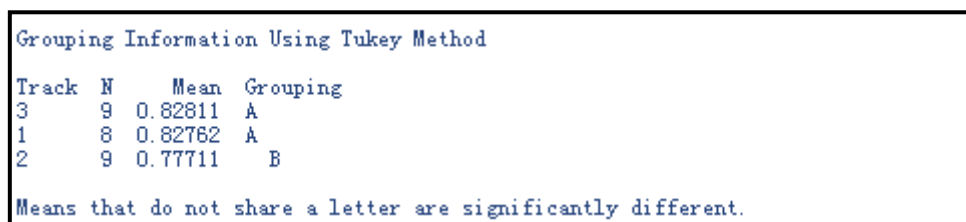


Figure 70 Grouping information (VCE 2010) [12]

The differences of the mean surface carbon contents between the Tracks are significant since the p-values are less than 95% confidence interval with $\alpha=0.05$, see in Figure 69. According to grouping information in Figure 70, track 1 and 3 are within the same group, and track 2 is in the other one which means that the average does not share a letter are significantly different.

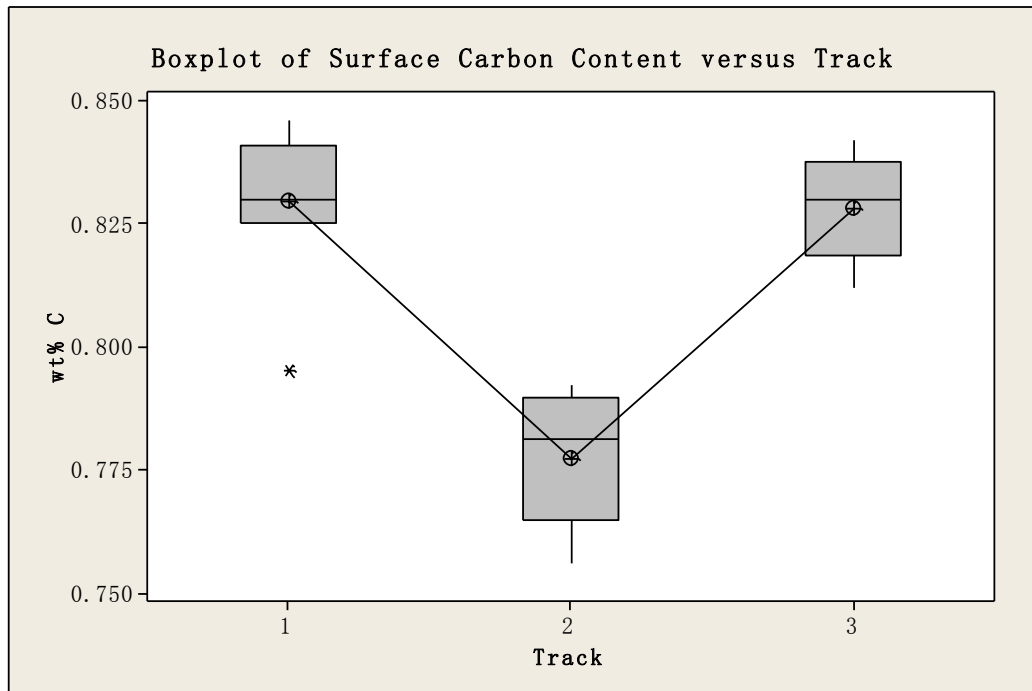


Figure71 Box plot of surface carbon content versus track (VCE 2010) [12]

The box plot in Figure 71 shows one outliers in track 1 with mean surface carbon content of 0.793 wt %. Track 3 is the most stable track of the three as the upper and lower whiskers have almost the same length and the median line is close to the mean value point.

The influence of factor of Position on response of surface carbon content is shown in Figure 72.

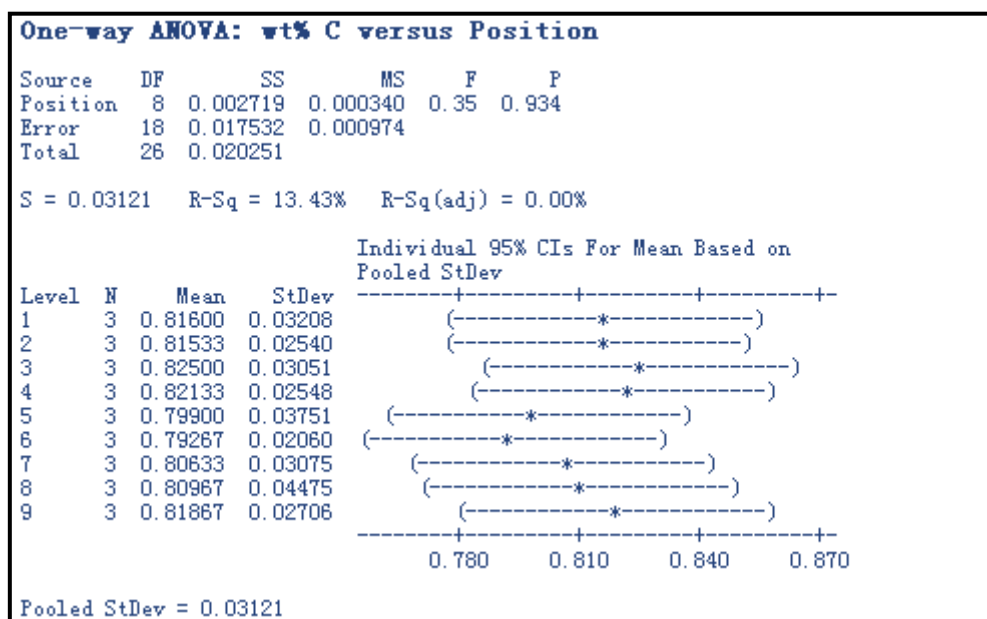


Figure 72 One-way ANOVA: Surface carbon content versus position (VCE 2010) [12]

Grouping Information Using Tukey Method			
Position	N	Mean	Grouping
3	3	0.82500	A
4	3	0.82133	A
9	3	0.81867	A
1	3	0.81600	A
2	3	0.81533	A
8	3	0.80967	A
7	3	0.80633	A
5	3	0.79900	A
6	3	0.79267	A

Means that do not share a letter are significantly different.

Figure 73 Grouping information (VCE 2010) [12]

The factors of positions are shown in Figure 72, p-value was really good at 0.934 and grouping information showed all positions stay in one group. All evidence proved that there is no significant difference from surface carbon content among positions.

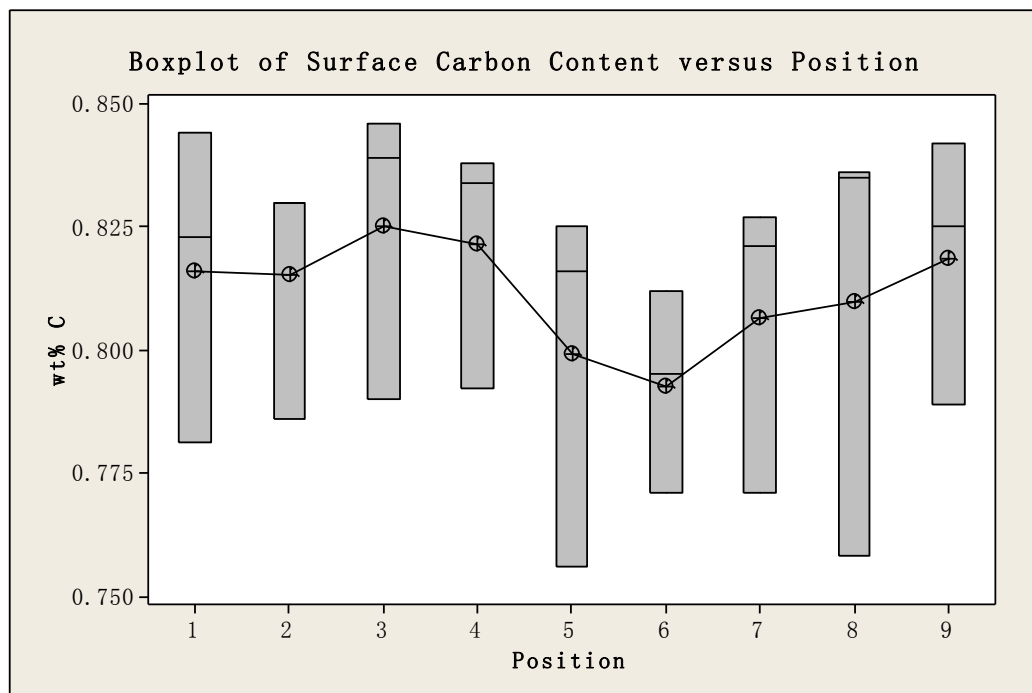
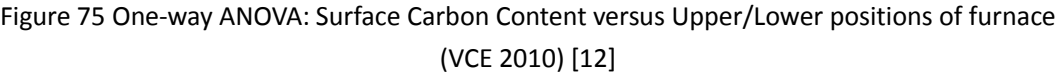


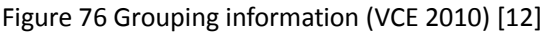
Figure 74 Box plot of surface carbon content versus position (VCE 2010) [12]

Note that position 8 in Figure 72 presents the largest box height, which leads to the spread for three values are the largest. The median value in position 8 is positive skewed. Position 6 presents the least box shape with mean and median at the center. The wide spread for all positions is probably due to the disturbance from the test on the first day.

The influence of the factor of Upper/Lower position on the response of Surface Carbon Content is presented in Figure 75.



The p-value in Figure 75 is 0.635 higher than level of significance ($\alpha=0.05$). The upper part of the furnace has a lower mean surface content than that of center and lower part. Note that the mean of the center is calculated from three values on each track.



Grouping information displayed three positions are in the same group. Note that all positions, Upper, Lower and Center, consist of the test results from Full loading condition (Day 1) and Empty loading condition (Day 2) which results in wide spread and skewness.

The influence of factor of Fully/Empty loaded track on response of Surface Carbon Content is shown in Figure 78.

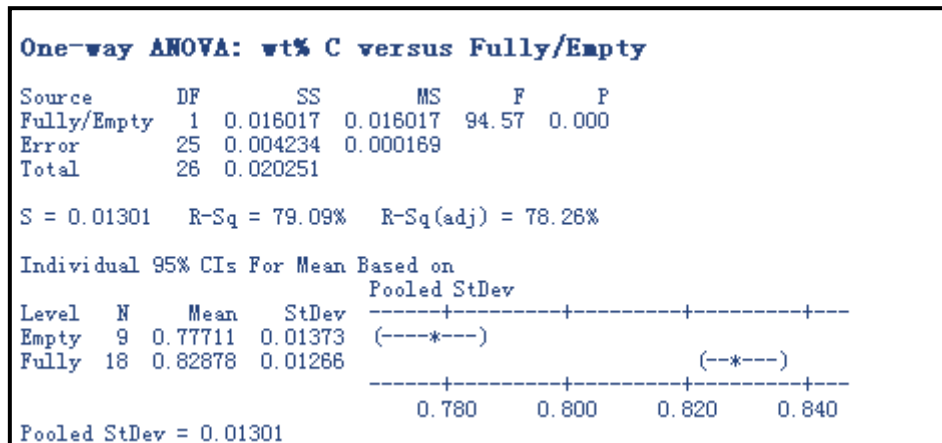


Figure 78 One-way ANOVA: Surface Carbon Content versus Fully/Empty [12]

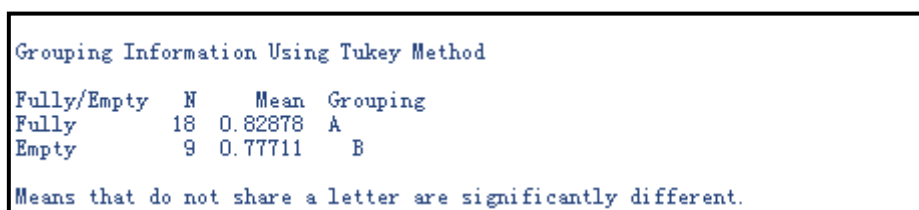


Figure 79 Grouping information and Tukey's output (VCE 2010) [12]

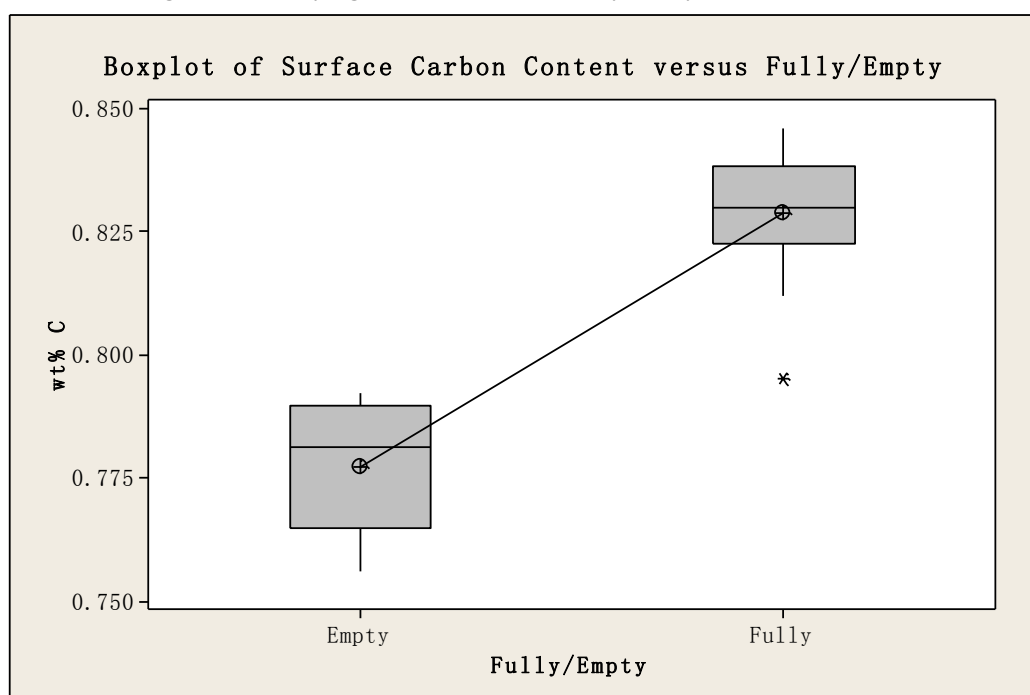


Figure 80 Box plot of Surface Carbon Content versus Fully/Empty loaded track (VCE 2010) [12]

The p-value for the factor of Fully/Empty loaded track is shown in Figure 78 which is zero. That means there is a significant difference between fully and empty loaded track. Grouping information in Figure 79 also explains that fully and empty loaded tracks provide two different performances. For fully loaded track, there are outliers close to lower whisker and the mean value and median shares the same position in the box. The box plot in Figure 80 shows the spread and tendency of two cases. For the case of empty loaded track, the median line shifts to the upper Q3 line which indicates the data are positive skewed, however, the lower whisker is longer than upper one which refers to the negative skewness tendency. One outlier appeared in the fully loaded track.

For comparing factor interactions on response of surface carbon content, multi-vari charts are used. These interactions are Track – Position, Track – Upper/Lower, Position – Fully/Empty and Upper/Lower – Empty.

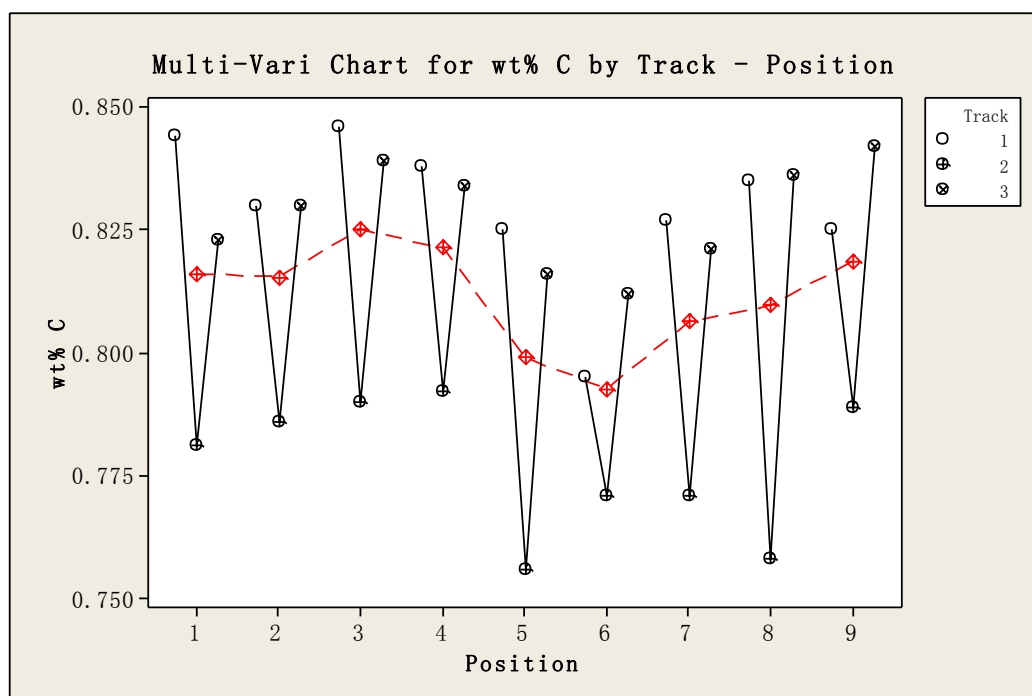


Figure 81 Multi-Vari Chart for surface carbon content by Track - Position (VCE 2010)

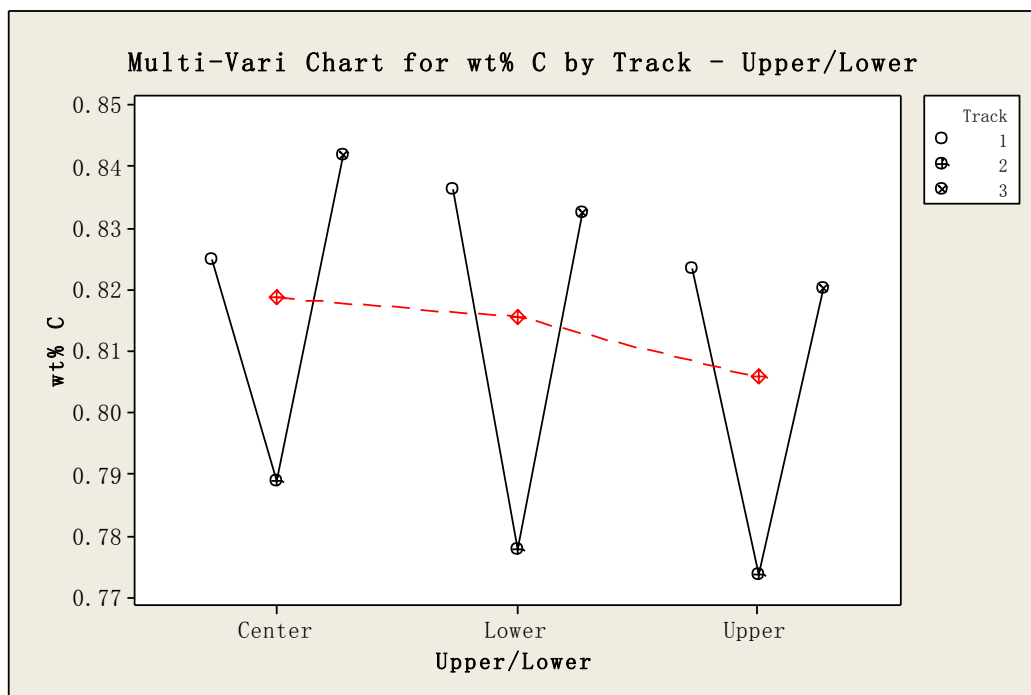


Figure 82 Multi-Vari Chart for surface carbon content by Track – upper/lower (VCE 2010)

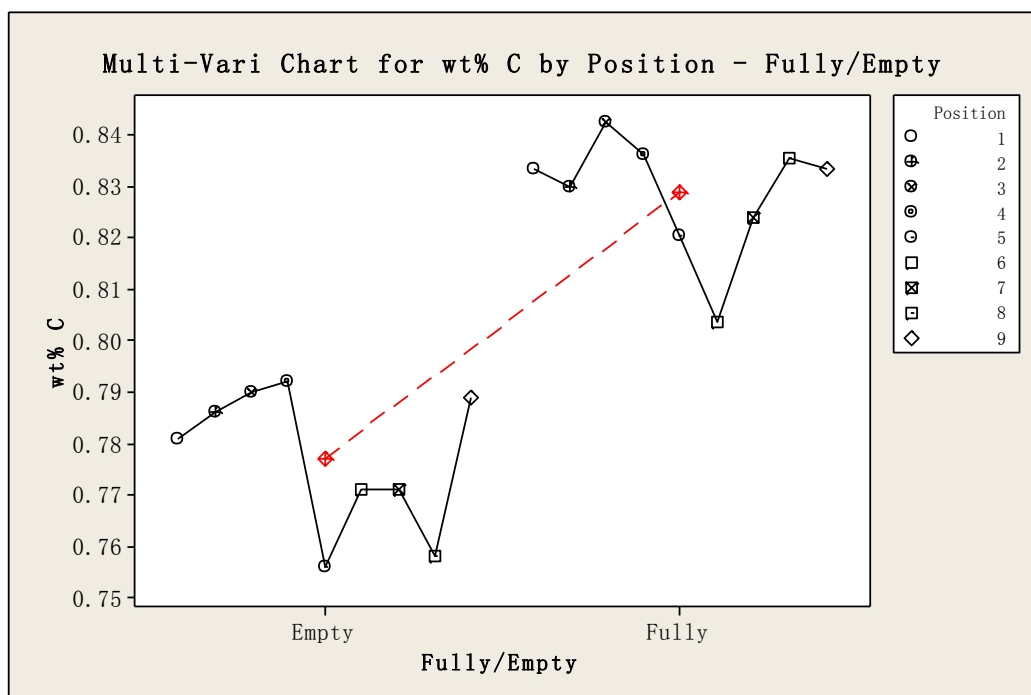


Figure 83 Multi-Vari Chart for surface carbon content by Position – Fully/Empty (VCE 2010)

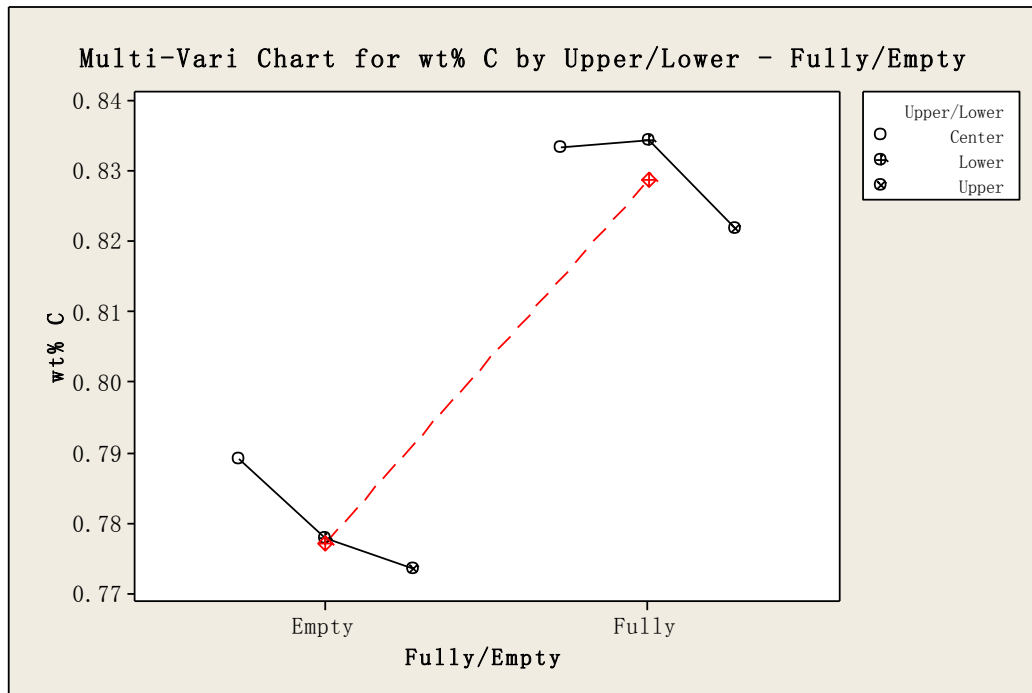


Figure 84 Multi-Vari Chart for surface carbon content (VCE 2010)

The multi-vari charts above compares two factor interactions on the single response surface carbon content. Figure 81 shows track 2 positions 5 and 8 have low carbon content. For track 1 and track 3, the lowest carbon content is at position 6. Figure 80 compares two factors “Track versus Upper/Lower” by surface carbon content. Mean surface content are ranked by center, lower and upper position. Figure 83 takes the influence of loading capacity into account. Note that for empty loaded case, mean value are calculated from track 2 which refers to the average of 9 samples, however, for fully loaded condition, the mean comes from 18 samples. Both curves show fluctuation at positions. The capacity for the furnace is 0.77 wt% C for empty loaded condition, and it could achieve 0.83 wt% C with fully loaded track, see in Figure 84.

Summary of capability study for surface carbon content of the samples from VCE furnace in 2010, track 2 which is tested on the second day shows the least surface carbon content. For capability studies, all tracks show good Pp values but relative low Cpm values. Track 3 is the most capable of meeting specifications since its high process capability indices. The Upper positions of the furnace show lower surface carbon content than that of the Lower positions. Fully loaded track shows higher surface carbon content than that of empty loaded track.

3.6. Temperature Uniformity Survey (TUS)

Temperature uniformity is defined as the temperature variations that stay within certain temperature range. The objective for temperature uniformity survey (TUS) is to ensure an even temperature in the furnace according to the procedure in AMS 2750D.^[2] By checking temperature distributions through the furnace, possible cold and warm zones can be identified which directly leading to furnace improvement actions. All requirements and procedures are written in AMS 2750D^[2] but the standard does not describe how to analyze the temperature data in a statistical way. For the temperature uniformity survey results, this report only covers the measurements from Getrag and VCE in 2010.

3.6.1. Getrag All Wheels Drive AB

To measure temperature a logger of the model T-paq 21 with 9 thermocouples (TCs) are used at Getrag in 2010. Four of them are located freely in upper positions of the furnace called “Air” or “Free” thermocouples (TCs). One is fixed in upper center. The remaining four are positioned within dummy samples at the bottom which are named “sample” or “non-free” TCs, see in the Figure 85.

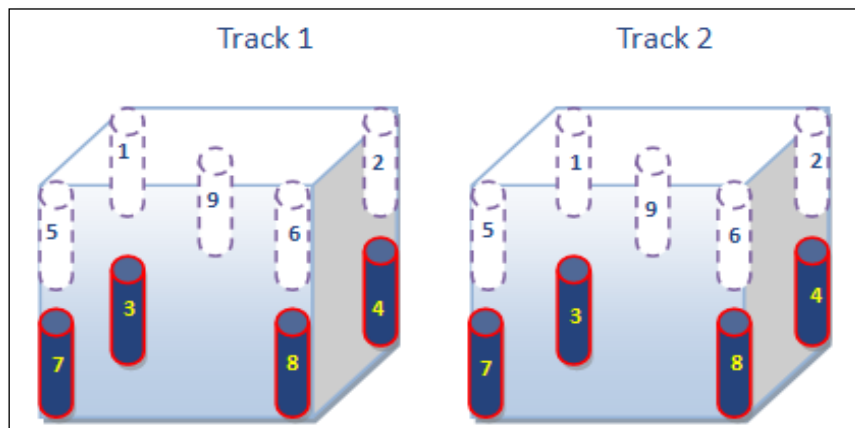


Figure 85 shows the positions of TCs in Getrag 2010

The purpose for two types of TCs, free and non-free, is to compare temperature variations. The temperature data are logged at the frequency of 5 Hz from room temperature till room temperature. However, according to requirements the logging at all positions with a frequency of at least two minutes and at most six minutes during the whole measurement. After the working temperature has been reached and the values are stabilized logging must be performed at least 30 minutes and under no circumstances may the TCs in a position less than or exceed the limits of tolerance.^[2] According to AMS2750D^[2], the furnace class is Five and target value is 910°C with the tolerances of $\pm 14^{\circ}\text{C}$ in the stable zone.

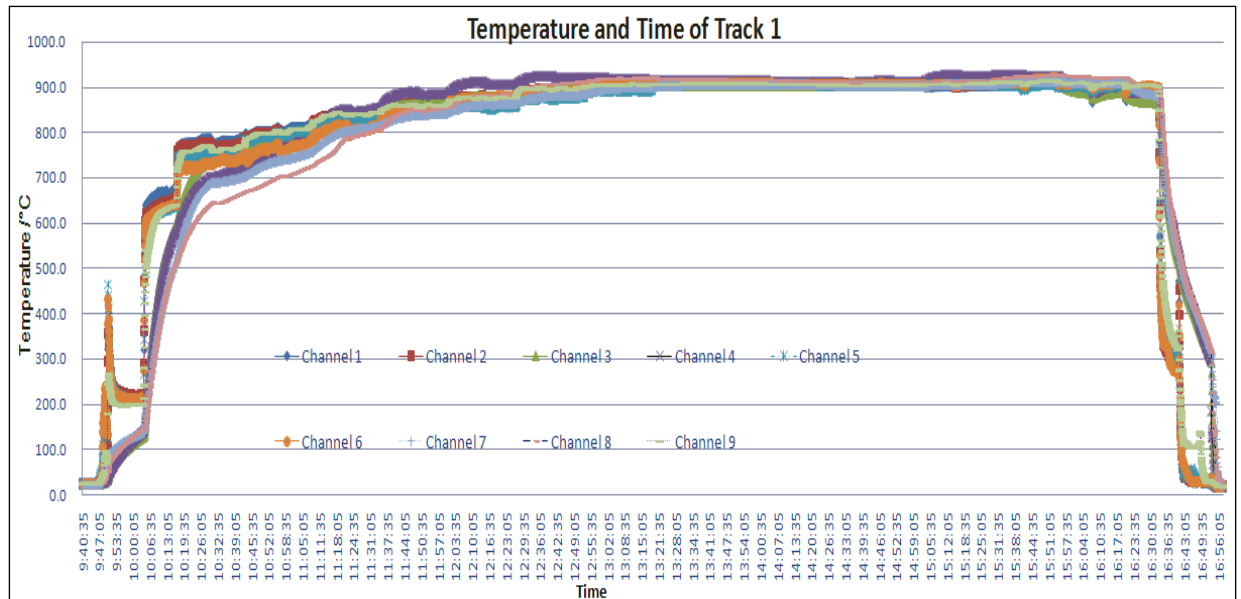


Figure 86 Temperature vs. Time of Track 1, Getrag 2010

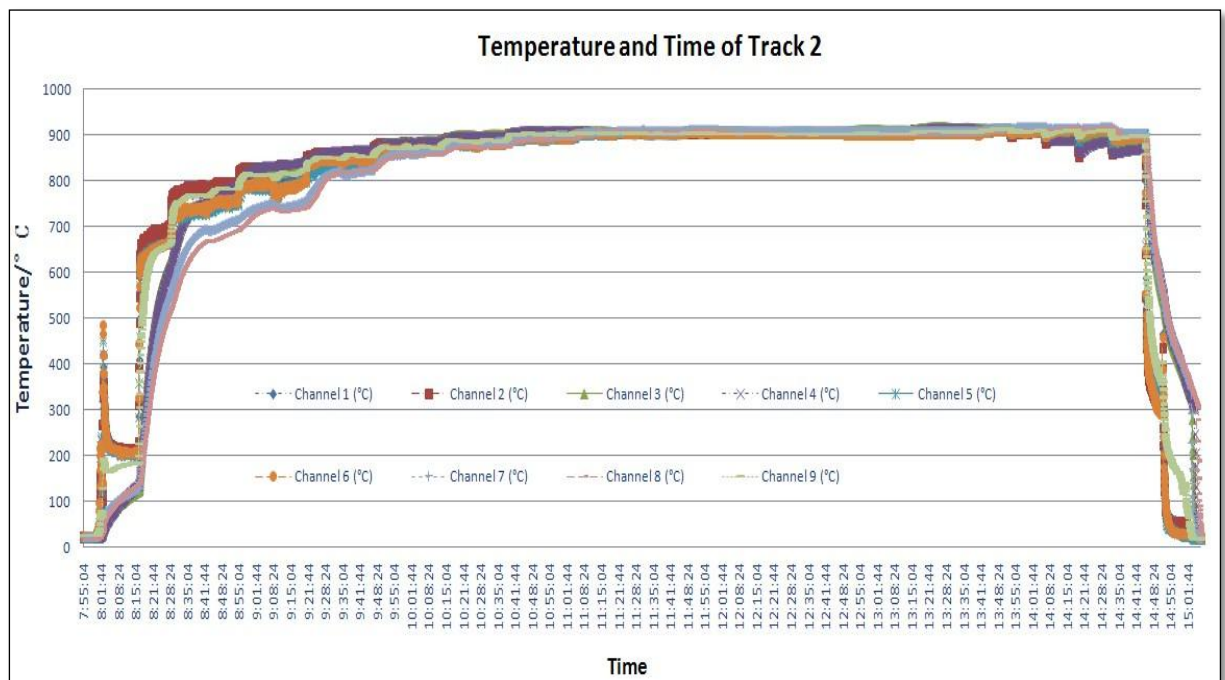


Figure 87 Temperature vs. Time of Track 2, Getrag 2010

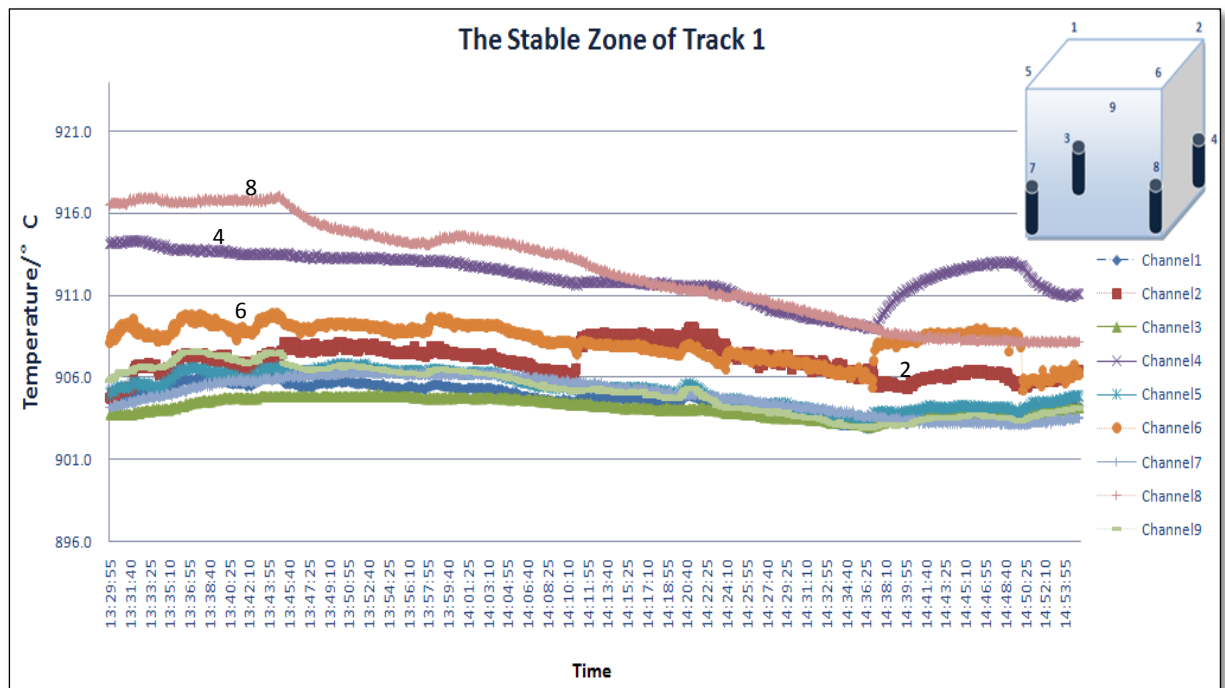


Figure 88 The sable zone of track 1, Getrag 2010

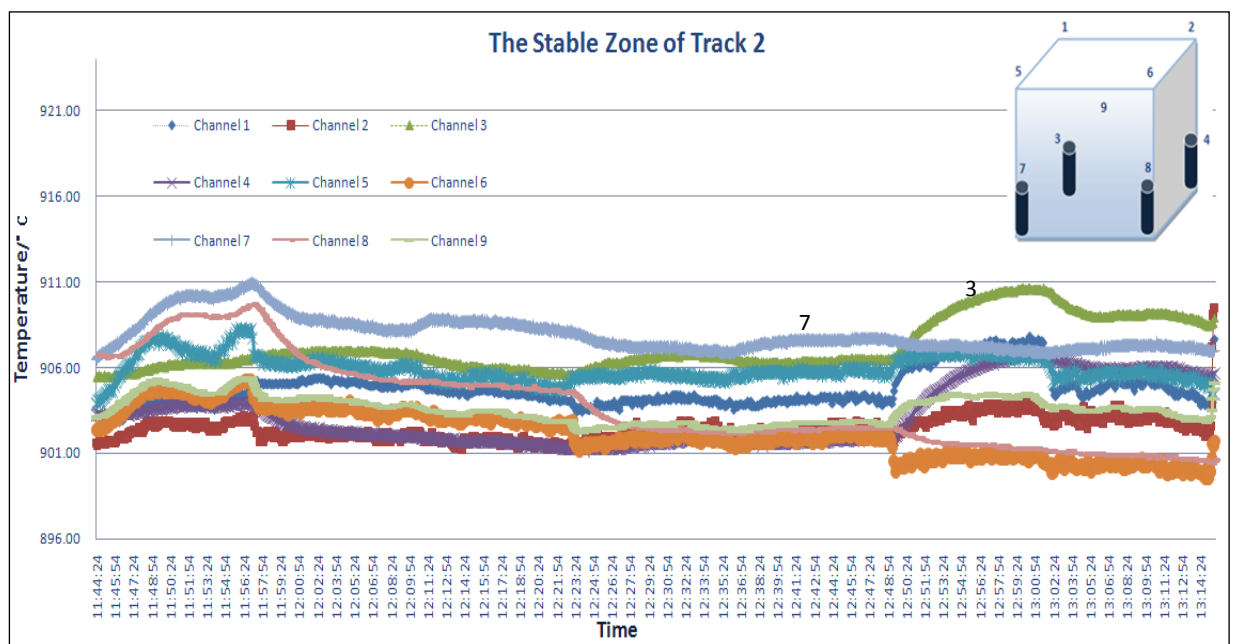


Figure 89 The stable zone of track 2, Getrag 2010

Figure 86 and 87 illustrate temperature versus time of the two tracks in Getrag. Figure 88 and 89 present the stable working temperature of both tracks. For the TCs 4 and 8 on track 1, both temperature curves show decline trends but TC 8 increases suddenly from 14:36:35 to 14:49:05, which is the same interval as the feed rate 13 min/position. The stable zone of track 2 shows in Figure 89, where TCs 3 and 7 show high temperature values. At time interval from 12:50:24 to 13:14:24, all temperature curves except 6, suddenly turn upwards and then back to their original level. For

temperature curve 6, the trend is opposite and temperature varies from 903°C to 901°C, then after 14 minutes back to 902°C.

It is impossible to use all logged temperature data within the stable zone because of the large amount of noises, but in accordance with AMS 2750 D ^[2] the temperatures should be recorded within the interval of 2 minutes to 6 minutes. Thus, different intervals are chosen and compared from 2 minute, 2.5 minutes, 3 minutes, and 3.5 minutes till 6 minutes to check which intervals give the best distributions and capability indices. The best interval for track 1 is 4 minutes, whereas for track 2 is 05:40.

Table 23 Statistical analysis results for track 1 (Getrag 2010)

Time Interval	P-value	Pp	Ppk	Cpm	Mean	Stdev	LSL	Target	USL
4 minutes	-	-	-	-	-	-	-	-	-
Channel 1	0.242	5.52	3.39	0.84	904.6	0.8460	896	910	924
Channel 2	0.911	4.82	3.75	1.40	906.9	0.9676	896	910	924
Channel 3	0.300	8.86	5.18	0.78	904.2	0.5268	896	910	924
Channel 4	0.393	3.42	2.89	1.80	912.2	1.3648	896	910	924
Channel 5	0.276	4.92	3.23	0.93	905.2	0.9482	896	910	924
Channel 6	0.072	4.48	3.87	2.13	908.1	1.0420	896	910	924
Channel 7	0.039	4.20	2.64	0.86	904.8	1.1100	896	910	924
Channel 8	0.055	1.45	1.21	1.17	912.3	3.2130	896	910	924
Channel 9	0.115	3.36	2.20	0.91	905.1	1.3882	896	910	924

Distribution from TC 7 on track 1 presents a low p-value which means it does not follow a normal distribution. Distribution from TC 8 shows the widest spread at 3.213 and the highest mean value in stable zone. Compared with 1.33 which is the benchmark value for capability index, TC 3 shows the best capability. Temperature from TC 6 has good process performance with Pp=4.48, Ppk=3.87 and Cpm=2.13.

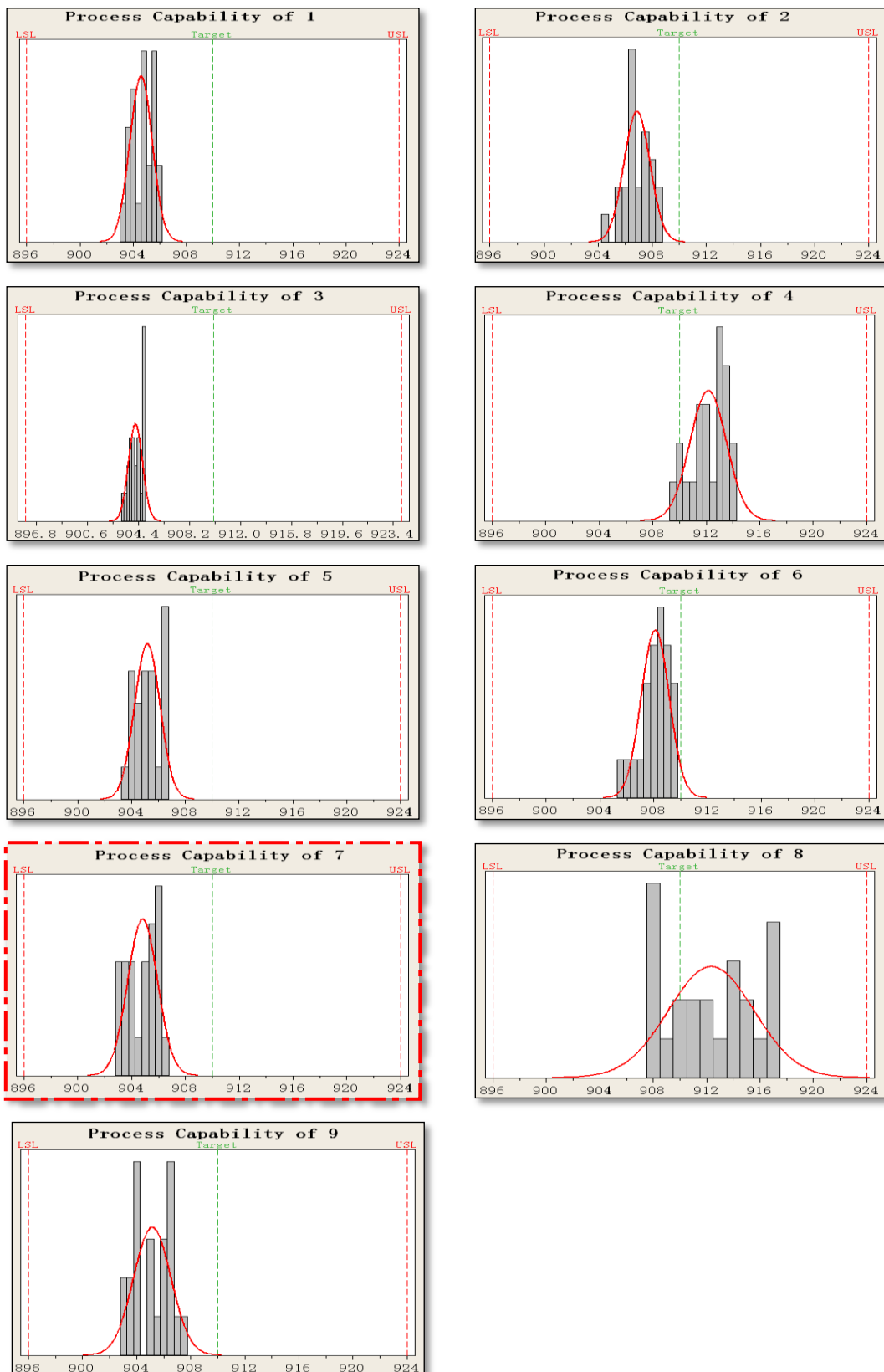


Figure 90 Process capability study of track 1: Histograms for 9 TCs; Note that TC 7 does not show normal distribution (Getrag 2010) [12]

Histograms in Figure 88 show the mean values and spread from 9 TC on track 1. TC 8 from track 1 gives the widest spread and highest mean value of all the others. TC 7 does not follow a normal distribution.

Table 24 Statistical analysis results for track 2 (Getrag 2010)

Time Interval	P-value	Pp	Ppk	Cpm	Mean	Stdev	LSL	Target	USL
0:05:40									
Channel 1	0.209	4.44	2.71	0.82	904.5	1.0506	896	910	924
Channel 2	0.416	7.30	3.32	0.59	902.4	0.6391	896	910	924
Channel 3	<0.005	3.49	2.67	-	907.1	1.4700	896	910	924
Channel 4	0.016	2.51	2.26	-	903.2	1.8400	896	910	924
Channel 5	0.265	4.70	3.30	1.06	905.8	0.9923	896	910	924
Channel 6	0.887	3.13	1.36	0.56	902.1	1.4928	896	910	924
Channel 7	0.050	4.28	3.62	1.89	907.8	1.0904	896	910	924
Channel 8	0.132	1.70	0.95	0.67	903.8	2.7486	896	910	924
Channel 9	0.520	5.30	2.84	0.69	903.5	0.8807	896	910	924

In Table 24 TCs 2, 5 and 9 show low spreads, which means the data are stable. TCs 3 and 7 show high mean values. TCs 3 and 4 from track 2 show relatively low p-values both of which are lower than 95% confidence interval with $\alpha = 0.05$, which results in rejecting of the null hypothesis and accepting the alternative hypothesis. For TCs 3 and 4, Pp and Ppk are calculated from software Minitab following non-normal distributions and no Cpm are obtained.

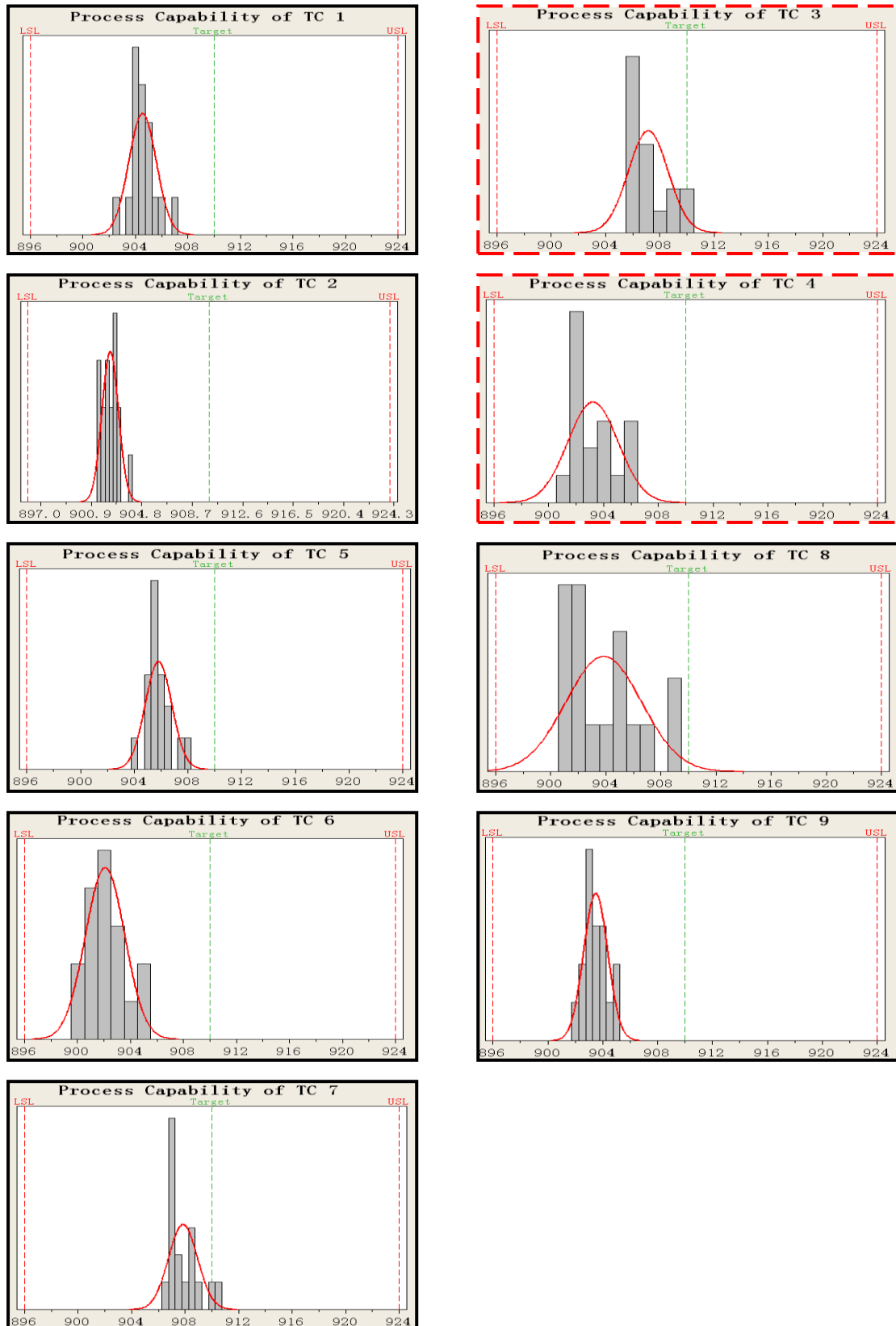


Figure 91 Capability Histogram of TCs from Track 2. Note that TCs 3 and 4 do not follow normal distributions (Getrag 2010) [12]

Capability histograms in Figure 91 show means and spreads of the distributions. Note that TC 7 is close to the target, TC 8 has a wide spread, and TCs 3 and 4 do not follow normal distributions. Also note that all distributions leftward shift which means the temperature mean values are lower than the target

One-way ANOVA is applied among factors such as Track, Position and Air/Sample and the response is mean temperature within the stable zone. The first analysis is based on factor as Track and the response is mean temperature in the stable zone.

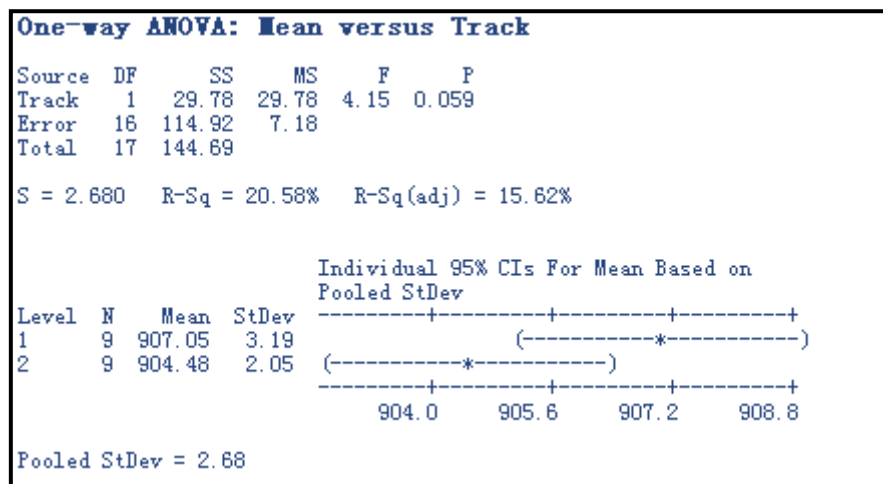


Figure 92 One-way ANOVA: Temperature mean versus Track (Getrag 2010) [12]

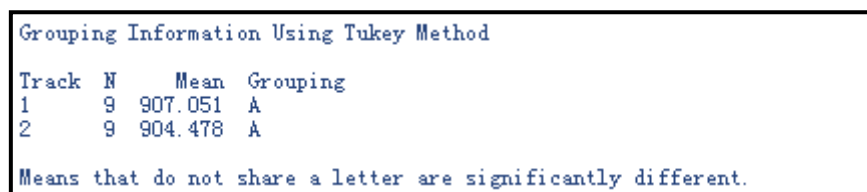


Figure 93 Grouping information and Tukey's output (Getrag 2010) [12]

In Figure 90, the p-value is 0.059 which is higher than 95% of confidence interval with $\alpha = 0.05$. It refers to there is no significant difference between tracks. Note that temperature mean of track 1 is higher than track 2 and it also has a higher standard deviation, see in Figure 92. Grouping information in Figure 93 reveals that track 1 and 2 do not share a letter were significantly different.

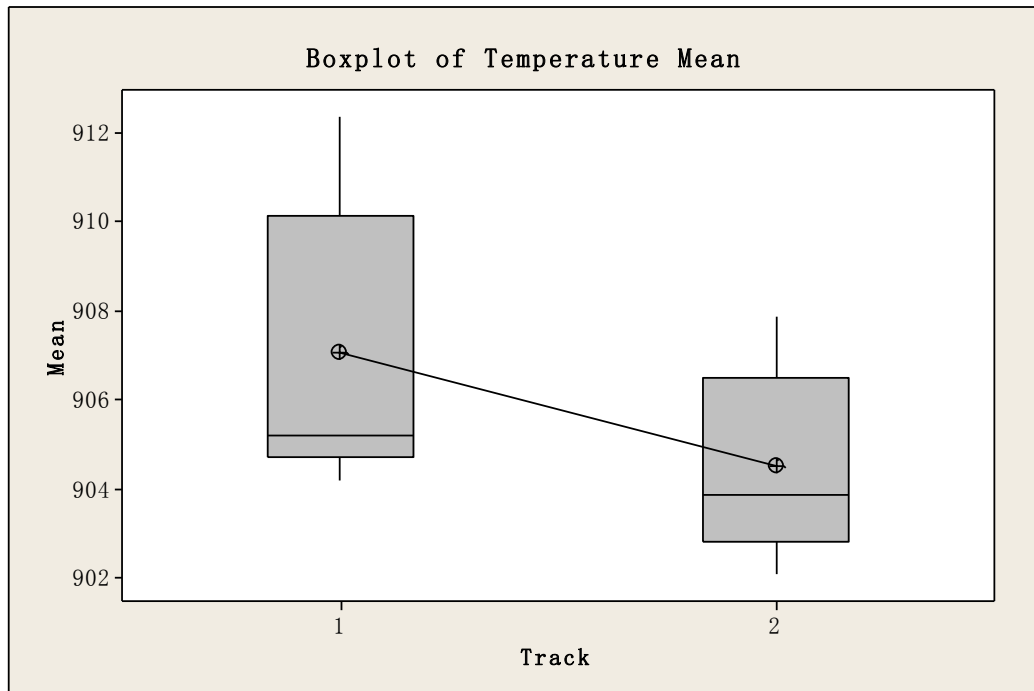


Figure 94 Box plot of temperature mean versus track (Getrag 2010) [12]

Box plot in Figure 94 shows a similar positive skewness for both tracks with longer upper whisker and the median lines are close to the first quartile line at the bottom. Track 1 also has a wider spread than track 2.

Next analysis is to investigate the influence of “Position” on mean temperature. One-way ANOVA method is applied by Mean versus Position.

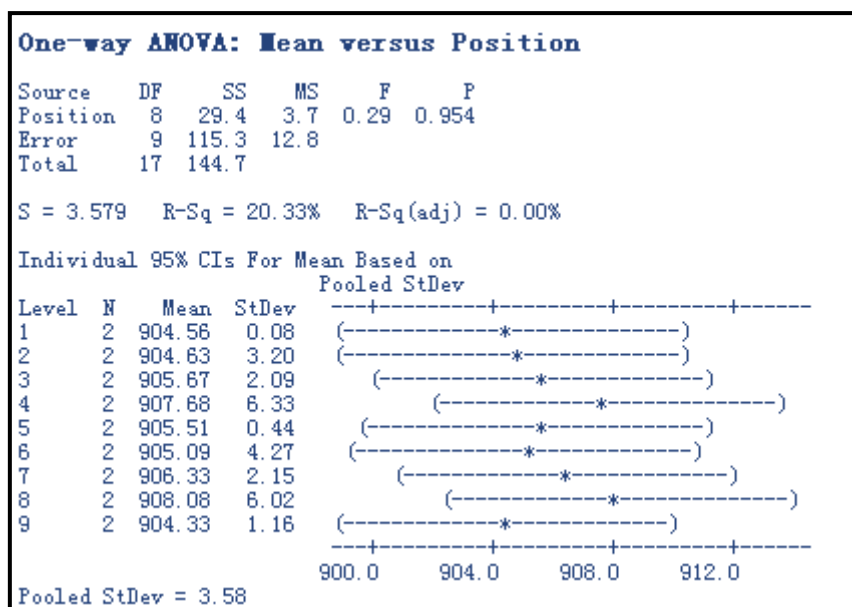


Figure 95 One-way ANOVA: temperature mean vs. Position (Getrag 2010) [12]

Grouping Information Using Tukey Method			
Position	N	Mean	Grouping
8	2	908.082	A
4	2	907.685	A
7	2	906.328	A
3	2	905.667	A
5	2	905.515	A
6	2	905.092	A
2	2	904.630	A
1	2	904.557	A
9	2	904.327	A

Means that do not share a letter are significantly different.

Figure 96 Grouping information (Getrag 2010) [12]

The p-value in Figure 95 is 0.954 higher than the level of significance ($\alpha = 0.05$). TC 8 has the largest mean and standard deviation of all TCs. The grouping information in Figure 96 reveals that all TCs are in the same group, thus the influence of position is not significant.

The next analysis is based on the type of the thermocouples (TC), either Free TC in the furnace atmosphere or Non-free TC in the test samples.

One-way ANOVA: Mean versus Air/Sample					
Source	DF	SS	MS	F	P
Air/Sample	1	19.90	19.90	2.55	0.130
Error	16	124.79	7.80		
Total	17	144.69			

S = 2.793 R-Sq = 13.76% R-Sq(adj) = 8.37%

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev	
Air	10	904.82	1.88	(- - - - - * - - - - -)	
Sample	8	906.94	3.64	(- - - - - * - - - - -)	

Pooled StDev = 2.79

Figure 97 One-way ANOVA: Temperature mean vs. Air/Sample (Getrag 2010) [12]

Grouping Information Using Tukey Method			
Air/Sample	N	Mean	Grouping
Sample	8	906.940	A
Air	10	904.824	A

Means that do not share a letter are significantly different.

Figure 98 Grouping information and Tukey's output (Getrag 2010) [12]

The p-value from one-way ANOVA in Figure 97 is 0.130 which means the differences between the TCs in the air and in the sample are not significant. Note that the mean of Free TC is lower than those in dummy samples. The grouping information shows Free and Non-free TCs share the same group and are not significantly different, see in Figure 96.

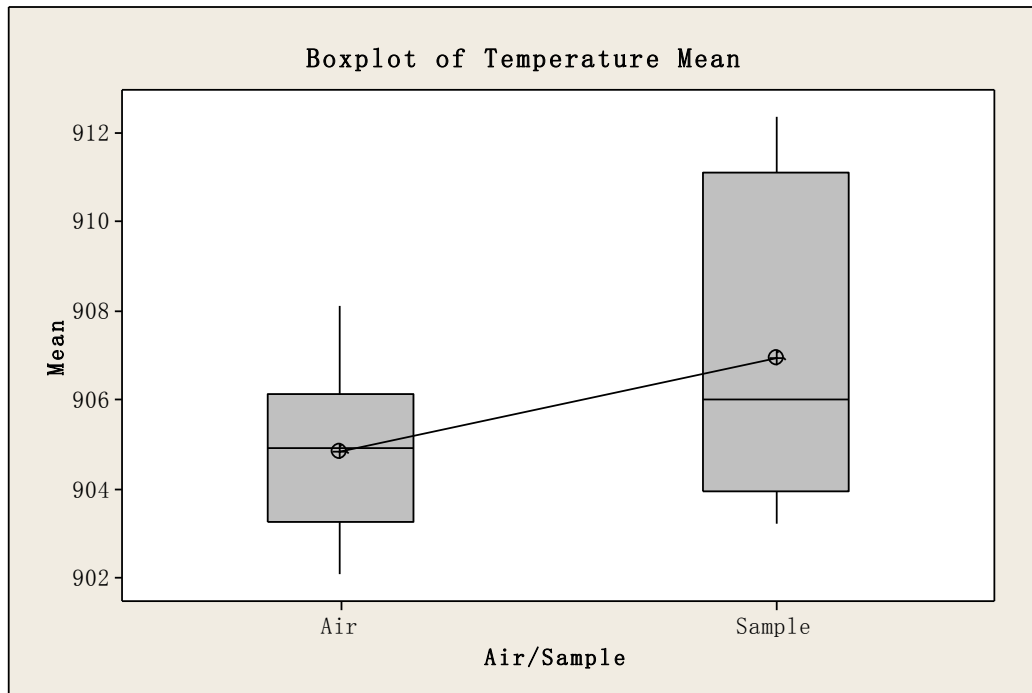


Figure 99 Box plot of Temperature mean (Getrag 2010) [12]

Box plot in Figure 99 shows temperature mean for Free and Non-free TCs. The medians for Free and Non-free TCs are similar. The box height reveals the spread of the mean value. For Non-free TCs, they have a wider spread than Free TC.

To analyze the influence of “Track side” on the response of mean temperature, one-way ANOVA test is implemented. Note that TCs 1, 3, 5 and 7 on track 1 and 2, 4, 6 and 8 on track 2 are determined as “Outer positions” in the furnace. The TCs 2, 4, 6 and 8 on track 1 and TCs 1, 3, 5 and 7 on track 2 are determined as “Inner position” of the furnace.

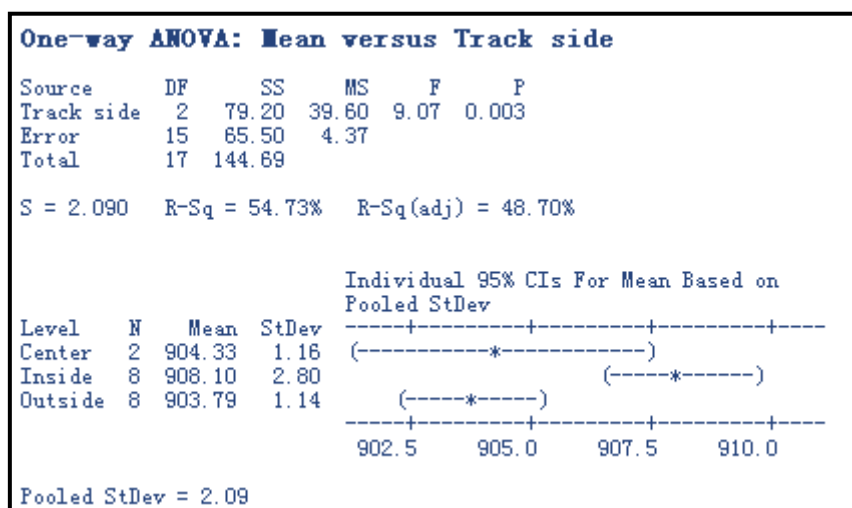


Figure 100 One-way ANOVA: Mean temperature versus Track side (Getrag 2010) [12]

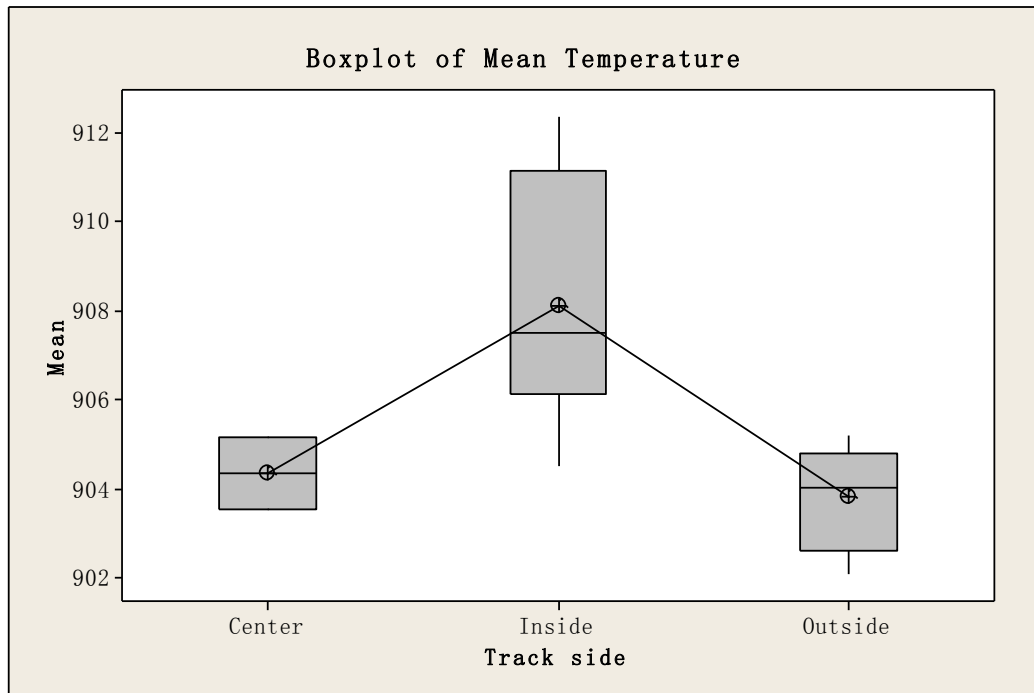


Figure 101 Box plot of Mean temperature (Getrag 2010) [12]

The p-value is obtained at 0.003 which is lower than 95% of confidence interval with $\alpha = 0.05$. The individual 95% confidence interval for mean is based on pooled standard deviation in Figure 100 shows that there is a significant difference between inner and outer part of furnace. In Figure 101, the box plot of inside TCs shows high mean temperature and negative skewness, while the outside positions reveals low mean temperature but positive skewness.

To compare two or more factors on the response, multi-vari charts are used. The multi-vari chart in Figure 102 shows temperature mean as a function of position. TCs 4 and 8 on track 1 showed higher mean than that of track 2. TCs 3 and 7 on track 2 shows higher mean than the same positions on track 1.

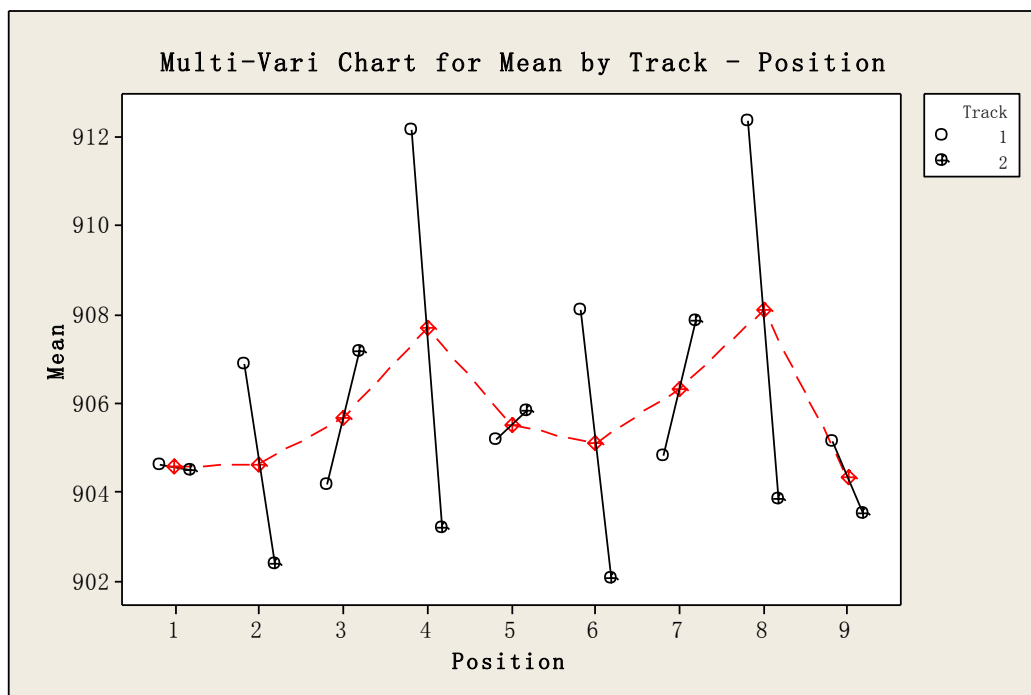


Figure 102 Multi-Vari Chart for Mean by Track – Position (Getrag 2010) [12]

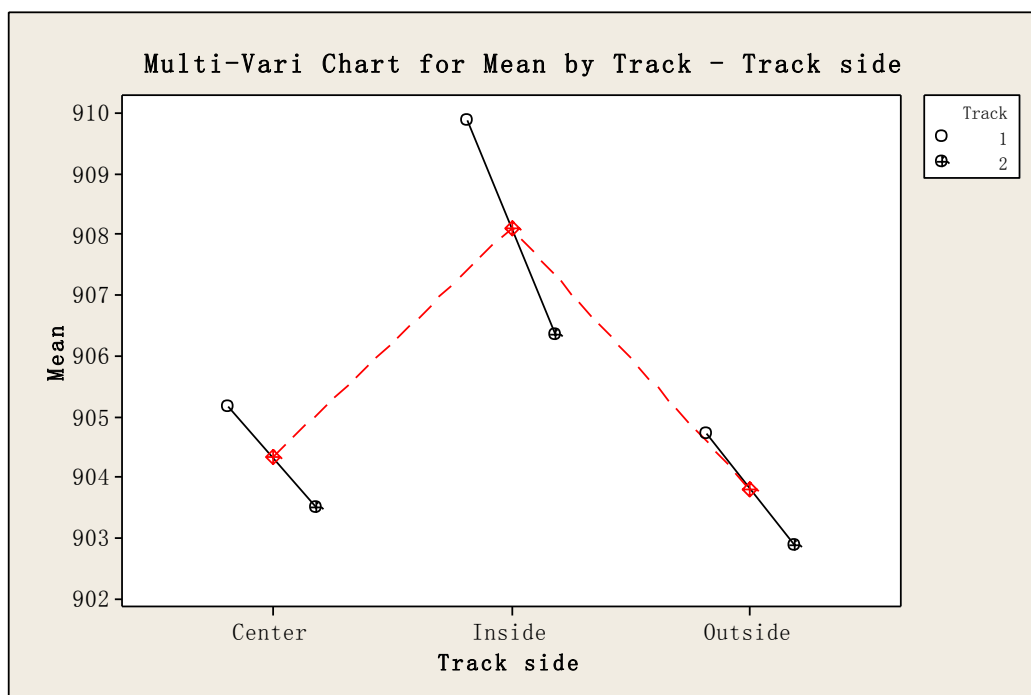


Figure 103 Multi-Vari Chart for Mean by Track – Track side (Getrag 2010) [12]

For TCs at inner positions of the furnace, they have high mean temperatures, and outer and central TCs have relatively similar means. In all positions, inside, outside and center, track 1 showed higher mean temperature than that of track 2, see in Figure 101 above.

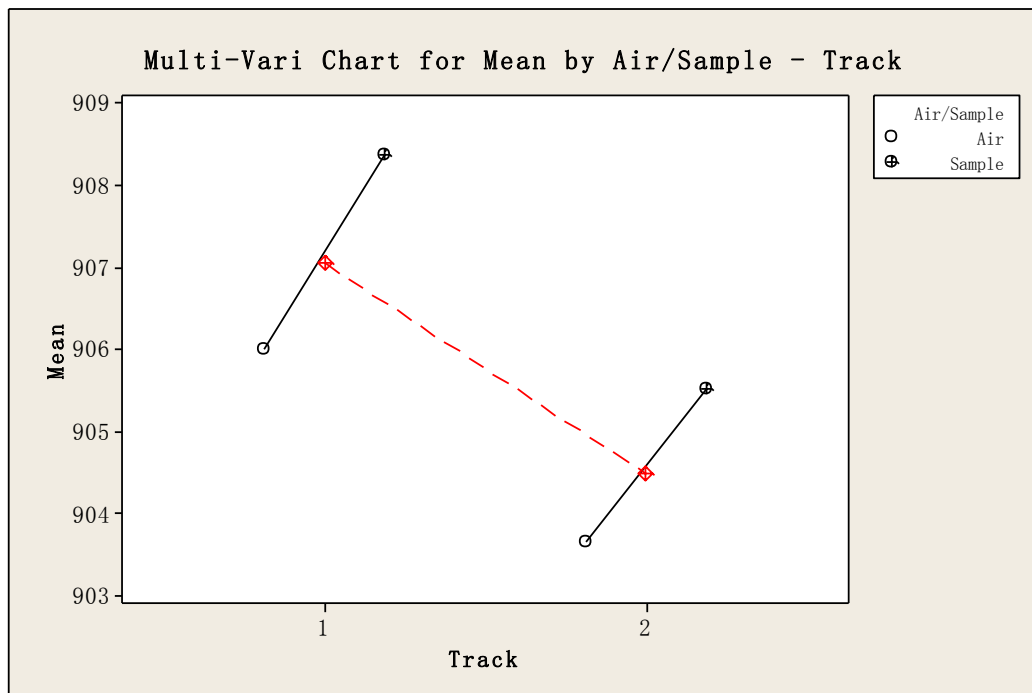


Figure 102 Multi-Vari Chart for Mean by Air/Sample – Track (Getrag 2010) [12]

Figure 104 illustrates the difference between free and non-free TCs at both tracks. The Non-free TCs on track 1 had the largest mean temperature than the other cases.

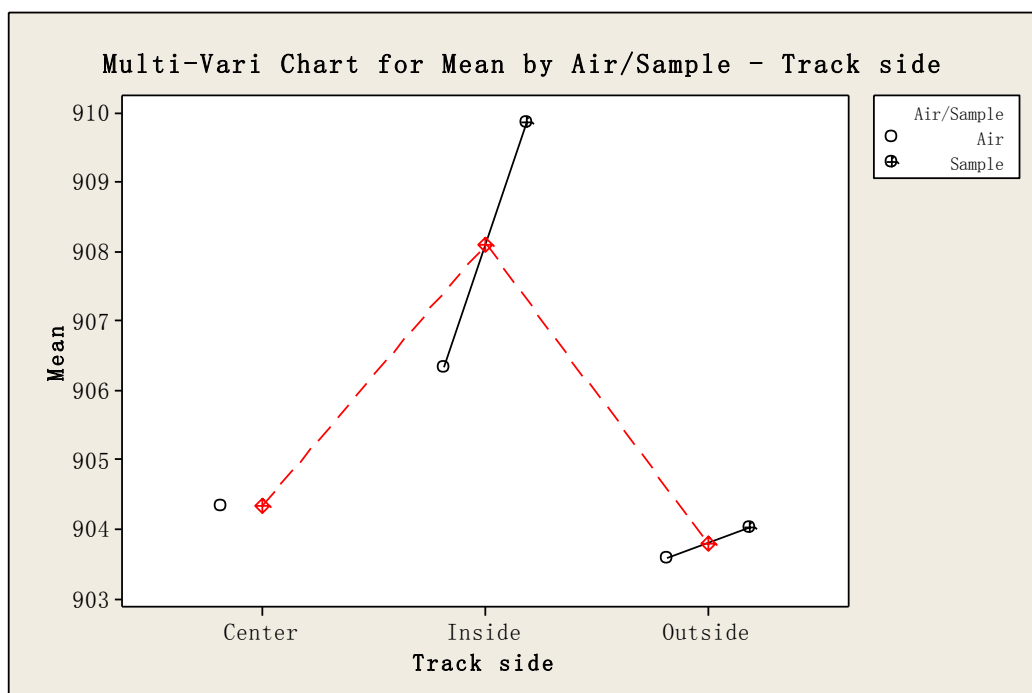


Figure 105 Multi-Vari Chart for Mean by Air/Sample – Track side (Getrag 2010) [12]

Figure 105 shows the interactions between Free/Non-free and Inside/Outside TCs. The inner non-free TCs show the highest temperature, and outer free TCs show the least extreme value.

Summary of TUS at Getrag in 2010:

- Track 2 is more stable than track 1 regarding temperature variation in the stable zone.
- Track 1 is about 2 degrees warmer than track 2 within the stable zone.
- The Non-free TCs are about 2 degrees warmer than that of Free type, which means the mean temperatures within the sample are warmer than the temperature in the furnace atmosphere.
- The inner bottom part of the furnace shows high mean temperature.
- Positions 4 & 8 on track 1 and positions 3 & 7 on track 2 present fluctuation of temperature within the stable zone.

3.6.2. Volvo Construction Equipment AB

Temperature uniformity survey was performed on track 1 and 3 by the same type of TCs at VCE in 2010. The measurements of temperature were logged at every five seconds, however, in accordance with AMS 2750D ^[2] the interval should be within 2 to 6 minutes. Thus, different intervals have been chosen to check whether it could obtain good distribution and capability indices or not. In the end, 3.5 minutes is chosen for track 1 and 4.5 minutes is chosen for track 3. The temperature versus time plots are illustrated in Figure 106 for track 1 and Figure 107 for track 3. The stable working temperature zone is presented in Figure 108 and 109, respectively.

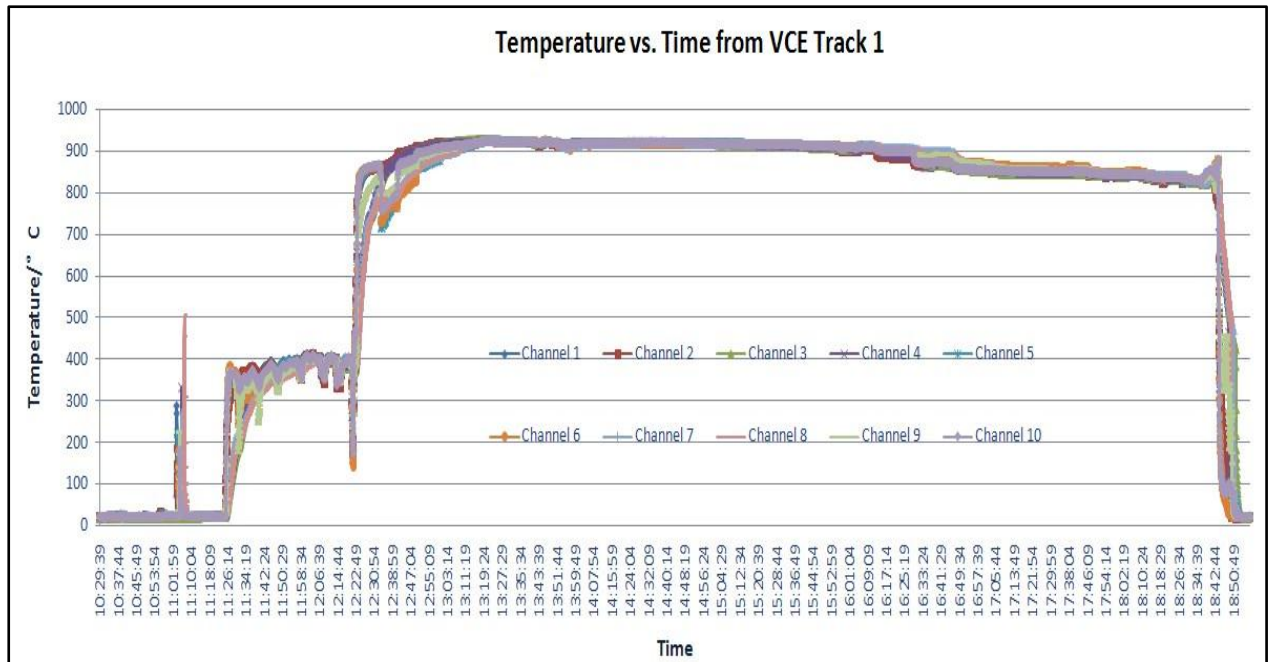


Figure 106 Temperature versus Time from VCE Track 1 (VCE 2010)

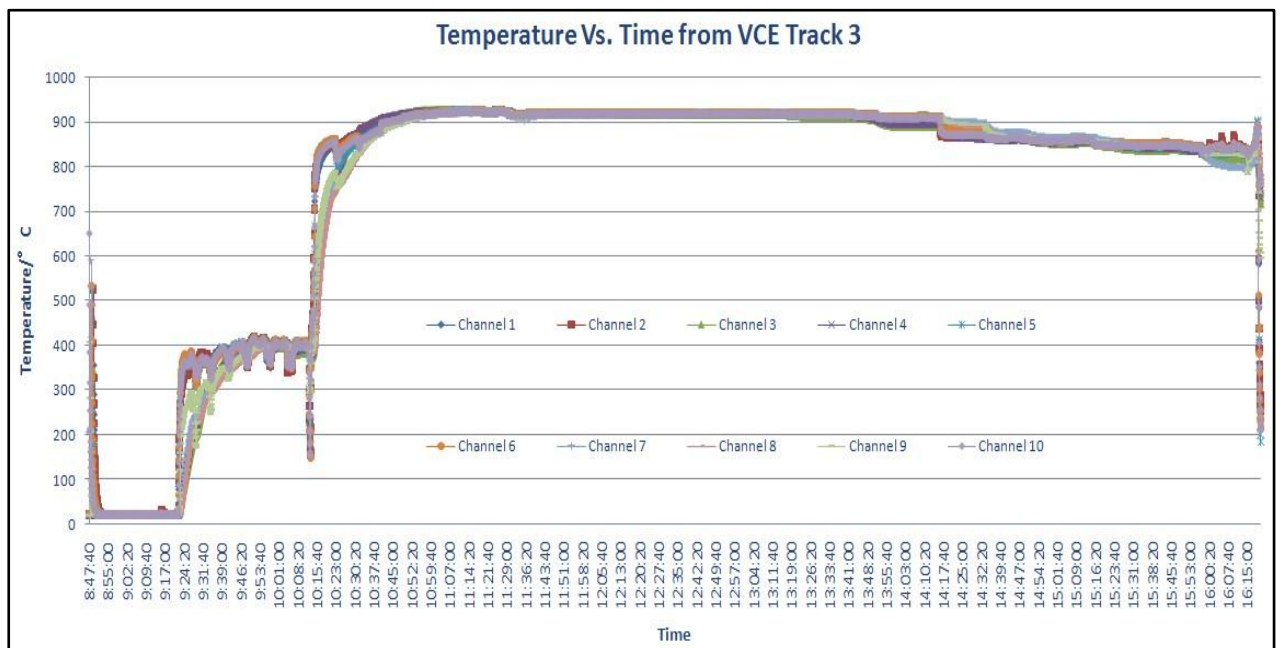


Figure 107 Temperature versus Time from VCE Track 3 (VCE 2010)

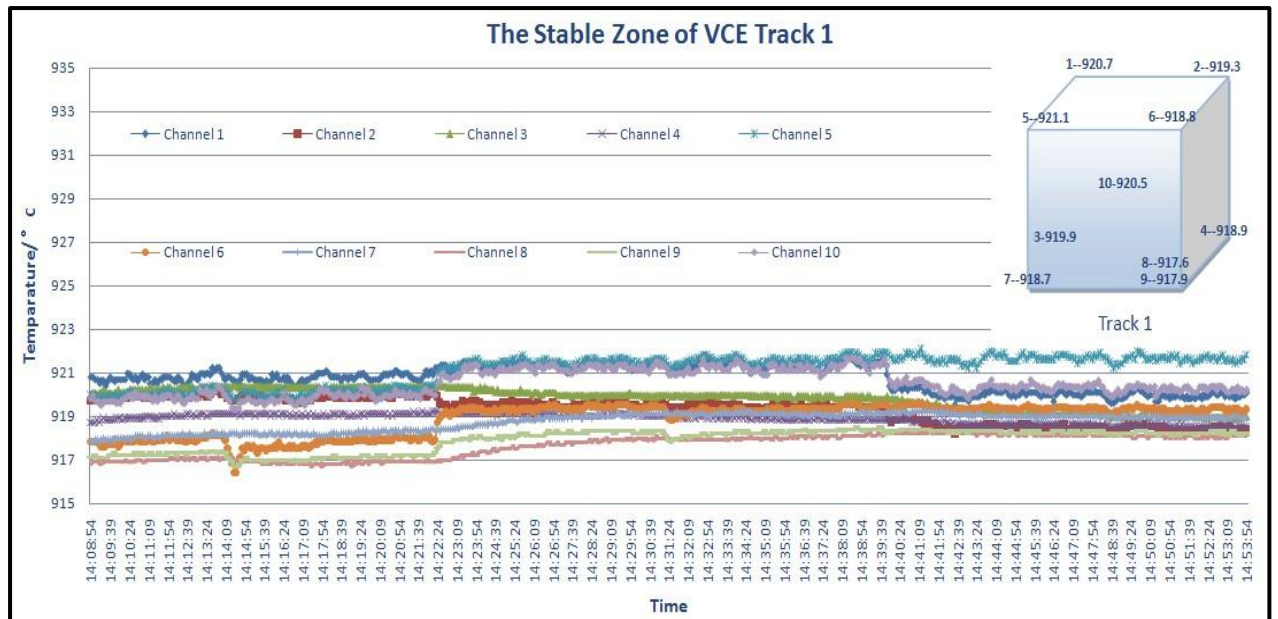


Figure 108 The Stable zone of Track 1 (VCE 2010)

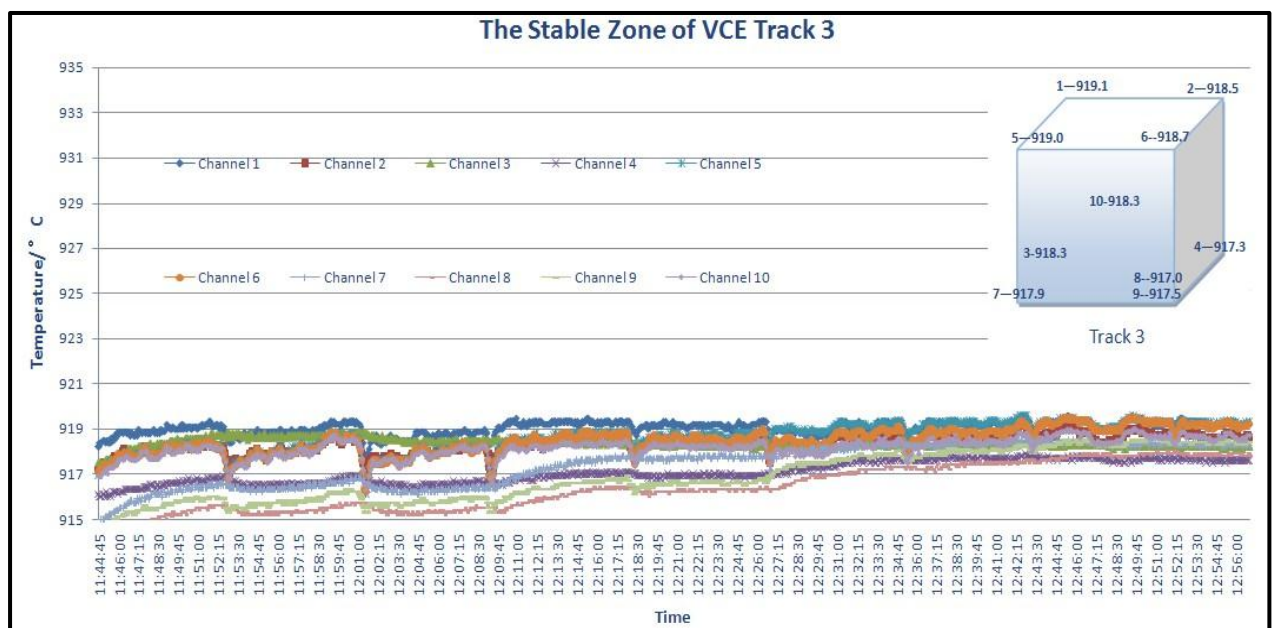


Figure 109 The Stable zone of Track 3 (VCE 2010)

Table 25 Statistical analysis result for track 1 (VCE 2010)

Track and positions	P-value	Pp	Ppk	Cpm	Mean	Stdev	LSL	Target	USL
Track 1	-	-	-	-	-	-	-	-	-
Channel 1	0.748	6.01	3.45	0.75	920.7	0.5550	915	925	935
Channel 2	0.047	6.29	2.71	0.56	919.3	0.5300	915	925	935
Channel 3	0.048	6.94	3.37	0.62	919.9	0.4810	915	925	935
Channel 4	0.114	14.54	5.61	0.52	918.9	0.2290	915	925	935
Channel 5	<0.005	4.450	2.710	0.81	921.1	0.7490	915	925	935
Channel 6	<0.005	4.410	1.690	0.52	918.8	0.7560	915	925	935
Channel 7	0.006	7.180	2.640	0.51	918.7	0.4640	915	925	935
Channel 8	0.008	5.580	1.450	0.43	917.6	0.5970	915	925	935
Channel 9	<0.005	6.400	1.820	0.45	917.9	0.5210	915	925	935
Channel 10	0.305	5.80	3.21	0.71	920.5	0.5750	915	925	935

Table 26 Statistical analysis result for track 3 (VCE 2010)

Track and positions	P-value	Pp	Ppk	Cpm	Mean	Stdev	LSL	Target	USL
Track 3	-	-	-	-	-	-	-	-	-
Channel 1	0.178	19.78	8.12	0.54	919.1	0.1685	915	925	935
Channel 2	0.318	17.00	5.95	0.49	918.5	0.1960	915	925	935
Channel 3	0.005	31.72	10.54	0.48	918.3	0.1050	915	925	935
Channel 4	0.007	8.16	1.90	0.42	917.3	0.4080	915	925	935
Channel 5	0.077	9.410	3.730	0.53	919.0	0.3540	915	925	935
Channel 6	0.618	8.390	3.140	0.51	918.7	0.3980	915	925	935
Channel 7	0.017	5.580	1.720	0.45	917.9	0.5690	915	925	935
Channel 8	0.292	3.980	0.790	0.40	917.0	0.8370	915	925	935
Channel 9	0.095	3.630	0.900	0.42	917.5	0.9190	915	925	935
Channel 10	0.174	13.00	4.35	0.48	918.3	0.2560	915	925	935

The capability indices in Table 25 and 26 are really good, which means the furnace is highly capable of meeting the specification limits. Although some of the distributions do not follow normal distributions, still mean value and spread could be compared with the ones that followed normal distributions. In temperature versus time plots in Figure 106 and 107, conclusion can be drawn that track 1 shows higher mean temperature than that of track 3. TCs 8 and 9 on track 3 show high standard deviations and a little lower than the rest TCs.

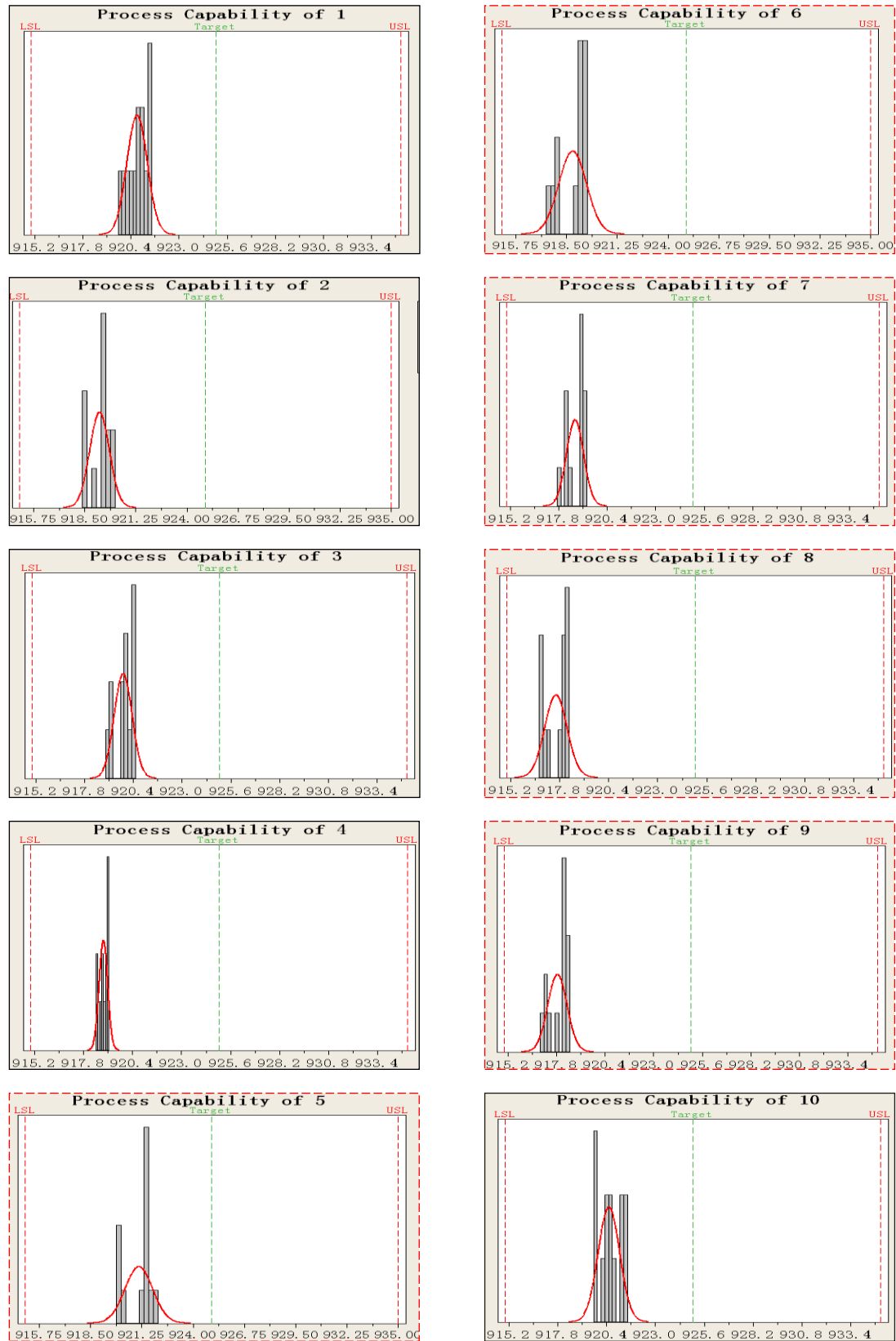


Figure 110 Capability Histograms from Track 1; Note that not all histograms (reddish lines) distribute normally (VCE 2010)

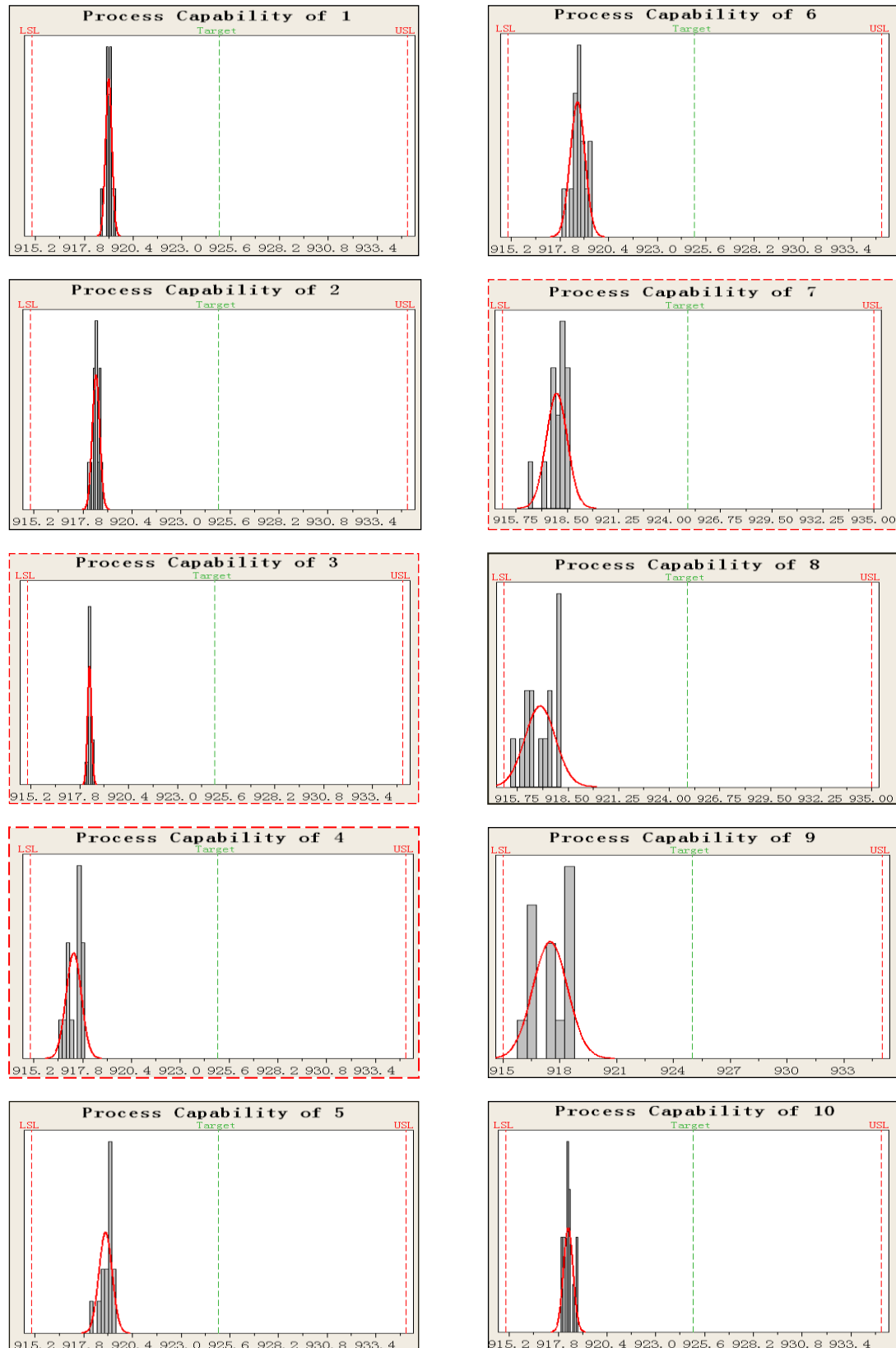


Figure 111 Capability Histograms from track 3.

Note that 3, 4 and 7 do not follow normal distribution (reddish lines). VCE 2010

Capability histograms of TCs 5, 6, 7, 8 and 9 have p-values lower than 0.05, see in Figure 110. However, comparisons could be made to find spread and shape of distributions as well. Note that TCs 8 and 9 are more shifted to the LSL side than the rests. In Figure 109, temperatures from TC 3, 4 and 7 do not follow normal distributions.

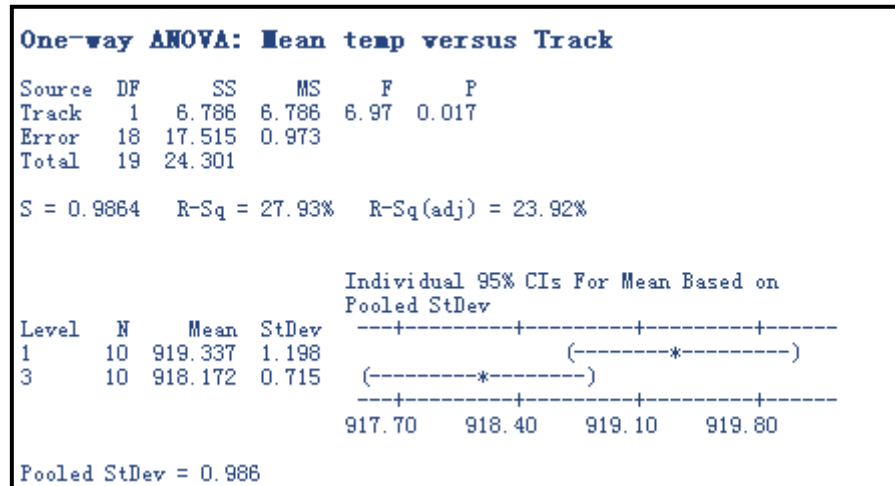


Figure 112 One-way ANOVA: Mean temperature versus Track (VCE 2010) [12]

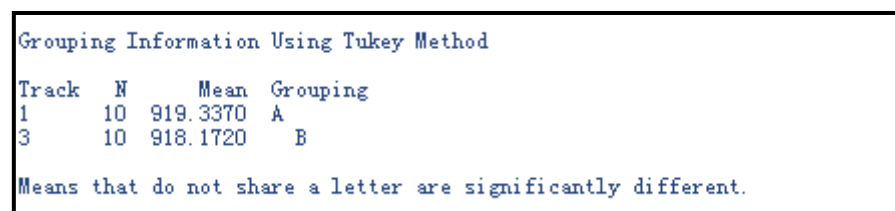


Figure 113 Grouping information and Tukey's output (VCE 2010) [12]

The one-way ANOVA analysis in Figure 112 show that there is a significant difference in mean temperature between track 1 and 3, therefore factor "Track" affects mean temperature.

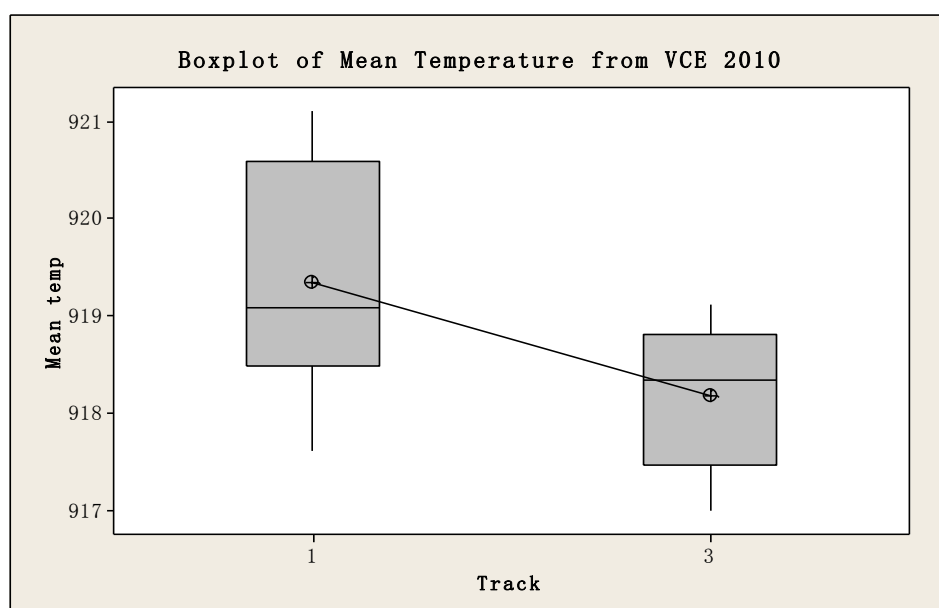


Figure 114 Box plot of Mean Temperature from VCE 2010 [12]

Box plots in Figure 114 shows that track 1 mean is higher than track 3. The median of track 1 is close to the Q1 line, while track 3's median line shifts to the Q3 line. Generally, the larger of box size, the wider of the spread.

To analyze the influence of "Position" on the response of Mean temperature, one-way ANOVA test is made.

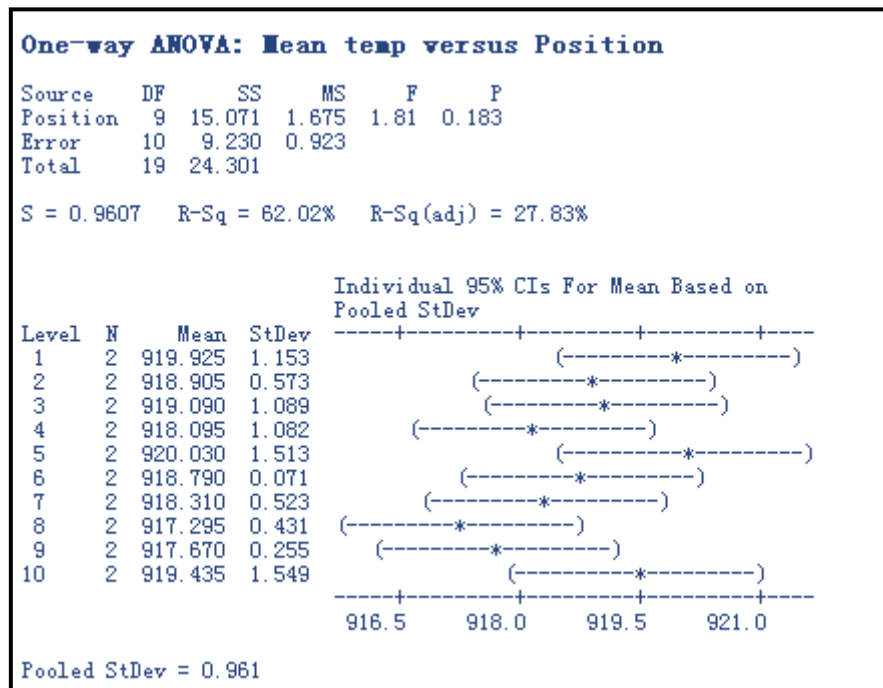


Figure 115 One-way ANOVA: Mean temperature versus Position (VCE 2010) [12]

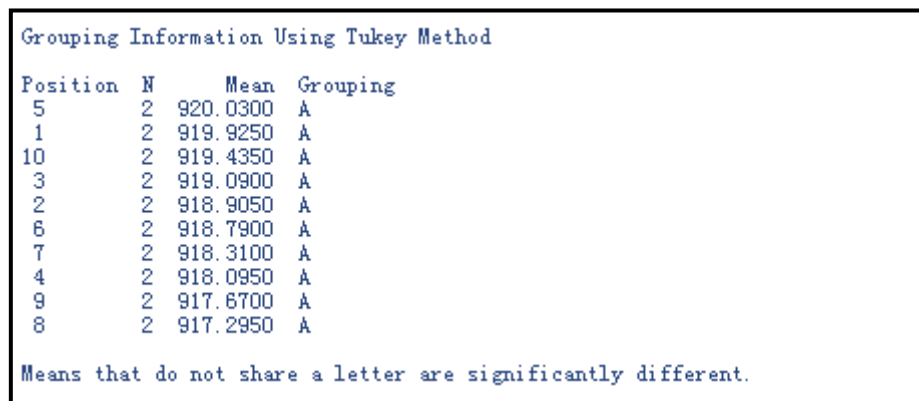


Figure 116 Hsu's MCB and grouping information (VCE 2010) [12]

In Figure 115, the p-value is 0.183 which is more than 95% of confidence interval with alpha equals to 0.05. It means there are no significant differences among mean temperature of positions. TC 8 and 9 give relative low mean temperatures. Grouping information in Figure 114 reveals that all positions are in the same group which means that do not share a letter are significantly different.

To analyze the influence of factor "Free/Non-free TCs" on the response "mean temperatures", one-way ANOVA test is made. Non-free TCs refer to the

thermocouples that insert in the samples in order to measure the temperature in the dummy samples. Free TCs refer to the thermocouples that attached freely in the furnace atmosphere to measure the temperature in the furnace.

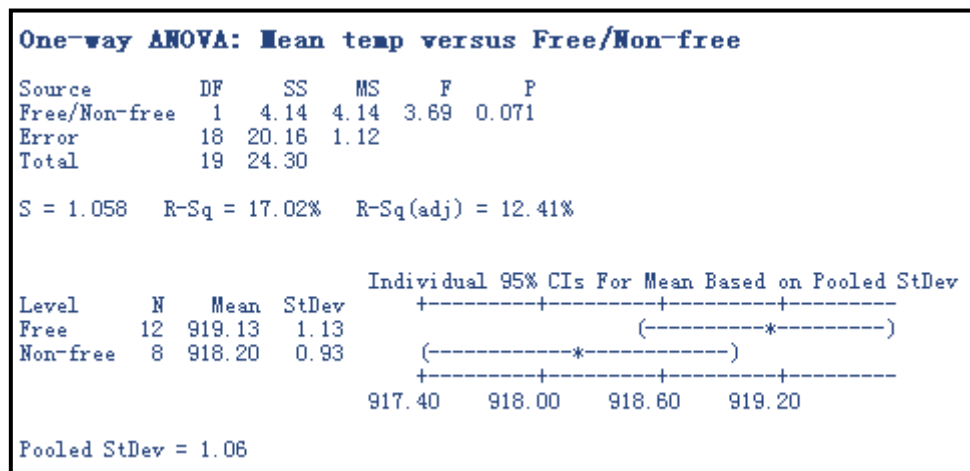


Figure 117 One-way ANOVA: Temperature Mean versus Free/Non-free (VCE 2010) [12]

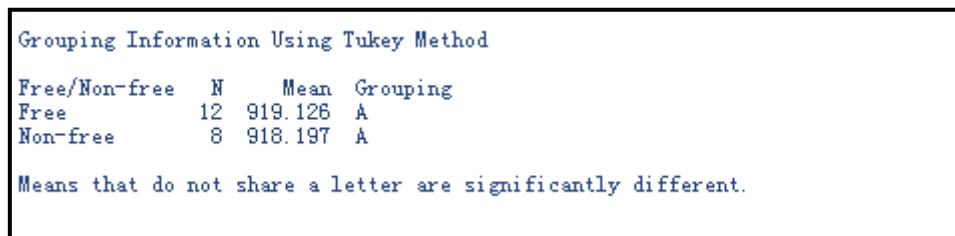


Figure 118 Grouping information and Tukey's output (VCE 2010) [12]

The result from Figure 118 and 119 shows that there is no significant difference between the Free/Non-free type TCs. In other words, factors "Free/Non-free" does not affect mean temperatures within the sable zone.

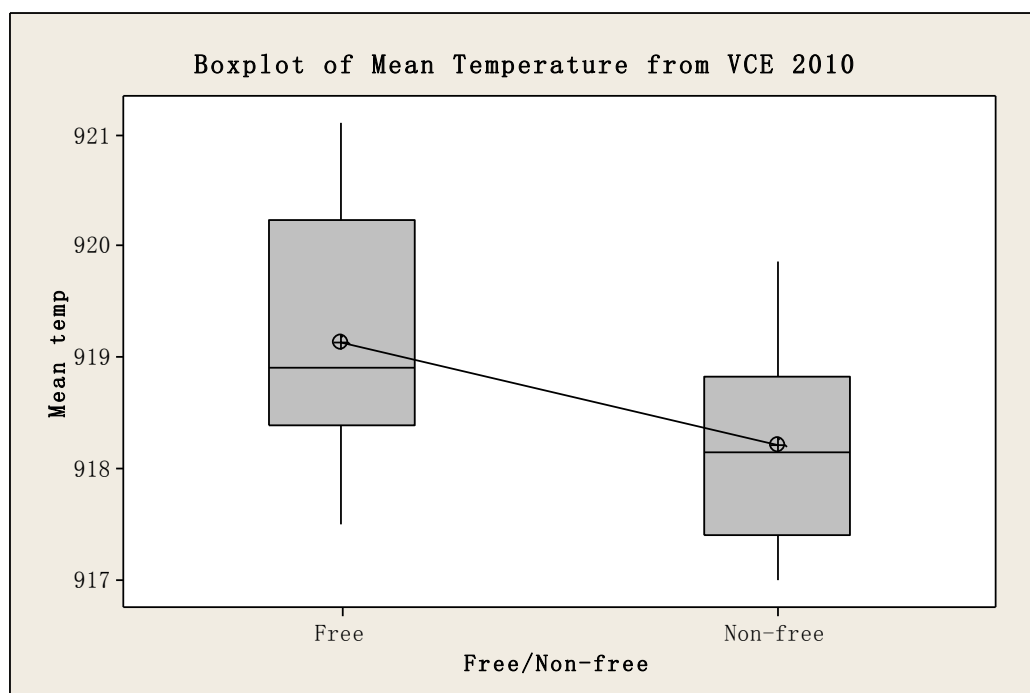


Figure 119 Box plot of temperature mean versus free/non-free (VCE 2010) [12]

The box plots in Figure 119 compares mean temperatures of Free and Non-free TCs. For Non-free TCs the mean value and the median are similar.

To make analysis of two factors, multi-vari charts were made in Minitab. In Figure 120, a multi-vari chart is shown with Mean temperature as response and Position and Track as factors.

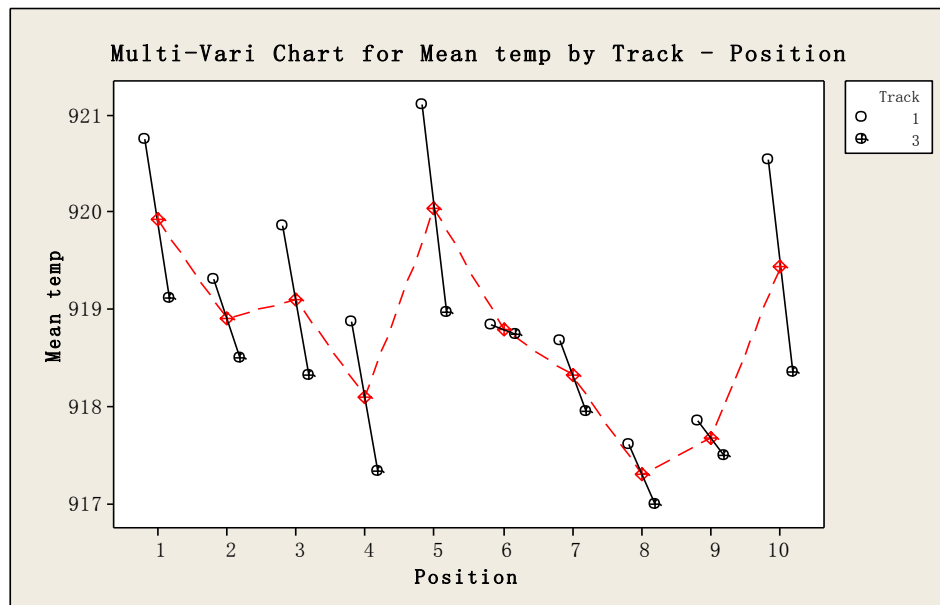


Figure 120 Multi-vari Chart for temperature mean by Track – Position (VCE 2010) [12]

In Figure 118, all positions on track 1 show higher mean temperature than that of track 3. Position 8 and 9 in both tracks shows low mean values.

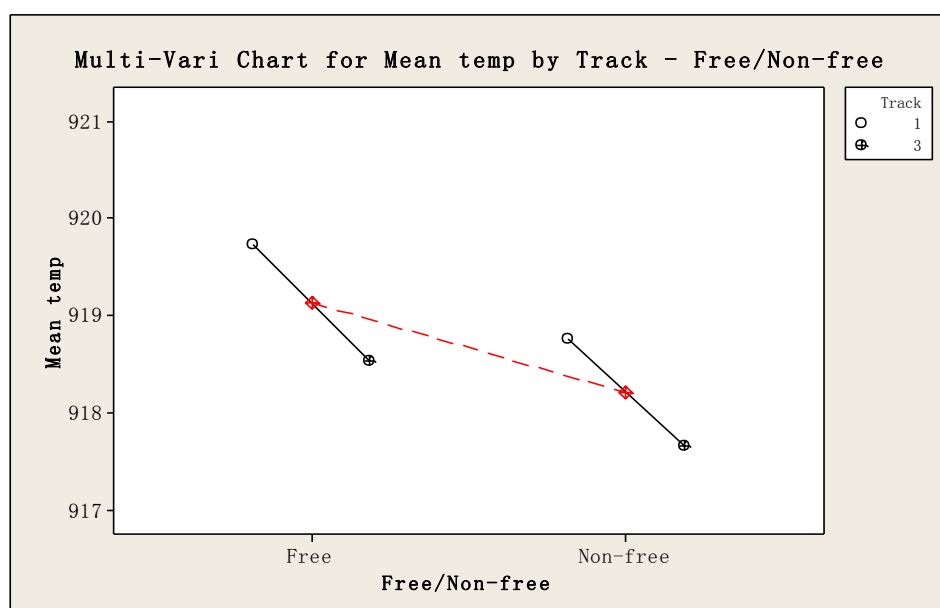


Figure 121 Multi-vari Chart for temperature mean by Track – Free/Non-free (VCE 2010)

In Figure 121, Free TCs have higher mean temperatures than that of Non-free TCs.

Summary of TUS at VCE in 2010:

- Track 1 is one degree warmer than track 3 within the stable working zone.
- Position 5 on both tracks is the warmest location and position 8 on both tracks was the coldest position.
- Free type of TCs (TCs) show higher mean temperature than Non-free TCs (TCs), which means the temperature of the furnace is higher than the temperature in the samples.
- Temperature from TC 4 on track 1 shows the highest capability indices within the stable zone.
- Temperature from TC 2 on track 3 shows the highest capability indices within the stable zone.

4. Discussion

4.1. Getrag All Wheels Drive AB

The TUS (temperature uniformity survey) was performed in 2010, therefore in this section only TUS results are discussed.

The stable zones for track 1 and 2 in section 3.6.1 show different means and trends. TCs 4 and 8 on track 1, which are non-free in samples show high mean temperatures in the stable zone. From 14:36:25 to 14:48:40, approximately 13 minutes, the mean temperature of TC 4 suddenly increases with 5 degrees. TC 6 on the same track also shows a similar variation at the same time interval, which is also a non-free TC. On track 2, TC 3 also shows a sudden increase from 12:48:54 to 13:00:54. Both tracks show similar phenomena is probably due to the fixture of the TCs in samples, however, the conclusion could not be drawn with certainty because all TCs mentioned above are located at inner bottom positions of the furnace. Other possible reason for the “Warm Zone” at inner bottom part of the furnace probably is due to the location of the electrical heating elements. The electrical heating elements are located at the central bottom positions of each track which could have influences on uniformity of the temperature within the stable zone.

4.2. Volvo Construction Equipment

In this section, both capability parameters and TUS results in 2010 will be discussed. For case hardening depth, track 2 shows deeper case depth than that of track 1 and 3. The reason for the difference is probably due to the loading condition. At the first test the furnace was fully loaded with components on track 1 and 3 while track 2 was loaded with empty trays. The test samples were loaded on track 1 and 3. At the second test the furnace was loaded in the same way as in the first test. The test samples were loaded on track 2 with empty trays in front and behind. Position 7 on track 1 shows the lowest CHD value, which could result from the error of one time measurement. For process capability index, track 2 shows good Pp but bad Ppk and Cpm values.

For surface hardness, the results for all three tracks show high capability indices. Track 3 shows higher Pp and Ppk values than that of track 1 which was tested under the same loading condition, with the same temperature and carbon potential.

For core hardness, due to segregations in the center of the samples the measurement is chosen at a position of 6 mm from the surface. In order to increase the accuracy of the measurement, three indentations are made. The results varied from position to position and from track to track. Note that the variations from three

measurements at one position is relatively small, however, the variations between positions and tracks are somewhat large. Core hardness is affected by combination of quenching variations and measurement error.

For surface carbon content, track 3 shows the largest Pp and Ppk values of three tracks but relative low Cpm value, which means the process of track 3 is capable of meeting specifications but not centered within the tolerances. Note that track 2 has the mean value close to the set value, but track 1 and track 3 have high carbon content due to production disturbance.

For TUS (temperature uniformity survey), high capability indices from both tracks show good capability of producing components within tolerances. For process capability studies, not all distributions follow normal distributions, but the temperature is stable and within the tolerance ranges, thus normality is not a critical issue for temperature at each position but it is the primary requirement for capability studies. For those TCs that do not follow normal distribution, mean temperature and the shape of distributions are studied.

The production disturbance in the furnace when conducting capability studies of Track 1 and Track 3.

Surface hardness increases with increasing of the temperature in the stable zone at VCE in 2010, however, surface hardness decreases slightly with increasing of the temperature in the stable zone at Getrag in 2009. (See in **Appendix E**)

Core hardness decreases slightly with increasing of the temperature in the stable zone at VCE in 2010, however, core hardness increases with increasing of the temperature of the stable zone at Getrag in 2009. (See in **Appendix F**)

Case depth increases with increasing of the temperature in the stable zone both in VCE 2010 and Getrag in 2009, however, the tendencies are not significant. (See in **Appendix G**)

Surface carbon content do not show enough evidence to prove the correlations between the mean temperatures of the stable zone in VCE 2010, while at Getrag surface carbon content decreases with increasing of the mean temperatures of the stable zone. (See in **Appendix H**)

Surface hardness decreases with increasing of surface carbon content both in VCE 2010 and Getrag 2009. (See in **Appendix I**)

There is no correlation between core hardness and surface carbon content, see in **Appendix J**.

Case depth decreases with increasing of surface carbon content in VCE 2010, while case depth increase slightly with increasing of surface carbon content in Getrag 2009. However, the trends are not significant. (See in **Appendix K**)

5. Conclusions and Guidelines

5.1. Getrag All Wheels Drive AB

The furnace in Getrag is OK which means temperatures in all positions are within tolerance limits, however, all positions show several degrees colder than the set point values. Track 1 is warmer than track 2 within the stable working zone. The mean temperatures measured with TCs in the samples are warmer than free TCs in the furnace atmosphere. The inner positions of both tracks are warmer than outer positions. Positions 4 and 8 on track 1 and Positions 3 and 7 should be paid special attention in future capability studies.

5.2. Volvo Construction Equipment

The furnace in VCE is good regarding temperatures in all positions, however, all positions shows several degrees of temperature lower than the set target values. Track 1 is warmer than track 3. The TCs free in furnace atmosphere are warmer than those within the samples. Position 5 is the warmest location on track 1 and 3, while position 8 is the coldest on both tracks.

Track 2 which is tested under a low loading condition achieves a deeper case depth, but lower surface hardness and lower surface carbon content than that of track 1 or track 3.

For a fully loaded track, track 3 achieves slightly deeper depth, lower surface hardness and slightly lower surface carbon content than track 1. Besides, track 3 also shows higher process capability indices (Pp, Ppk and Cpm) than track 1 with regard to case depth, surface hardness and surface carbon content.

5.3. Guideline for Process Capability Studies

One aim of this project is to try to find out suitable methods for evaluation of process capability studies in heat treatment. Figure 122 illustrates a possible road map for how to realize it step by step. The first step is to make MSA (Measurement System Survey) or SAT (System Accuracy Test) to assure that the measurement system has enough accuracy to obtain measurement data. The next step is measurement of data. After measurement calculation is made to obtain mean values and standard deviations. For advanced statistical analysis using software such as Minitab is then performed. The next step is to analyze cause of variation for the identified variations and deviations. The final step is to create an action plan for e.g. furnace maintenance.

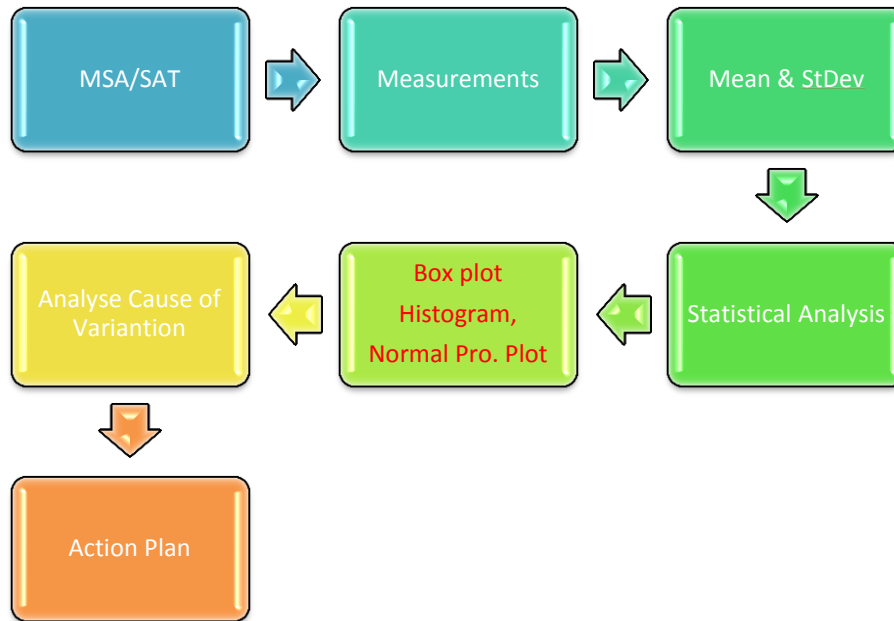


Figure 122 Process Capability Studies in Heat Treatment Road Map

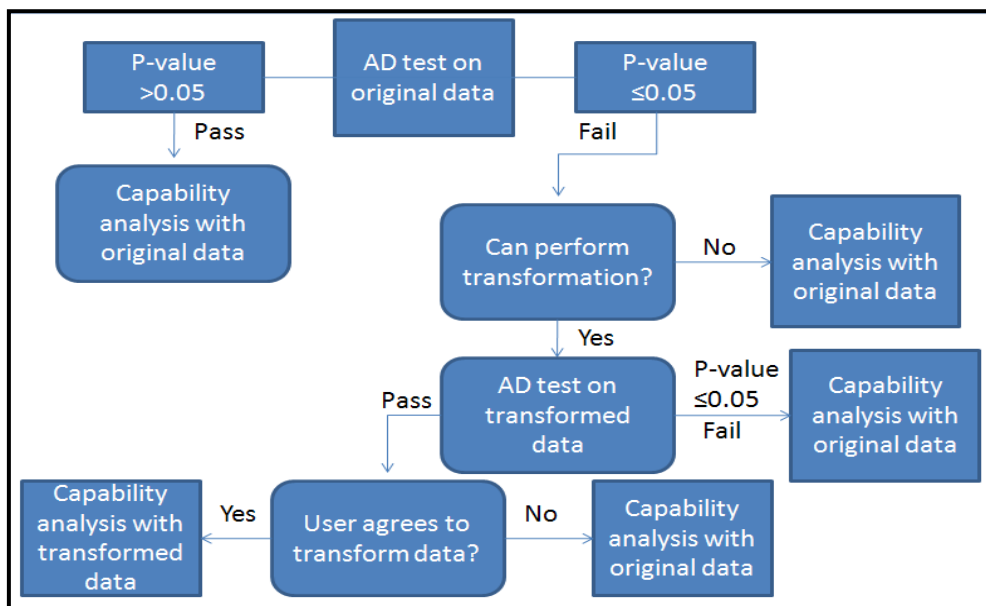


Figure 123 Process Capability Analyses [12]

Figure 123 shows the method for analyzing non-normal distribution data. Typically, there are two available methods to perform a valid capability analysis if the current distribution is non-normal.

- Transform the non-normal data by Johansson or Box-Cox transformation so that it fit to a normal distribution.
- Try to find an alternative distribution that fit to the current distribution e.g. the exponential distribution.

6. Future work

Recommendations are that both companies continue to perform the complete capability studies and make comparisons of results from consecutive years. The capability parameters should be measured by same methods and using same equipment in order to eliminate error.

If possible, the interactions among surface hardness, core hardness, surface carbon content, case depth and temperature within stable zone should be studied. For example, the interactions between mean temperature in stable zone and surface hardness, surface carbon content, core hardness or case depth from dummy samples, or the relationships between case depth and surface carbon content.

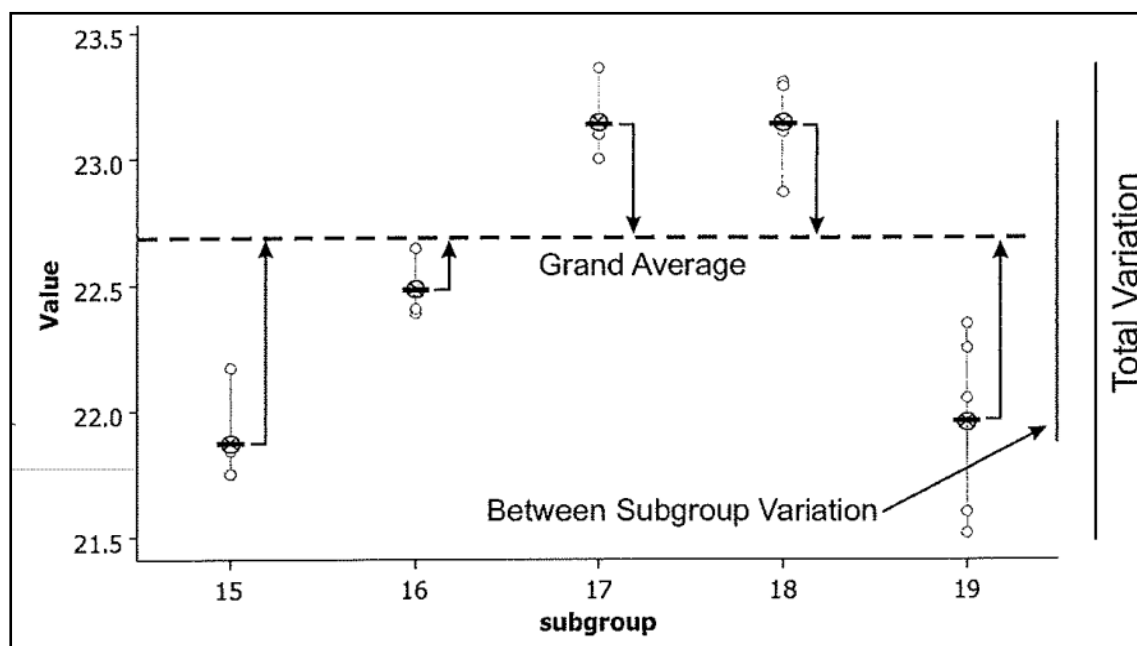
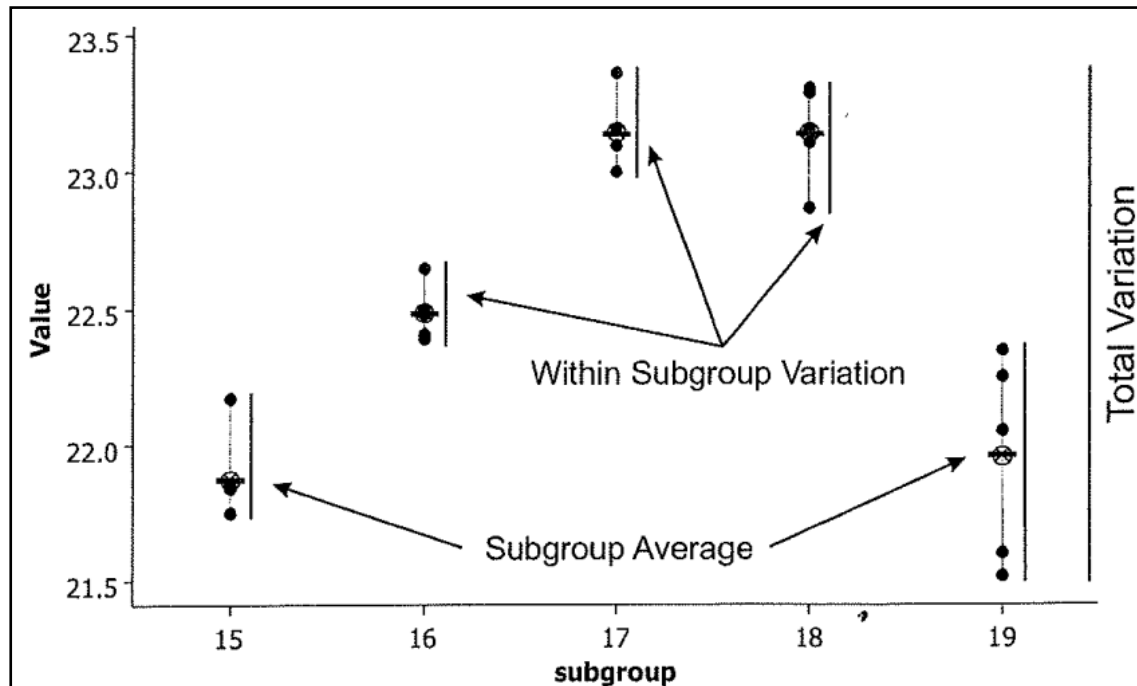
It is also recommended that the future work should cover sample material analysis e.g. using chemical composition of the sample for CCT diagram (continuous cooling transformation diagram) calculations to study the cause of variations in core hardness and microstructures. The problems with segregations in the samples material should be investigated by using e.g. different heat treatments such as homogenization annealing and/or quenching and tempering for “clean” steel with a minimum of inclusions like manganese sulfides.

Typically, in a six sigma project involves “DMAIC” which refers to Define, Measure, Analyze, Improve and Control. The current project only involves in the four first steps without the next. Thus, in future work it is important to collect other factors that affect quality parameters during production. The next step for this project is to improve the current process or furnace based on the root causes and make control in the end.

References

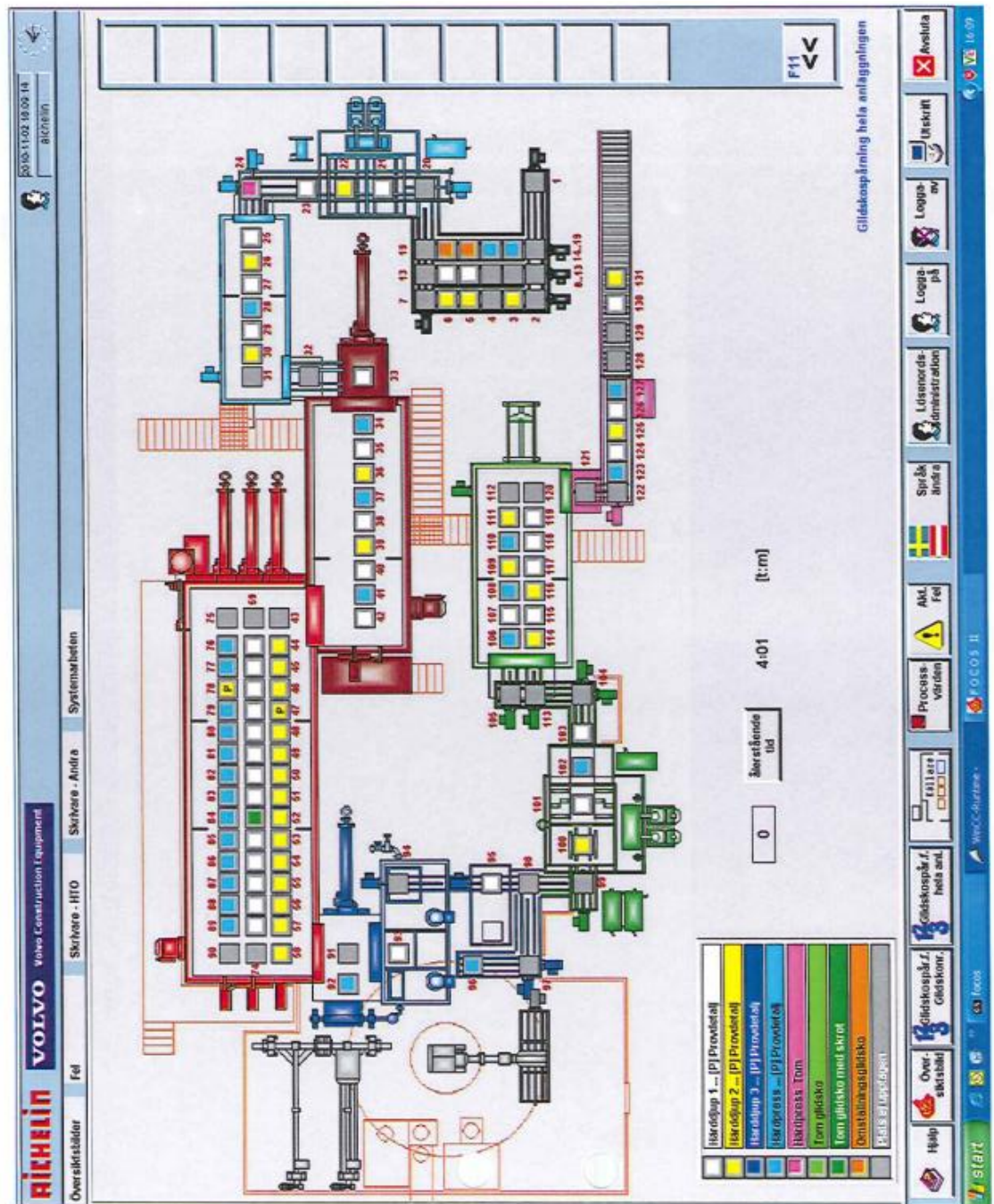
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Appendix A: Within- and Between- Subgroup Variation



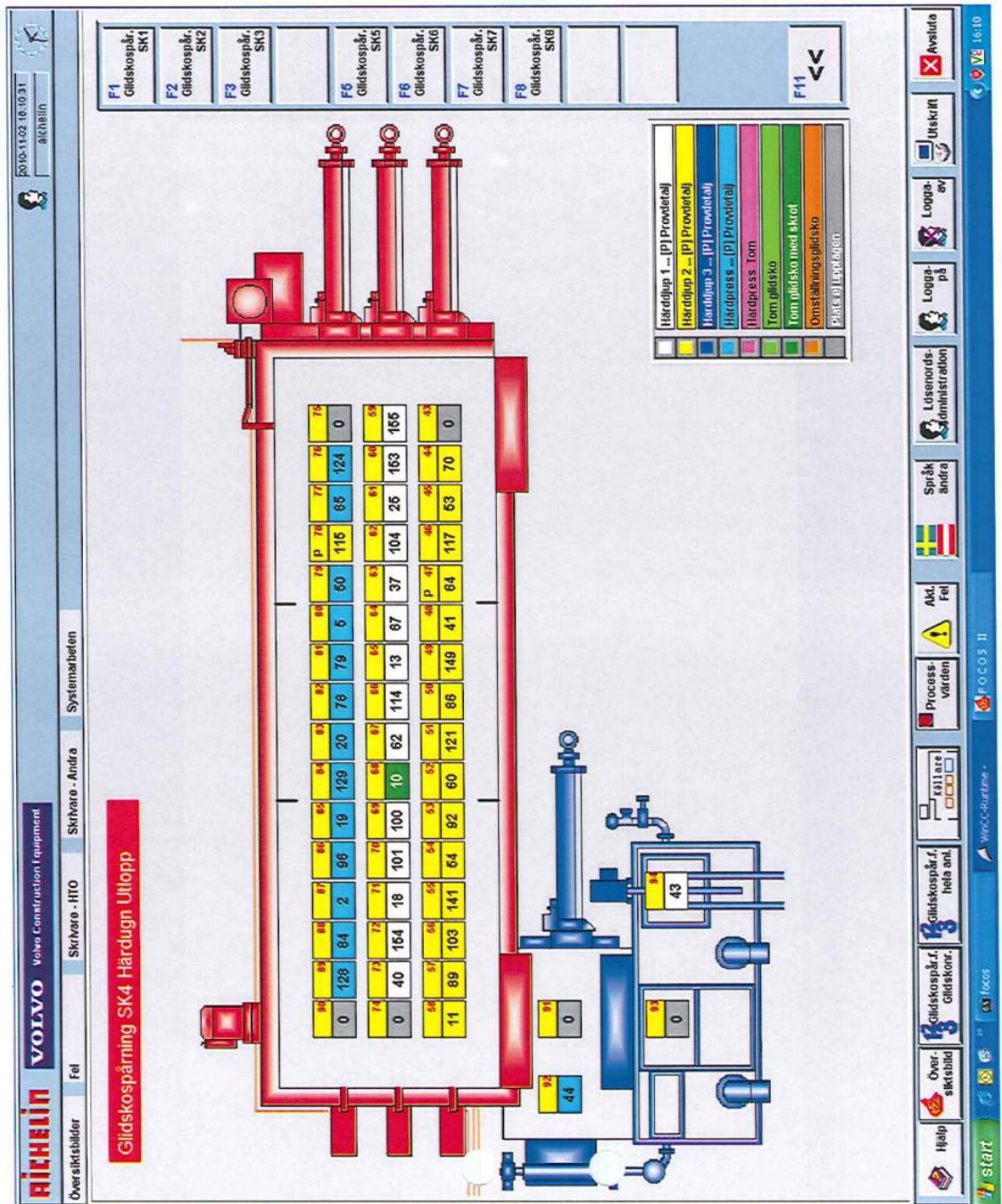
Within-subgroup variation takes into account of the shift and drift within subgroup. Between-subgroup variation ignores the shift and drift within subgroup but considers between subgroups.

Appendix B: VCE Heat Treating System

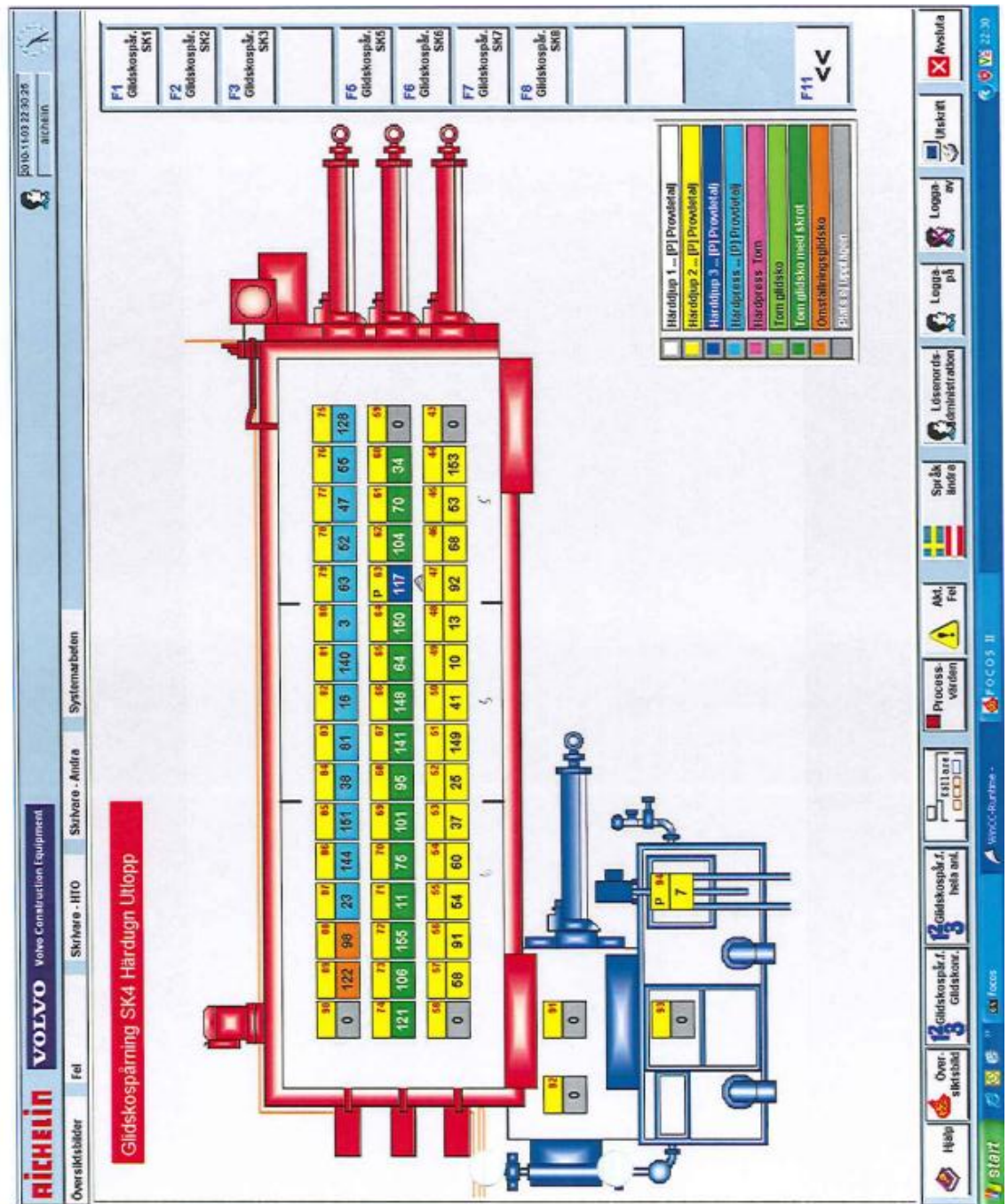


Symbol “P” in the main heating furnace refers to the position of the stacking tray with test specimens.

Appendix C: The Main Furnace of VCE



Symbol "P" in Yellow Square refers to the position of the stacking tray with test specimens. Track 1 and 3 were fully loaded with test samples and components, only Square 10 in Green of Track 2 is empty loaded.



Symbol “P” in Blue Square refers to the position of the stacking tray with test specimens. Green Square refers to empty loaded position and the other colors refer to fully loaded condition. Track 2 was only loaded with test samples, while track 1 and 3 were fully loaded with other components.

Appendix D: Temperature Uniformity Survey (Getrag 2009)

Mean value, standard deviation and the variance for each TC from Track 1 [13]

Tid [h]	Kanal #1	Kanal #2	Kanal #3	Kanal #4	Kanal #5	Kanal #6	Kanal #7	Kanal #8	Kanal #9	Kanal #10	Medelvärde	St.Dev	Varians
3,60	905,1	906,0	904,2	910,9	905,1	907,4	903,4	911,9	911,9	906,7	907,3	3,2	10,2
3,67	904,5	905,3	904,3	910,6	904,6	906,7	903,6	911,6	912,9	906,0	907,0	3,4	11,5
3,73	904,7	905,7	904,3	910,6	905,1	907,0	904,0	911,3	912,7	906,3	907,2	3,2	10,1
3,80	904,6	905,5	904,1	910,3	905,2	907,0	904,1	910,9	912,3	906,2	907,0	3,0	9,2
3,87	904,7	905,7	904,0	910,1	905,3	907,2	904,1	910,7	912,6	906,3	907,1	3,0	9,2
3,93	904,9	905,8	904,1	910,0	905,4	907,4	904,3	910,8	912,0	906,5	907,1	2,8	8,1
4,00	904,9	905,8	904,2	909,9	905,5	907,4	904,5	910,7	912,1	906,6	907,2	2,8	7,8
4,07	904,6	905,6	904,2	909,7	905,2	907,1	904,4	910,6	911,6	906,4	906,9	2,7	7,5
4,13	904,9	905,7	904,2	909,4	905,1	906,9	904,3	910,0	912,3	906,2	906,9	2,8	7,6
4,20	905,1	906,0	904,4	909,3	905,1	906,9	904,4	909,6	912,3	906,4	907,0	2,6	6,9
4,27	905,0	905,8	904,4	909,2	905,0	906,8	904,3	909,4	912,1	906,3	906,8	2,6	6,7
4,33	905,0	905,9	904,5	908,9	905,1	907,9	904,4	909,3	911,5	906,4	906,9	2,4	5,8
4,40	905,1	906,1	904,5	908,9	905,2	907,9	904,4	909,1	911,5	906,4	906,9	2,4	5,6
4,47	905,1	905,9	904,5	908,9	905,1	907,6	904,5	909,0	911,2	906,3	906,8	2,3	5,2
4,53	905,2	904,8	905,0	910,6	905,2	908,4	904,4	908,8	911,5	906,3	907,0	2,6	6,8
4,60	905,6	905,2	905,6	912,0	905,4	908,7	904,4	908,8	911,8	906,7	907,4	2,8	7,7
4,67	905,5	905,2	905,9	912,6	905,3	908,6	904,4	908,7	911,8	906,6	907,5	2,9	8,2
4,73	905,5	905,7	905,9	911,9	905,2	905,9	904,4	908,6	910,8	906,5	907,0	2,5	6,4
4,80	905,9	906,2	906,1	911,5	905,6	906,5	904,5	908,5	911,1	907,0	907,3	2,3	5,5
4,87	906,1	906,2	906,5	911,7	905,5	906,9	904,7	908,5	911,2	907,0	907,4	2,3	5,5

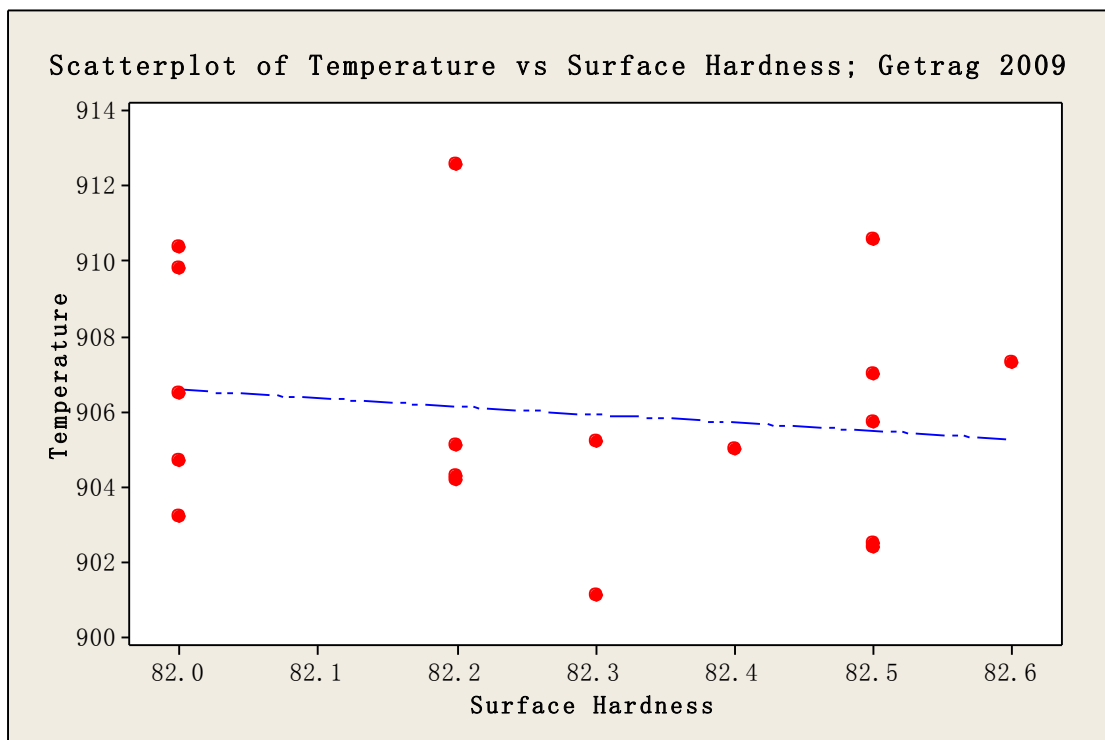
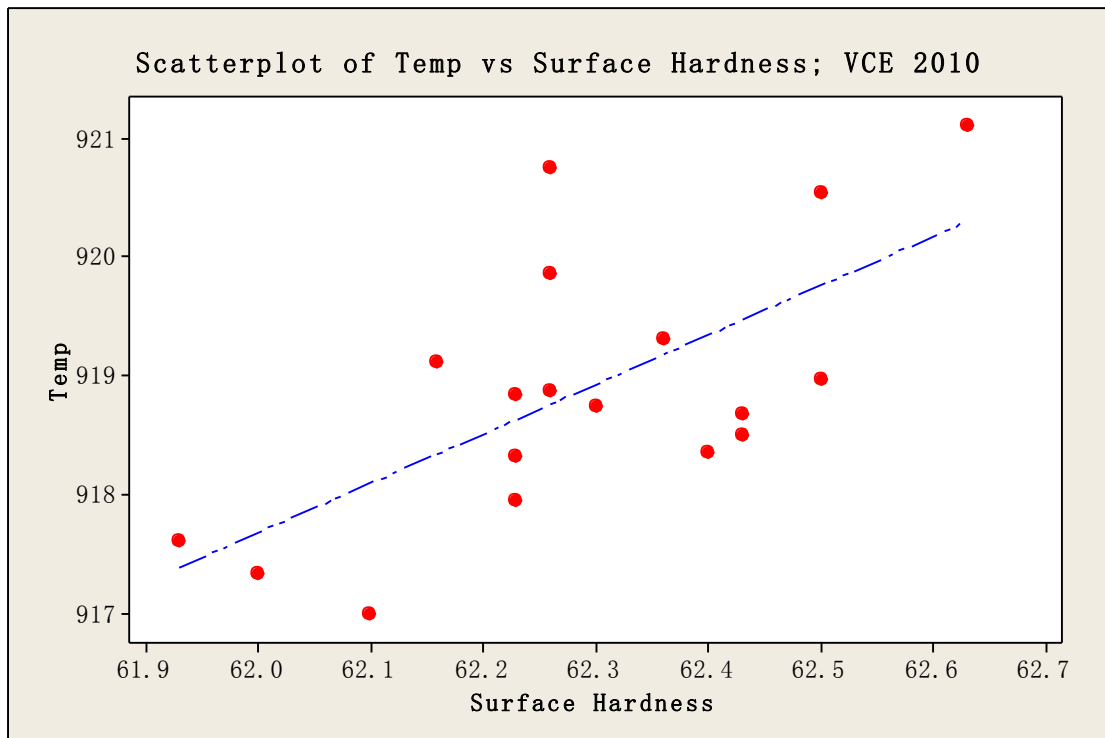
Mean value, standard deviation and the variance for each TC from Track 2 [13]

Tid [h]	Kanal #1	Kanal #2	Kanal #3	Kanal #4	Kanal #5	Kanal #6	Kanal #7	Kanal #8	Kanal #9	Kanal #10	Medelvärde	St.Dev	Varians
3,60	905,7	903,9	913,6	904,9	906,4	905,0	916,7	909,0	907,6	906,2	907,9	4,1	17,2
3,67	907,5	904,5	912,4	903,8	907,9	904,3	915,8	908,3	904,0	906,0	907,5	4,0	15,7
3,73	907,4	904,6	911,3	902,5	907,5	904,2	914,6	907,0	903,5	905,8	906,8	3,7	13,8
3,80	907,1	904,1	910,8	902,0	907,2	903,7	914,0	906,4	903,1	905,6	906,4	3,7	13,5
3,87	909,9	904,0	910,6	901,6	906,9	903,5	914,3	905,9	902,9	905,6	906,5	4,0	15,9
3,93	909,7	904,2	910,9	901,4	906,7	903,6	915,1	905,8	903,0	905,9	906,6	4,2	17,4
4,00	909,1	904,0	910,6	901,2	906,3	903,4	914,8	905,5	902,7	905,5	906,3	4,1	16,9
4,07	909,1	903,8	910,3	901,0	906,4	903,2	914,5	905,3	902,4	905,4	906,1	4,1	16,9
4,13	906,3	901,5	909,3	899,8	904,9	902,1	911,9	903,3	901,7	903,0	904,4	3,8	14,4
4,20	906,5	901,8	909,1	899,3	904,2	902,1	911,2	902,5	901,5	903,0	904,1	3,7	13,8
4,27	906,3	901,8	908,9	899,1	904,6	901,9	910,8	902,0	901,4	903,2	904,0	3,7	13,4
4,33	906,1	901,3	909,2	899,0	903,4	901,7	911,6	901,6	901,2	902,8	903,8	4,0	15,7
4,40	906,3	901,7	909,4	899,1	903,8	902,2	911,9	901,6	901,5	903,2	904,1	4,0	15,8
4,47	906,0	901,6	909,4	899,2	903,7	902,0	911,7	901,6	901,3	903,4	904,0	3,9	15,4
4,53	905,3	900,7	909,8	899,8	903,1	900,6	910,9	900,7	898,9	902,7	903,3	4,2	17,4
4,60	906,2	901,3	910,7	900,9	903,7	901,1	910,3	900,0	899,1	903,3	903,7	4,1	17,1
4,67	906,8	901,6	911,3	901,6	903,7	901,1	910,1	899,8	899,2	903,7	903,9	4,2	17,7
4,73	906,1	901,4	911,2	901,9	903,2	900,7	910,4	899,7	898,6	903,1	903,6	4,3	18,6
4,80	906,0	901,2	911,3	901,9	903,1	900,5	910,8	899,2	898,4	903,0	903,5	4,5	20,2
4,87	906,2	901,1	911,7	901,9	903,0	900,5	910,7	899,1	898,1	903,0	903,5	4,6	21,4

Mean temperature of the stable zone from Track 1 and 2:

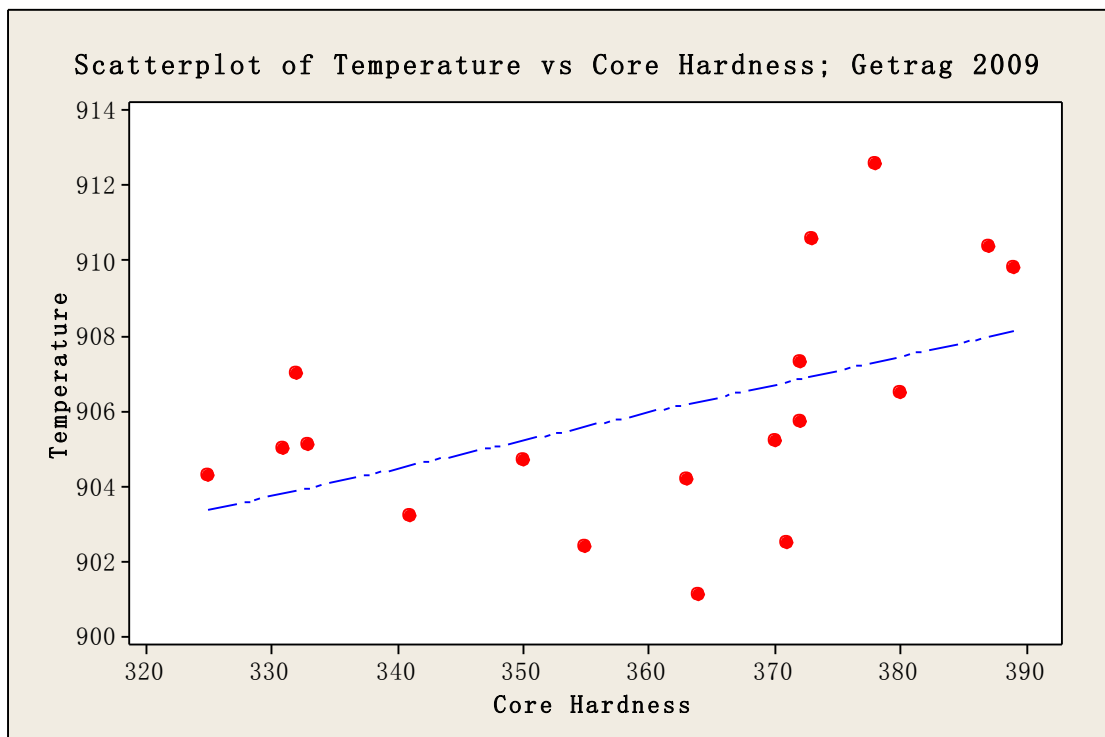
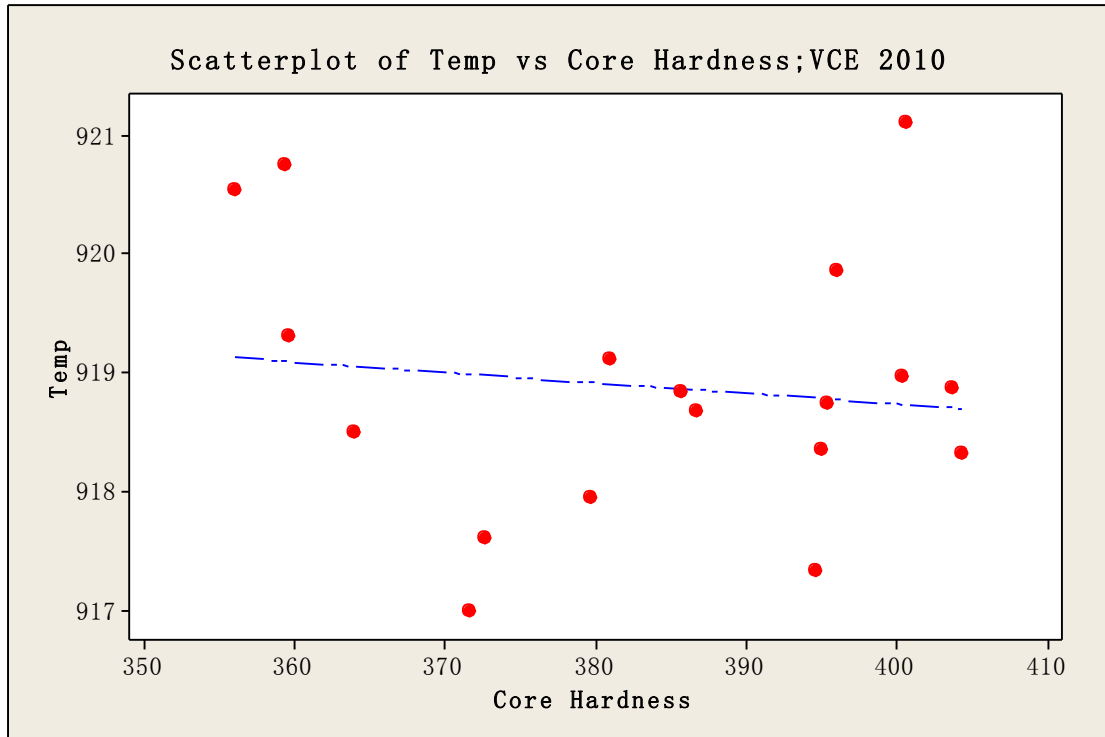
Track	T1	T2	T3	T4	T5	T6	T7	T8	T9
1	905.1	905.7	904.7	919.4	905.2	907.3	904.3	909.8	906.5
2	907.0	902.5	910.6	901.1	905.0	902.4	912.6	903.2	904.2

Appendix E: Mean temperature versus Surface Hardness



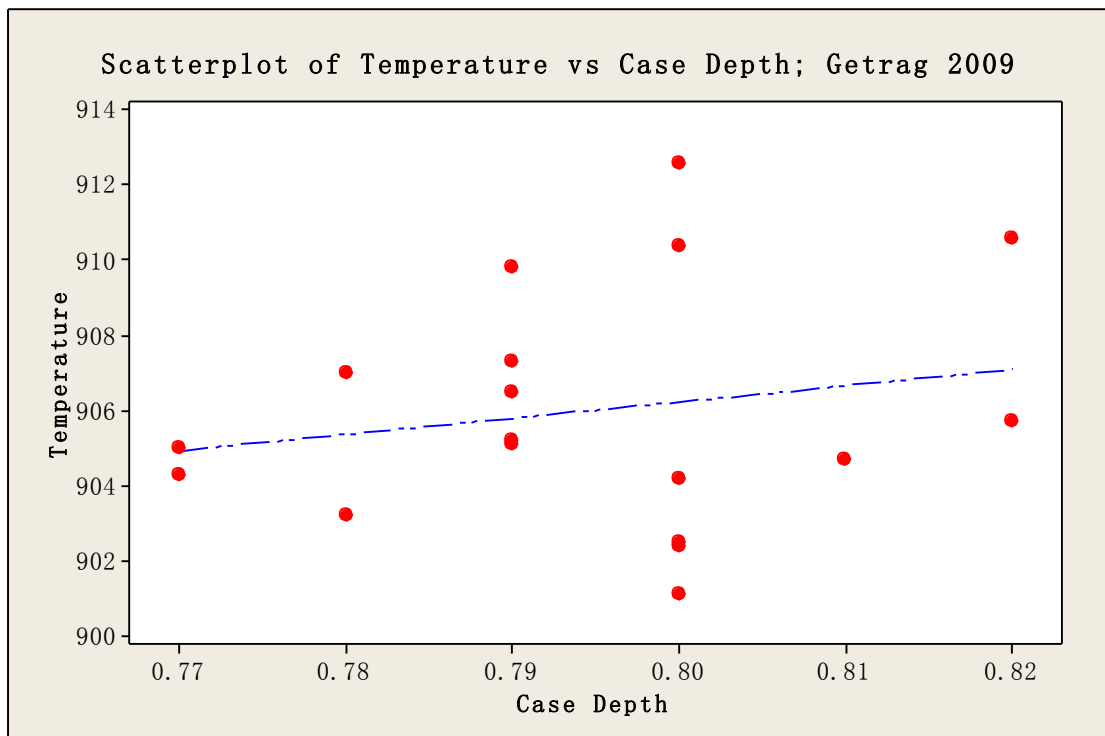
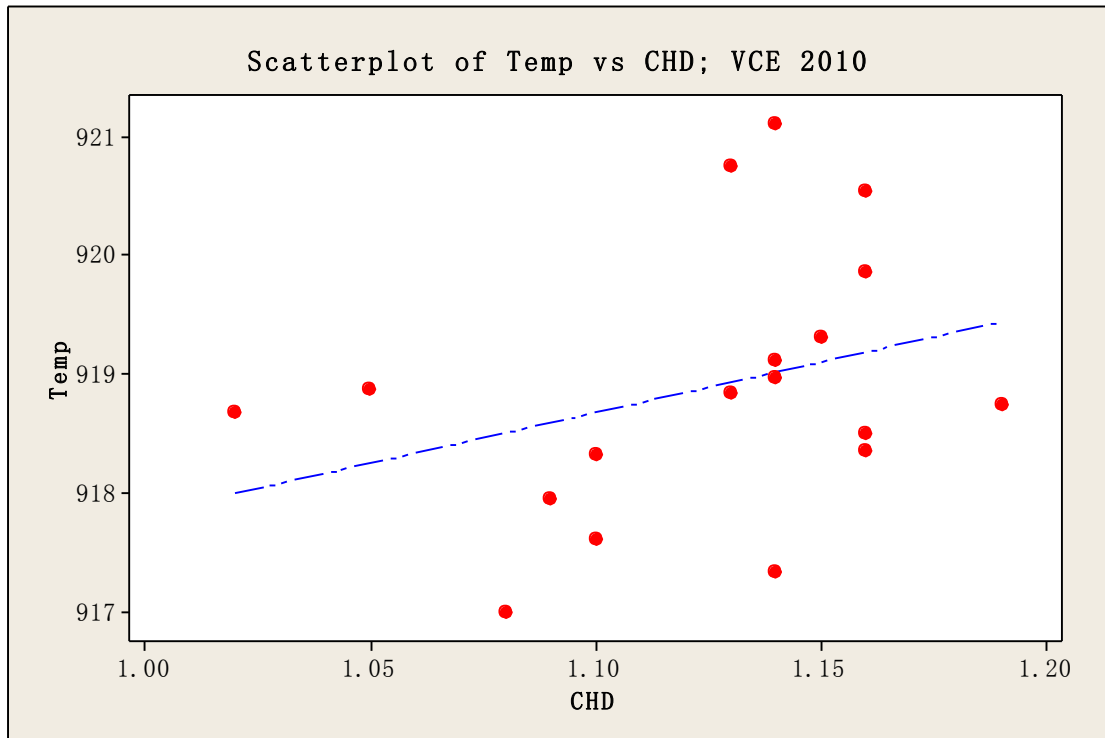
In the first diagram for VCE in 2010, surface hardness increases with increasing of mean temperature. In the second diagram for Getrag in 2009, the interaction is not significant.

Appendix F: Mean temperature versus Core Hardness



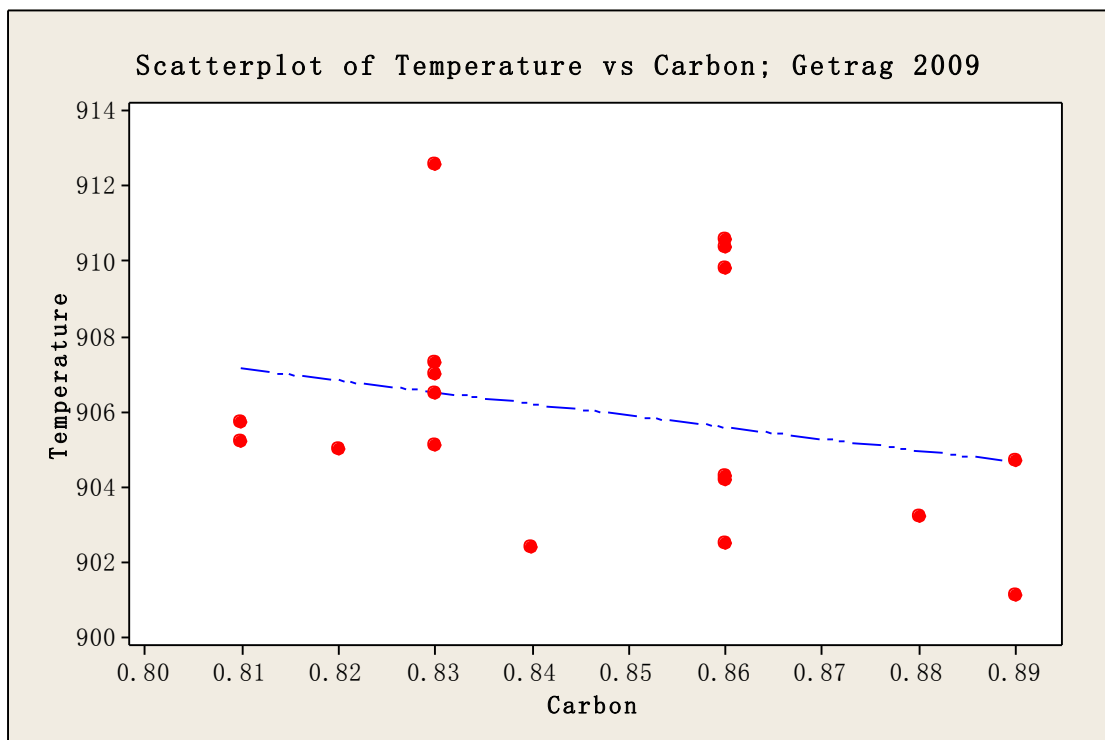
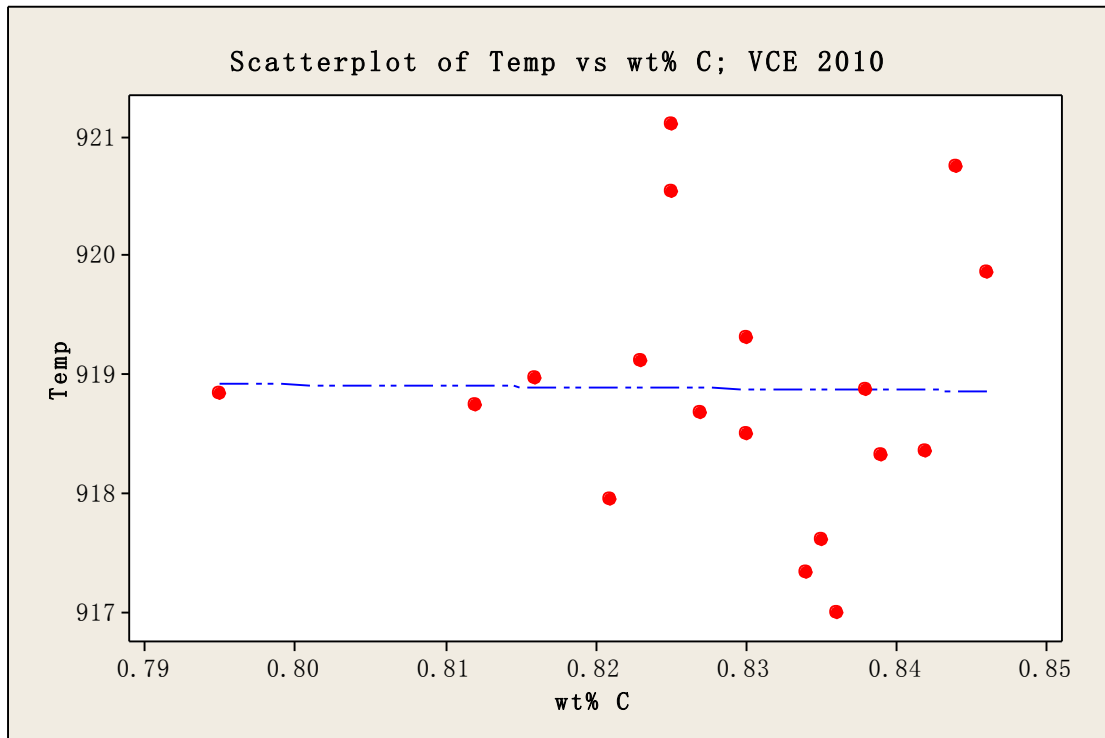
In the first diagram for VCE in 2010, the interaction of core hardness with mean temperature within the stable zone is not significant. In the second diagram for Getrag in 2009, core hardness increases with increasing of mean temperature within the stable zone.

Appendix G: Mean temperature versus Case Hardening Depth



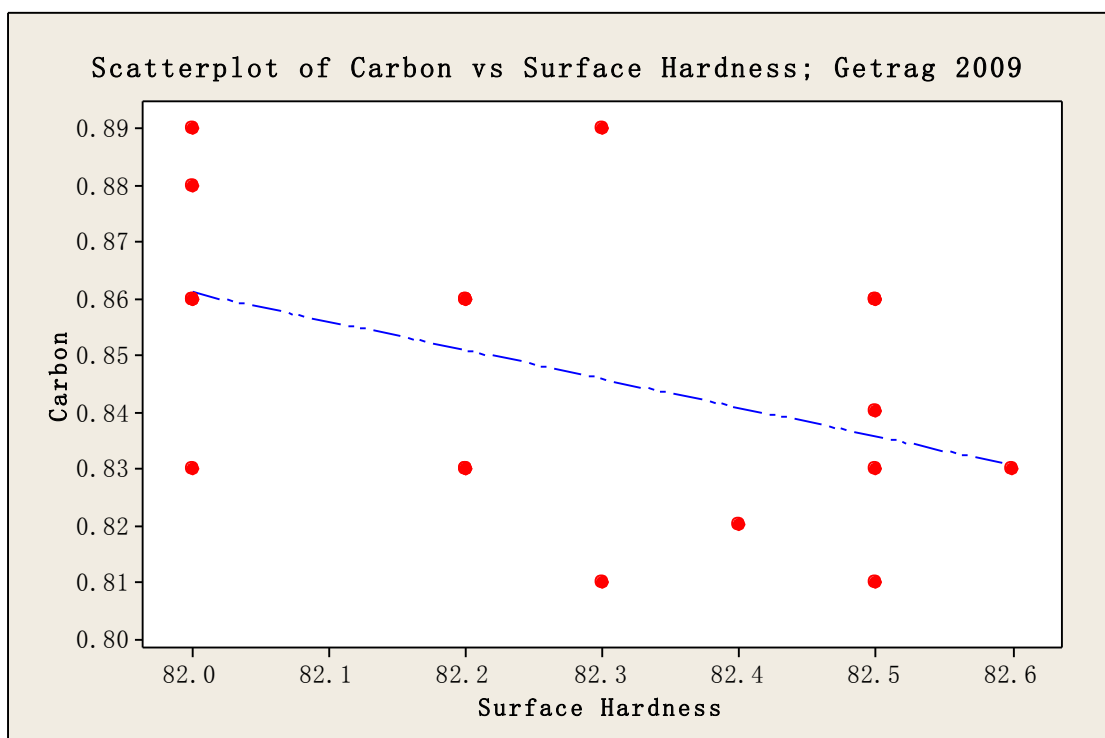
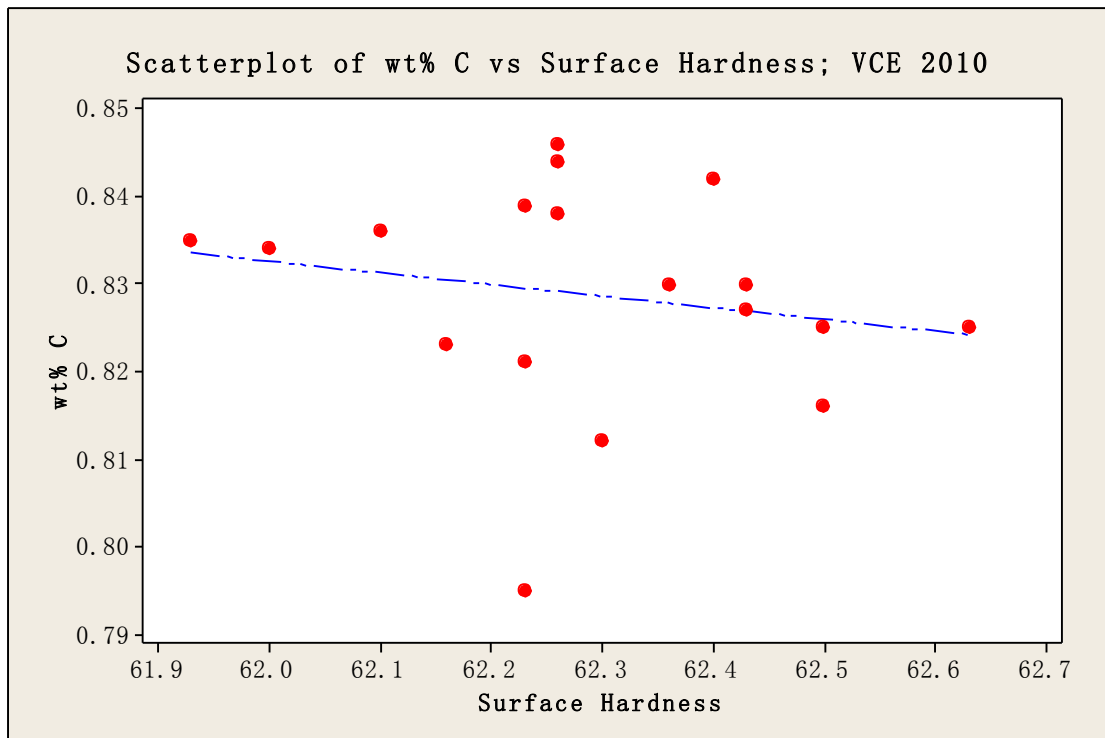
In both diagrams for VCE in 2010 and Getrag in 2009, the interaction between case hardening depth and mean temperature within the stable zone is not significant.

Appendix H: Mean temperature versus Surface Carbon Content



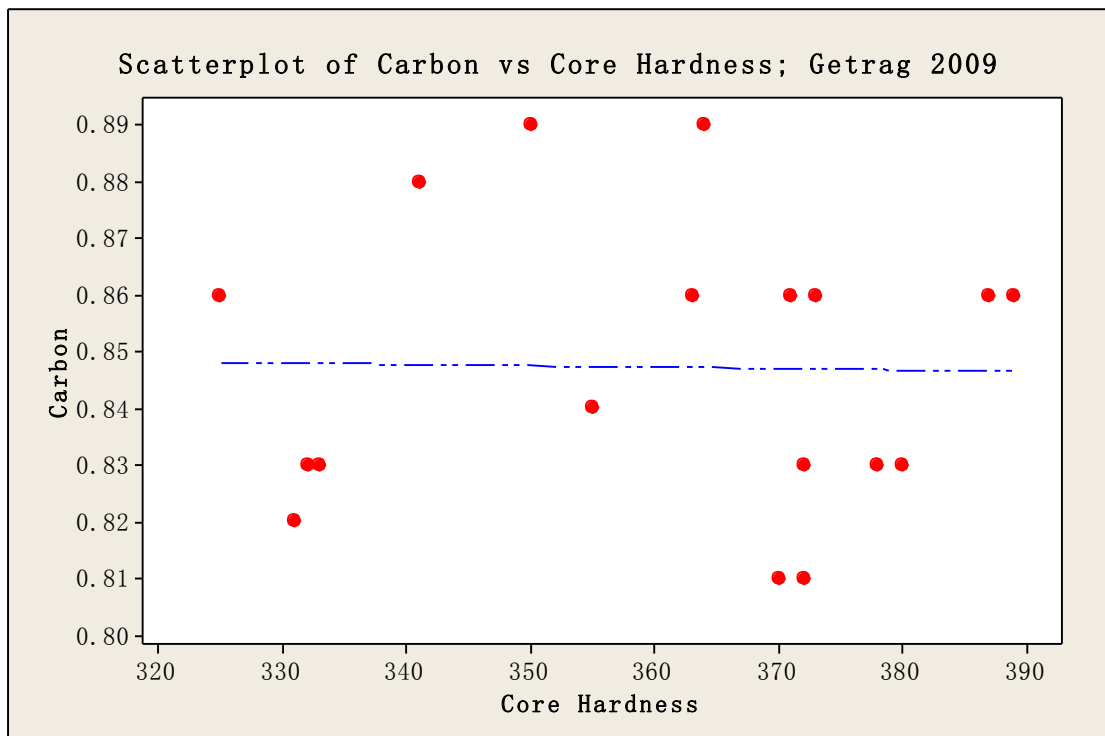
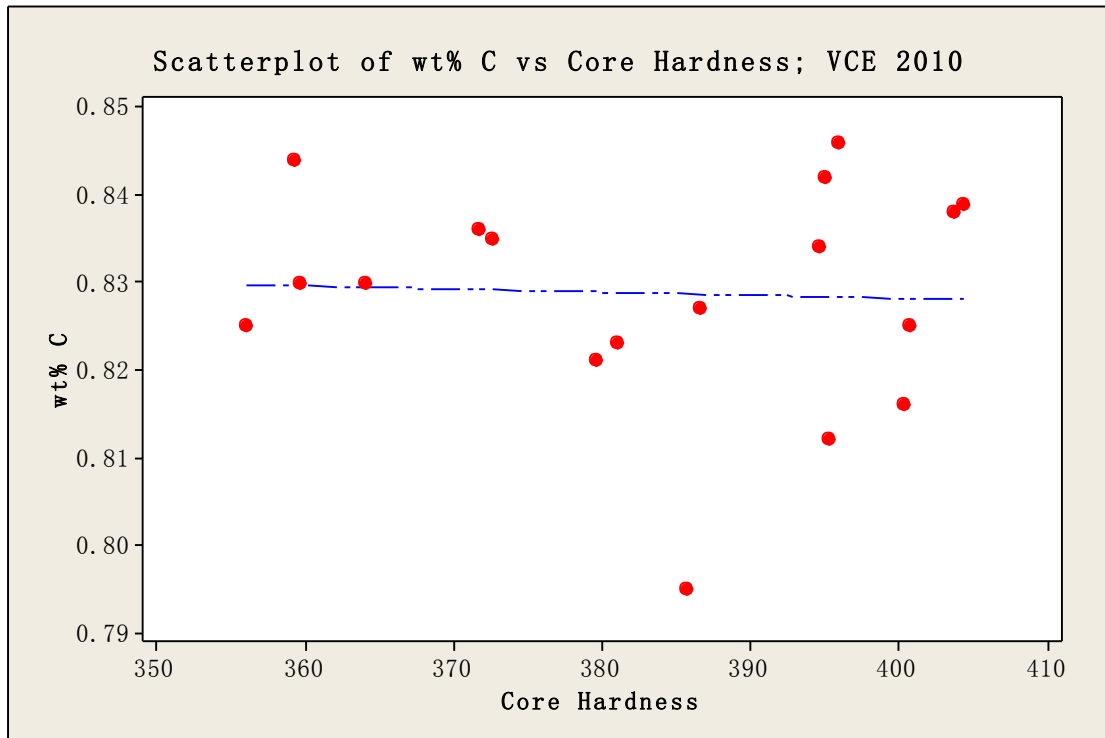
In both diagrams for VCE in 2010 and Getrag in 2009, the interaction between surface carbon content and mean temperature within the stable zone is not significant.

Appendix I: Surface Carbon Content versus Surface Hardness



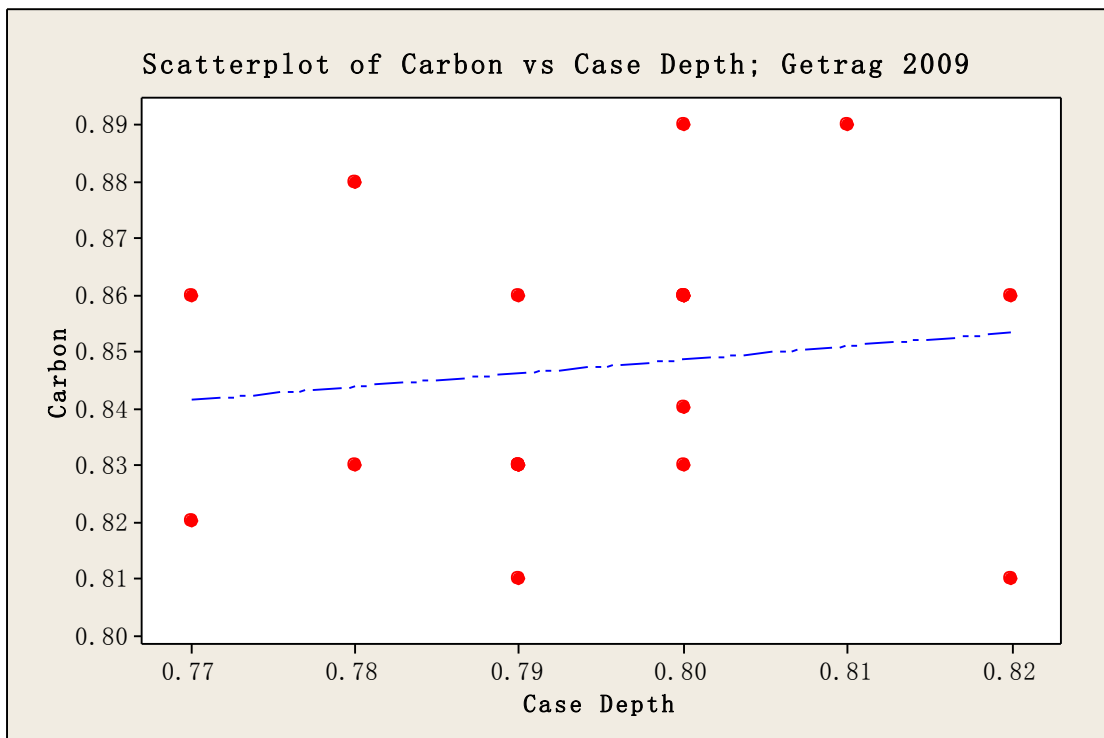
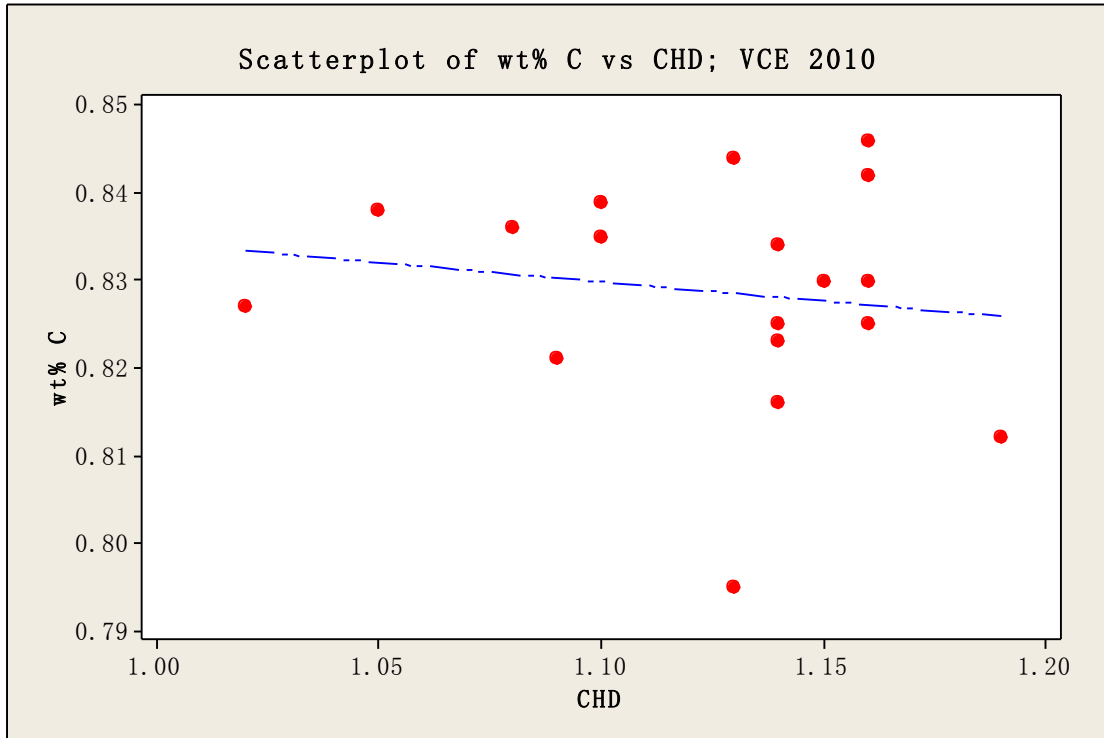
In both diagrams for VCE in 2010 and Getrag in 2009, surface hardness increases with decreasing of surface carbon content.

Appendix J: Surface Carbon Content versus Core Hardness



There is no sign for relations between core hardness and surface carbon content.

Appendix K: Surface Carbon Content vs. Case Hardening Depth



In the first diagram for VCE in 2010, CHD increases with decreasing of surface carbon content. In the second diagram for Getrag in 2009, CHD increases with increasing of surface carbon content.