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Manufacturing the 7000 Gear Train Mechanical Assembly

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ABSTRACT

This study is based on the SIX SIGMA concept applied to the keyway fabrication method used in the shaft of a 7000 gear assembly. After several preliminary studies and design changes by the engineers, the operators continue with frequent changes of the machine setup and cutter types, generating different types of dimensions in the width of the keyway. Additional rework are also required since some keys cannot be assembled due to the incorrect size of the keyway. This additional set up and rework is adding significant cost to the project. The company has been designing, manufacturing and selling automatic doors since conception. The product range in automatic door industry includes:

1. Automatic Sliding Doors
2. Automatic Swinging Doors
3. Automatic Folding Doors
4. Revolving Doors (Security Revolving)
5. Service Windows
6. Presence and Motion Detection Systems
7. Controls and Operators to meet both Commercial and Industrial Applications
8. Automated People Mover (APM) Transit Doors and Vehicle Door Operators

Keywords: *Six Sigma, Manufacturing, Process Mapping, Design of Experiments, Process Capability.*

LIST OF ACRONYMS

B8 Machine	A machine dedicated to cut the raw material in different slices
B10_LB200	CNC machine for shafts
CCR	Critical Customer Requirements
CS	Cutting Speed
CNC	Computer Numeric Control
DIA	Diameter
DMAIC	Define Measure Analysis Improve Control
DOE	Design of Experiments
DOP	Dimension Over Pins
DPMO	Defect Per Million of Opportunity
DPO	Defects Per Opportunity
DPU	Defects Per Unit
FR	Feed Rate
FTQ	First Time Quality
GR&R	Gage Reproducibility and Repeatability
I	Individual
ID	Inside Diameter
LH	Left Hand
MR	Moving Range
MSE	Measure System Evaluation
NEM	Numeric Evaluation Metric
OD	Outside Diameter
PD	Post Detection
PFMEA	Process Failure Mode Effects Analysis
PMAP	Process Map
PO	Post Occurrence

PS	Post Severity
QC	Quality Control
RH	Right Hand
RPM	Revolution Per Minute
RPN	Risk Priority Number
RTY	Rolled Throughput Yield
SIPOC	Supplier Input Process Output Customer
Soft.	Software
Spec.	Specification
TMAP	Thought Process map (Mental Map)

1. INTRODUCTION

For many years companies have been looking for a methodology that helps to solve and control manufacturing problems and product design issues. Sigma is a Greek letter (σ). This is used to assign the standard deviation in the output of any process. The Six Sigma Methodology is an efficient and effective way to handle business, complete tasks, accelerate processes and resolve problems. The model to follow is the DMAIC, which means Define, Measure, Analysis, Improve and Control. Six Sigma is a metric measure that indicates the performance of a process, and some of the measurements include the following:

1. The capacity of the process to accomplish the tasks without any defects.

2. The higher the σ, the better the process is.

3. The frequency of the defects and how often they occur.

The old way to doing business was *Cost + Profit = sale's price.* Now, if we want to be more competitive, we need to use (*Market's price - Cost= Profit).* This means that we need to accelerate our quality and productiveness in order to be one of the best companies. Therefore, the Six Sigma methodology can be the right option for a company to follow.

Six Sigma is a philosophy of business. This is focused in continuous improvement and prevention of defects with the use of the statistical tools; It is opposite of defect detection methodology.

The philosophy of 6σ is to reduce costs while identifying and reducing the undesirable sources of variation. There are many failure modes in the assembly process. A PFMEA is to be used to identify the main problems and root cause of the failures. Currently, the lane is divided in two parts; the manufacturing process for Gear and Shafts, and the flow line assembly where all the parts are assembled together in order to complete the 7000 Gear Box.

2. DESCRIPTION OF THE PROBLEM

The automatic swinging door uses the 7000 series gear drive in order to open and close the door. This mechanical assembly is based on three shafts and three gears, and each gear is attached to a shaft by the employment of a key. The most common type of key is the flat key. The main function of the key is to transmit the torque from a component to a shaft. Assuming that the force, P, acting on the side of the key is uniform and the torque, T, is to be transmitted from the shaft to the gear.

$$P = T / r$$

Where:

P= the force (N)
r = the radius of the shaft (m)
T = the transmitted torque (Nm)

On the shaft, the keyway or keyseat is classified according the process which it is made. The width of the key is approximately ¼ of the diameter of the shaft. The 7000 series gear drive uses two shafts with a keyway; the assembly C7024 uses a key width of 3/16" and also the assembly C7113.

The most common failures occurring in the assembly C7113-2 are:

1. The Gear C7017-1, which is assembled with the shaft C7034-2, can come loose.
2. The tooth's shaft C7034-2 is broken.
3. The Gear C7017-1 does not fit the shaft C7034-2.
4. The key does not fit in the keyseat. This causes a scrap part.
5. Broken keys

This study considered the fourth failure mode in the assembly C7113-2, but the same test could apply to the others assemblies C7111 and C7024-2. Figure 1 shows the specifications of the part C7034 that is in the assembly 7113-2.
The first step is to measure the parts. A sample of the production schedule for a day was taken to see the values in the shaft diameter, width and depth of the keyway, and the length with the key assembled in the keyway. For the shaft C7034, the diameter should be 0.499 inches

(+0.0005, -0.0010), for a low limit of 0.498 inches and upper limit of 0.4995 inches and the width of the keyway should be 0.188 inches (+0.002, -0.000), it is from **0.188 to 0.190** and the depth should be ½ inches of the 3/16 inches (0.1875"/2 = 0.09375"). The length of the shaft plus the key has to be from **0.5775 to 0.5875 inches.** The first step is to collect sample data from various days about the depth and the width of the keyways to record their individual variances and the daily variances. Figure 2 depict the series 7000 gear train assembly and sub-assembly.

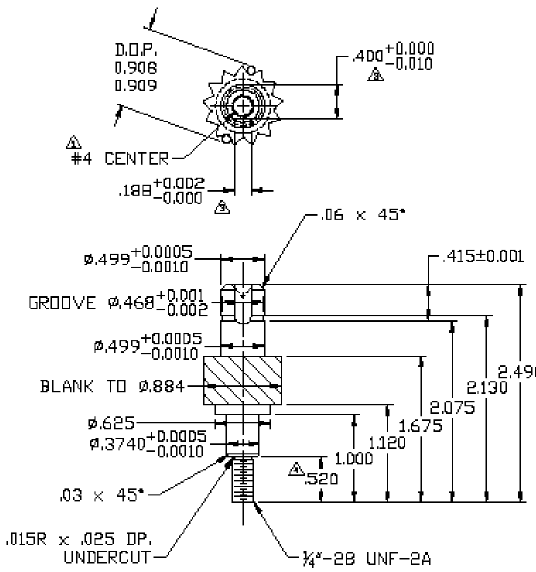

Figure 1. Specifications for the Shaft C7034

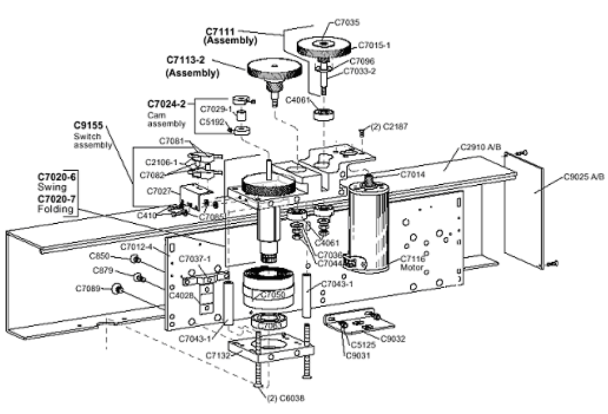

Figure 2. Series 7000 Gear Train Assembly

As shown in Tables 1 - 4, there are problems with the Width and the Length and Heat Treatment does not affect the dimensions of the part. All parts were assembled in the manufacturing process without any problem at least at the time of assembly.

Table 1. Part Number C7034, Second Transfer Shaft with integral output. (Before Heat Treatment)

Shaft	Shaft Diameter (0.498,0.4995)	Key Width (0.188,0.190)	Key + shaft length (0.582,0.59325)
1	0.4995	**0.194**	**.594**
2	0.499	**0.1955**	.593
3	0.4985	**0.195**	**.595**
4	0.499	**0.195**	**.594**
5	0.4995	**0.195**	.589
6	0.499	**0.1945**	.593
7	0.499	**0.195**	.590
8	0.499	**0.194**	.5935
9	0.499	**0.195**	.591
10	0.498	**0.1945**	.589

Table 2. Part Number C7034, Second Transfer Shaft with integral output. (After Heat Treatment)

Shaft	Shaft Diameter (0.489,0.4995)	Key Width (0.188,0.190)	Key + shaft length (0.582,0.59325)
1	0.498	**0.196**	.586
2	0.498	**0.197**	.588
3	0.498	**0.196**	.587
4	0.499	**0.197**	.587
5	0.498	**0.196**	.590
6	0.498	**0.1965**	.590
7	0.498	**0.197**	.587
8	**0.497**	**0.1965**	.590
9	0.4985	**0.196**	.592
10	0.498	**0.196**	.589

The data in Table 2 was obtained with a 0.83" depth and a 4 flute cutter.

Table 3. Part number C7034, Second Transfer Shaft with integral output, before Heat Treatment and 2 Flute End Mill

Shaft	Shaft Diameter (0.489,0.4995)	Key Width (0.188,0.190)	Key + shaft length (0.582,0.59325)
1	0.499	0.189	.592
2	0.489	**0.187**	.593
3	0.498	0.189	.593
4	0.498	**0.187**	**.594**
5	0.4985	0.188	**.5935**
6	0.498	0.188	.5915
7	0.498	0.189	**.594**
8	0.498	0.190	.592
9	0.498	0.188	**.5935**
10	0.498	0.190	.592

The data in Table 3 was obtained with a 0.83" depth and a two flute End Mill machine.

The part rejected from the manufacturing line could not be assembled with the Gear. The symptom presented was "That Gear C7017 came loose". The Gear C7017-1 is loose in the assembly with the shaft with dimensions shown in Table 5. It seems that the diameter dimension of the shaft is short, and it caused the gear and the shaft not stay tight in the assembly.

Table 4. Part number C7034, Second Transfer Shaft with integral output, After Heat Treatment

Shaft	Shaft Diameter (0.489,0.4995)	Key Width (0.188,0.190)	Key + shaft length (0.582,0.59325)
1	0.498	0.189	.593
2	0.498	0.188	.592
3	0.498	0.188	.593
4	0.4985	0.188	.5925
5	0.498	**0.1875**	.590
6	0.498	0.189	.591
7	0.498	0.189	**.594**
8	0.498	0.1895	.592
9	0.498	0.189	.593
10	0.497	0.190	.5915

Table 5 Dimensions of a part with "gear loosed" in the assembly

Shaft Diameter (0.489,0.4995)	Key Width (0.188,0.190)	Key + shaft length (0.582,0.59325)
0.495	**0.199**	**0.572**

3. SUPPLIER INPUT PROCESS OUTPUT CUSTOMER (SIPOC)

SIPOC (Supplier, Input, Process, Output, and Control) is the tool used in the Six Sigma methodology to understand the manufacturing process with all the input and output that are involved in the manufacturing of the product. Figure 3 shows the process of the gear C7017, it starts with receiving of the raw material C1981 and the first machine is the CNC, finishing with the Test Area.

Table 6-11 represent the SIPOC of the above process. Step 1 is to draw the manufacturing process of the part C7017, and this is done in the Figure 3. Step 2 is to write the output of each process that affect the part, and this is done in the column of Outputs in the Table 6. For example the output of the part number C1981 is the correct diameter from the supplier. Step 3 is to write the customers for each output, the customer for the raw material is the CNC machine, and the customer for CNC is hobbing. Step 4 was used to write the requirement for each customer, for example the CNC machine expects from the raw material a dimension of 15/32 * 3 1/8 inches, and the supplier of the raw material. The step 5 was used to write the inputs required to enable the process, what inputs are required to enable the process? In this case, the input is to have on time the material C1981.

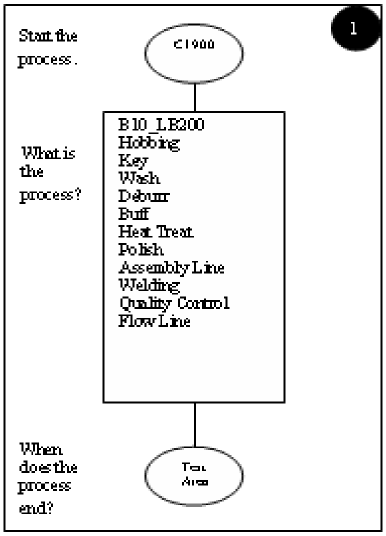

Figure 3. Process of the gear C7017

Figure 4 shows the process of the shaft C7034, it looks to have more steps than the gear C7017 in the Figure 3, it starts with the receiving of the raw material C1900 and the first manufacturing process is the B10_LB200, and the end of the process is the testing area.

Table 7 represents the SIPOC of the manufacturing process of the part C7034 that was drawn in the Figure 4. The step 2 shows the outputs for the process that affect the part, and all of these outputs are in the column marked as a circle number 2. For example, the output of the C1900 is a virgin tube of 1 1/16 inches diameter and the customer is B10_LB200. The second output is a blank part of 0.884 inches, this output came from the B10_LB200 and the customer's requirements are in the column as number 3.

The step 5 is a list of all the inputs to the process, the process is the Figure 4, and all of these inputs have suppliers that are listed in the column as number 6. The manufacturing requirements are written in the block as number 7, these requirements are to enable the process. For example the Hobbing process that is the second raw needs a sharp cutter and also correct parameters, the requirement is No wear out cutters and trained operator.

The same logic is used for the following SIPOC of gears and shafts. The SIPOC of gear C7015 starts with the step 1 that is the process flow in Figure 5. SIPOC of gears and shafts. The SIPOC of gear C7015 starts with the step 1 that is the process flow in the Figure 5.

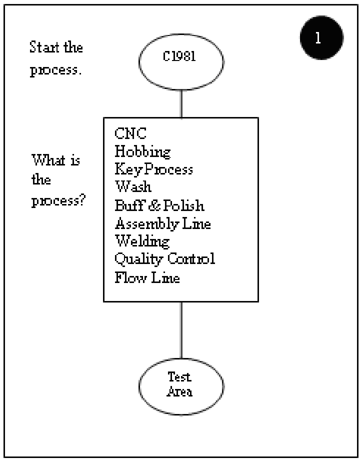

Figure 4. Process of the shaft C7034

The second step is the output of each step in the process, these outputs have customers in the step 3 and the requirements are in the step 4. The inputs to enable the process are in the step 5 and the requirements to the process in the step 7.

For example, in the row 2 of the Table 8, the output of the B8 Machine is a gear with 0.400 inches in wide, the customer for this output is the CNC B9, and this machine expects that the gear has the dimension of 0.400 inches in wide and also the part should have 4 inches in diameter. The input is the cutter to the machine B8 and the operator is the supplier of the parts. See the Table 8 in the row 2 for more details.

Table 6. SIPOC of Gear C7017-1

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material C1981	**Requirements** 15/32" * 3 1/8" Diameter	Part with the correct diameter.	**Requirements** 15/32" * 3 1/8"	CNC Machine
Operator	Cutter	No wear out cutters, broken, or any bad condition.	Outside Diameter	Outside Diameter = 3.070" +/-	Hobbing area
Operator	Correct setup	It mush have the correct parameters depending the piece to cut.	Inside Diameter Width Circular Form	0.004 Inside Diameter = 0.497" +0.0005 -0.0000 Width = 0.375 +/- 0.001 No egg form	
Operator	Correct setup	The operator should have the correct knowledge to make the correct setup to the hobbing machine.	Part with the correct Dimension over Pins	Dimension Over Pins = 3.107 +/- 0.002	Key area
Operator	Sharp cutter	No wear out cutters, broken, or any bad condition.			
Operator	Sharp cutter	No wear out cutter	A keyway in the gear	Width = 0.188 +0.002 - 0.000	Assembly line

Table 7. SIPOC of Shaft C7034

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material C 1900	**Requirements** 1 1/16" CF 4140 Steel Rod	A virgin tube	**Requirements** C 1900	B10_LB200
Operator	Cutter	No wear out cutter	A blank shaft	Blank part diameter = 0.884 inches	Hobbing area
Operator	Cutter Parameters	Trained Operator		Part size that is connected to the gear= 0.499+0.005-0.0010 inches Part size that goes to the bearing= 0.3740+0.0005-0.0010 Dimension over pins = 0.908/0.909 inches	
Operator	Sharp Hobbs	No broken cutters, sharp cutters	shaft with teeth	The shaft C7034 and the gear C7017 should fir with the key.	Key area
Operator	Correct set up in the cutting machine	Use tooling left hand helical			
Operator	Sharp cutter	No wear out cutter with the correct flute	keyway in the shaft		Assembly area
Operator	Correct set up in the Bridgeport	Have the correct RPM and feed rate to mill the shaft			

Table 8. SIPOC of Gear 7015

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material C 1402	**Requirements** The raw material should have a diameter tube of 3 ¼ inches.	A circular plastic tube with part number C1402	**Requirements** Circular Plastic Part	B8 Machine
Operator Operator	Cutter Cutter Parameters	The cutter tube of the B8 machine should cut the tube in	A gear with a width of 0.400 inches.	The CNC requires a single gear with dimension of 4 inches in diameter.	CNC B9

		several parts with a width of 0.400inches			
Operator	Cutter	The cutter is right hand helical and has 60 teeth.	A gear with the following dimensions: Width = 0.377 +/- 0.003 Diameter = 3.070 +/- 0.004	The gear should have the correct diameter, width and the inside diameter of 0.470+0.000-0.001 inches	Hobbing area
Operator	All the inputs to have the part within specification are an effective inspection.	Correct inspection is the base to detect incorrect parts before the flow line.	The main output from the process is to achieve the dimensions specified by the drawing.	Correct gear with all dimension within specification.	Flow Line

Table 9. SIPOC of Shaft 7033

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material C 1402	**Requirements** Blank tube with a diameter of 7/8 inches.	Blank Part	**Requirements** The raw material should have 7/8" of diameter.	B10 LB200
Operator	Sharp cutter in the hobbing process.	No wear out cutters and use the tooling Left hand helical cutter 12 teeth.	A part of 0.032 inches of wide.	A correct coming part from B10 LB 200.	Hobbing
Operator	Cutter	No wear out cutter	The shaft after hobbing has dimension over pins and the teeth are done on it.	Dimension over pins = 0.713 +/- 0.002 inches	Washing
Operator	Water	Enough Water	Clean shaft	Clean Part	Deburr
Operator	Deburr Tooling	The deburring machine needs electricity to run.	No burrs attached to the part.	Clean parts and within of specification.	Assembly Line.
Operator	Assembly C7111 that consists of gear C7015 and shaft C7033.	The assembly C7111 is installed to the 7000 mechanical assembly annually.	The assembly is attached to the shaft by a screw on the gear.	Correct Assembly	Flow Line

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Table 10. SIPOC of Gear 7019

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material	**Requirements** The C1982 should have 19/32*3 1/8 inches	Circular piece of metal	**Requirements** Outside diameter=3.014 inches Inside diameter = 0.747 + 0.005 – 0.0001 inches	CNC_B9
Operator	Cutter	The cutter should be right hand helical with 52 teeth	Gear with outside diameter = 3.014 inches; Inside diameter = 0.747+0.0005-0.0001 inches	A gear with a dimension over pins of 3.120 +/- 0.002 inches	Hobbing Key Process Buff and Polish Assembly Line Welding Flow Line
Operator	Cutter	No wear out cutter	The gear has teeth and correct dimension over pins.	The keyway should be 0.188+0.002-0.000	
Operator	Water	The part is washed until no steel particles and no amount of oil are inside the gear.	No oil on the gear.	Smooth Part	
Operator	Gear C7019; Shaft 7023 Key	The parts are assembles together by the operator.	The gear is assembled with the shaft.	The gear, shaft and key have to match between them.	
Operator	Parts	Parts should have the correct dimension to run perfectly on the 7000.	Assembly C 7024	Correct parts	
Operator	Good solder ability	The operator should have the good ability to solder the parts	Welded parts	Correct Welding	

Table 11. SIPOC of Shaft 7023

Supplier (Providers of the required resources) **6**	**Input** (Resources required by the process) **5**	**Process** (Top level description of the activity) **7**	**Outputs** (Deliverables from the process) **2**	**Customers** (Stakeholders who place the requirements on the outputs) **4**	**3**
Company	Raw Material C 7008	**Requirements** Receive the material cleaned.	Receive the material C 7008.	**Requirements** Drill 5/32" * ¼ inches deep.	Drilling and Tapping process.
Operator	Cutter	No wear out cutters.	Shaft machined	A keyway has 0.63 inches wide	key area.
Operator	Machine Shop	Setup the machine with correct RPM and feed rate.			
Operator	Machine Shop	Electricity	A shaft with keyway in it.	The part should be treated 1.6 minutes.	Heat Treat
Operator	Gear C 7019 Shaft C 7023 A key	These three parts must have correct dimensions.	A hard part	All the parts should fit together.	Assembly Line
Operator	Soldering	Electricity	The assembly of shaft C 7023 and gear C 7019	No peaks on the soldering	Welding Area
Operator	Assembly C7024	One operator assembles the C7024 in the 7000 mechanical assembly.	A welded part	The assembly C 7024	Flow line

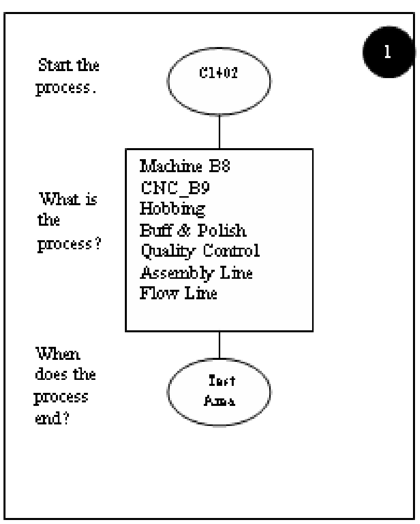


Figure 5. Process of the gear C7015

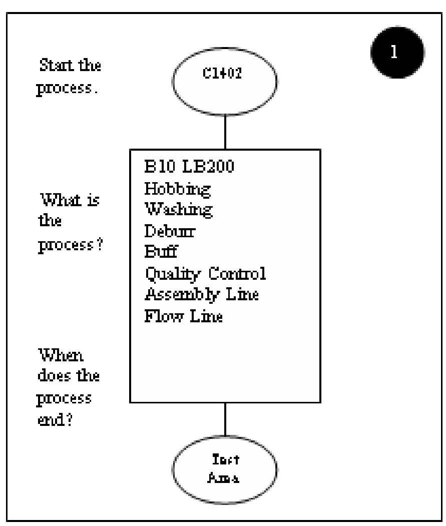


Figure 6. Process of the shaft C7033

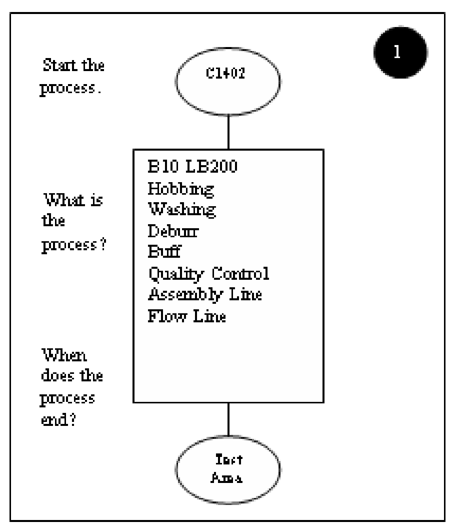


Figure 7. Process of the gear C7019

Figure 6 shows the process of the shaft C7033, it starts with the raw material C1402 and the manufacturing process consists in 7 steps, and the testing area is the end.

Table 9 represents the SIPOC of the above process and the Figure 6 shows the first step that is the process flow of C7033. The step 2 that is in the Table 9 shows the outputs for the process that affect the part and the requirements for these outputs. The difference of the last assembly (C7111) with the assembly C7024 is that this is not welded, and both parts (gear C7015 and shaft C7033) are connected each other by a screw. The gear C7015 is made by plastic, and the others two gears (C7017 and C7019) are made by steel.

For Figure 7, the manufacturing line receives the raw material C1982 and this is cut by the CNC_B9 to have the correct dimensions (For more details, see requirements of customer in Table 10.

The keyway process is an important factor in the performance of the 7000 mechanical assembly, and the study developed try to find the best setting to have the best keyway.

For the shaft C7023, the process in the Figure 8, the part is not passed by the hobbing area but it is passed through the heat treat process. The shaft C7023 and the gear C7019 are assembled together and welded after the assembly line. See the Table 11 for outputs and requirements for every individual process.

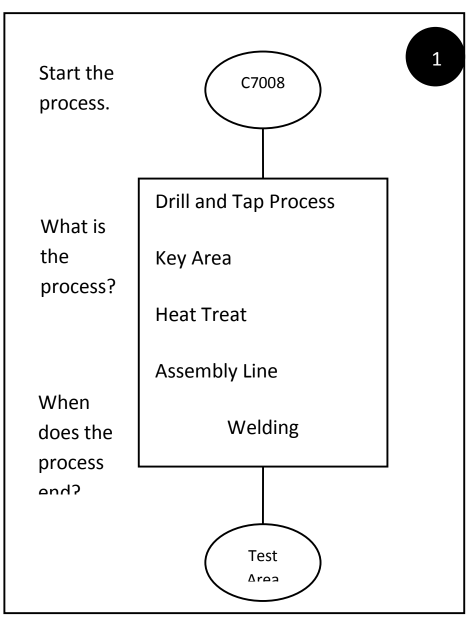


Figure 8. Process of the shaft C7023

Basically there are three gears and three shafts in the Series 7000 Gear Train Mechanical Assembly, the process to manufacture these parts is almost the same with some differences in the requirements and tooling used in the fabrication. As shown in the Tables 11 and 12, there are some similarities and differences between the parts and their processes.

Table 11. Similarities and differences in the Gears used in the sub-assembly Series 7000

Similitude & Differences	Gear 7015	Gear 7019
Raw material part number	C1402, 3 ¼" DIA.	C1982, 3 1/8" DIA.
Hobbing Area: Diameter Over Pins (DOP)	DOP = 3.107 +/- .0005	DOP = 3.120 +/- 0.002
Outside Diameter (OD)	OD = 3.070 +/-0.004	OD = 3.014 +/- .002
Inside Diameter (ID)	ID = 0.470 +0.000 -0.001	ID=0.747" +0.0005 -0.0001
Machined by	RH Helical 60 teeth	RH Helical 52 teeth

Shaft C7034 is of concern now. This is included in the SIPOC Shaft 7034, the vertical end milling machine is located in the area named "Key Area" that is after the Hobbing. This key is assembled in the Assembly Line where the Gear 7017 and the shaft 7034 are assembled together to made the final subassembly 7024. The Assembly Line is the place where we can detect the keyways or shafts are out of specification but there is no inspection before the Assembly Line.

3.1 Measurement Phase

The measurement phase consisted of the development of the Mental Map, FMEA (Failure Mode and Effect Analysis), Process Map, and the Numeric Evaluation Measurement. Although the problem is the keyway on the shaft, process maps were made for every shaft and gear of the Series 7000 electric swing door operator gear drive. It is our intention to have the whole process documented and to know the inputs, outputs and the requirement for each customer in each part of the process.

A PFMEA was developed in order to identify all the types of problems in the manufacturing line, With the help of the PFMEA, the most critical problems were identified and one were selected to which apply Six Sigma. In this case, the problem with the highest RPN was “the key that was too loose in the keyway”.

Table 12. Similarities and differences in the Shafts used in the sub-assembly Series 7000

Similitude & Differences	Shaft 7034	Shaft 7033	Shaft 7023
Raw material part number	C1900, 1 1/16”	C1971, 7/8”	C7008
Hobbing Area: Diameter Over Pins (DOP)	DOP = 0.908 - 0.909	DOP = 0.713 +/- 0.002	Not used Not used
Blank part diameter	0.884 inches	0.0680 +/- 0.001	Not used
Machined by	LH Helical 13 teeth	LH Helical 12 Teeth	Drill 5/32” X ¾” Deep
Drilled by	Not used	Not used	Tap #10-24 X ½” Deep Countersink #10 X 0.35”

The data for the Numeric Evaluation Metric was collected from pieces that were ready to be assembled, and all of these had passed the manufacturing processes. The objective was to make several control graphs, and learn the variation between the parts. Some of the graphs developed were: Individual Graphs, Moving Range graphs, the X-Bar, and the R-Bar.

The TMAP was helpful to document the entire question answered during the analysis of the problem, TMAP addressed all the questions that represent the heart of the problem.

3.2 PMAP or Process Map

The following tables are the Process Maps of the gears and shafts in the 7000 mechanical assembly. All of these tables follow the steps recommended to perform the Process Maps.

Step 1

List every input and output of each part of the process. Example: For the PMAP Shaft 7034 in the table 12, the input for the LB200 is the raw material and the output is a shaft with diameter of 0.884 inches in the blank part.

Step 2

Identify all the steps that add value to the process. Example: LB200, Keyway, Hobbing, Wash, Deburr, etc.

Step 3

Identify all the key output for every part of the process. Example: For shaft C7034, after key process, the keyway should have a width of 0.188 inches and a depth of 0.09375.

Step 4

Make a list of the key inputs in the process. Example: Machine, Cutter and setup are the key variables for the Key process.

Step 5

Add specifications of each operation and the goals of the process. Example: Width of 0.188 inches and depth of 0.09375 inches.

Table 13 shows that the inputs to the keyway process are the cutter type, machine, and setup. The outputs are 0.188 inches wide and 0.09375 inches in deep. The gear C7017 (Table 14) also needs a keyway of 0.188 inches to match with shaft and the key, remember that the key dimension is 3/16 inches.

For the Process Map of S7000 output shaft, C7023-4 (Table 15). The keyway requirement has the same width dimension; it is 0.188 inches as shown in the Process Map C7034, Table 13. For the gears C7017 and C7019, Table 14 and 16 respectively, the keyway width has the same dimension and the variables to be controlled are cutter, machine and setup but the keyway process for gears has different machine, different setup and different cutter. This study is only to solve the keyway dimension in shafts, especially in the C7034. Tables 17 and 18 don’t include the keyway process, the gear C7015 is made by a plastic raw material and the shaft C7033 is made by steel plate, and both parts are joined by a metal screw.

3.3 PFMEA

The PFMEA showed in Figure 9 is indicating the highest Repeatability Priority Number in the manufacturing line. The PFMEA indicates that the Key machine process has the highest Repeatability Priority Number (RPN) with the effect of “key that was too loose on the shaft”.

Table 13 Process Map of the Second Transfer Shaft with part number C7034

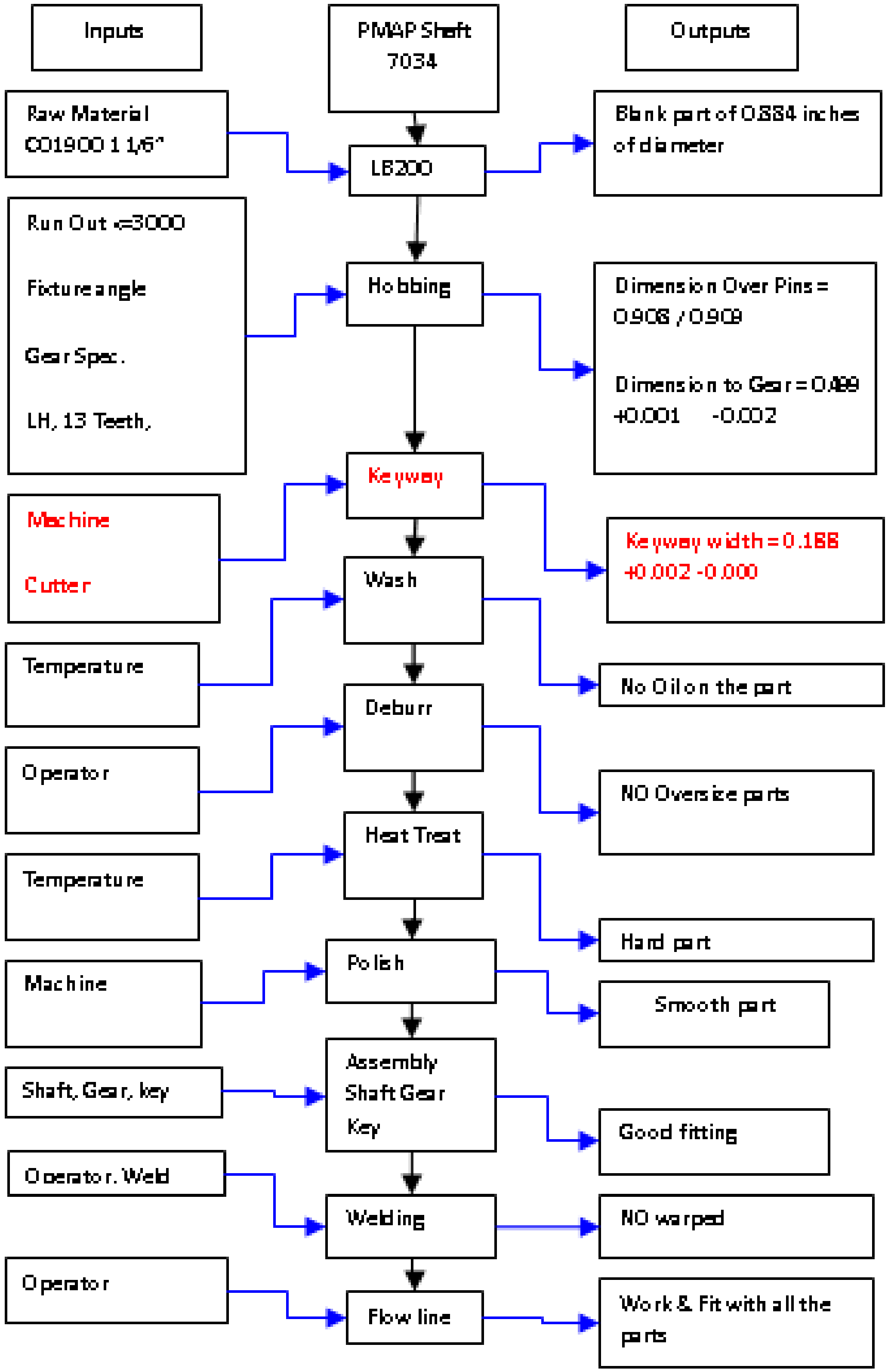


Table 14 Process Map of Second Transfer Shaft, Input Gear C7017-1

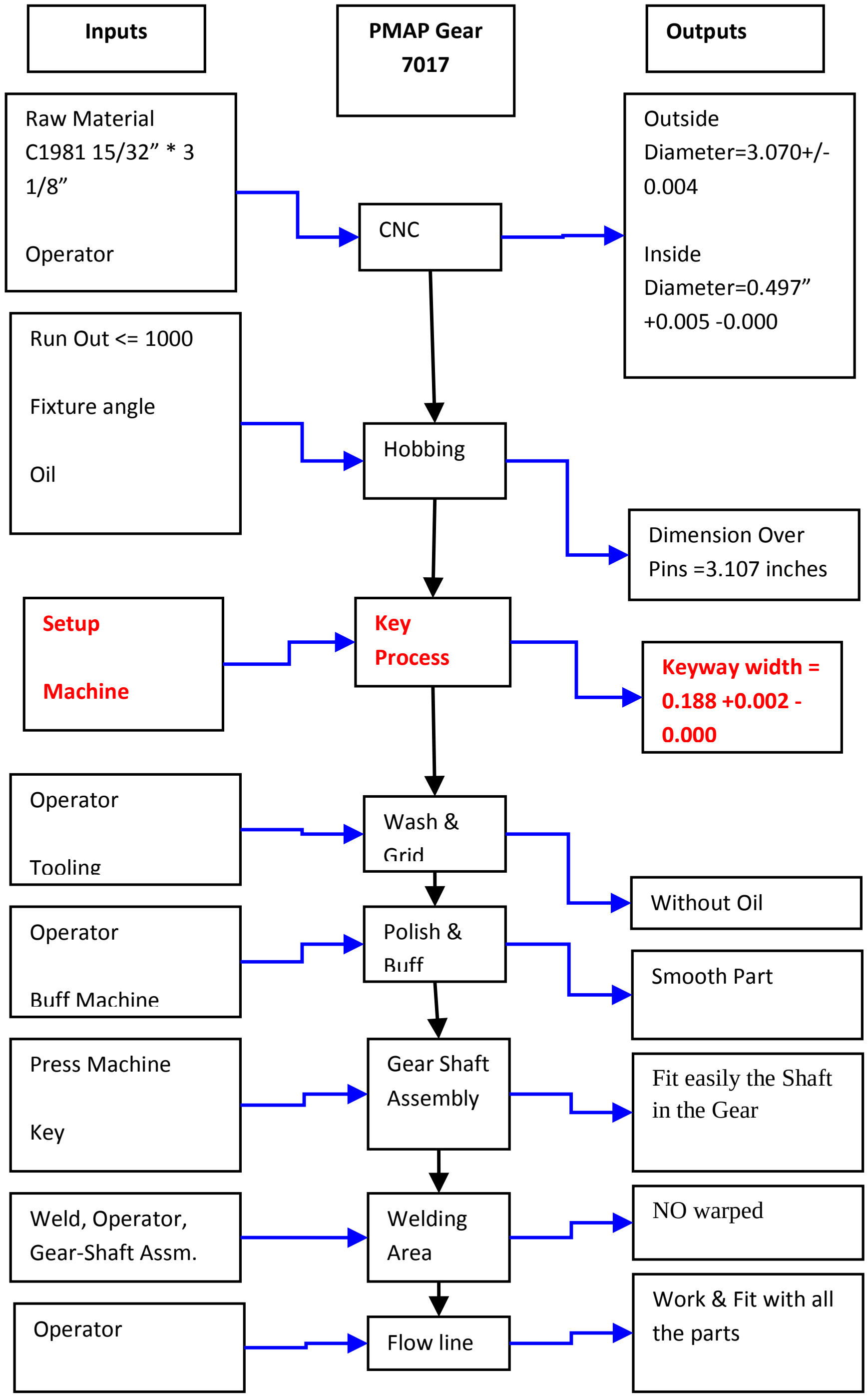
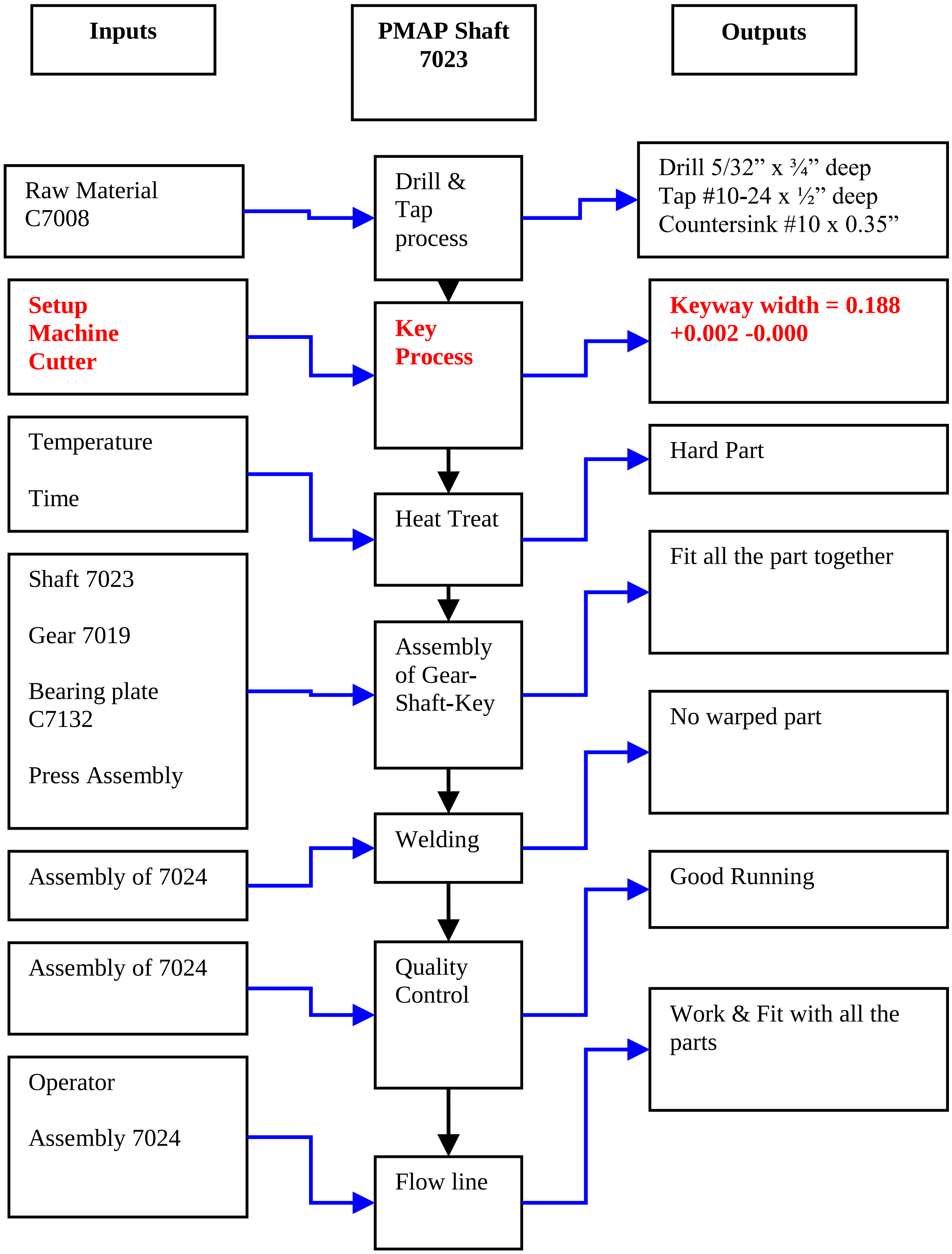


Table 16 Process Map of Output Shaft Gear, C7019-2



ISSN: 2049-3444

Table 17 Process Map of First Transfer Shaft with integral output, C7033

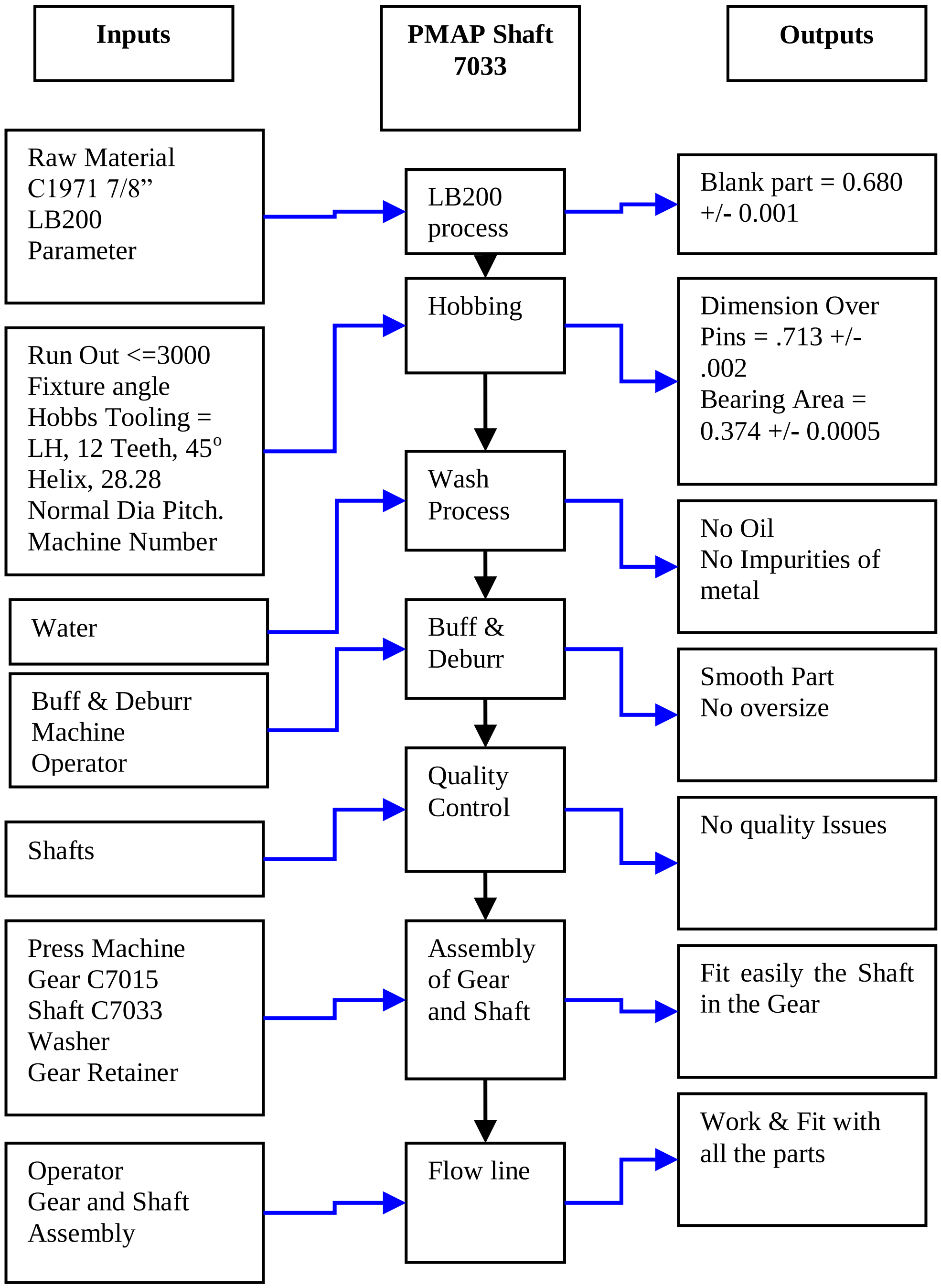
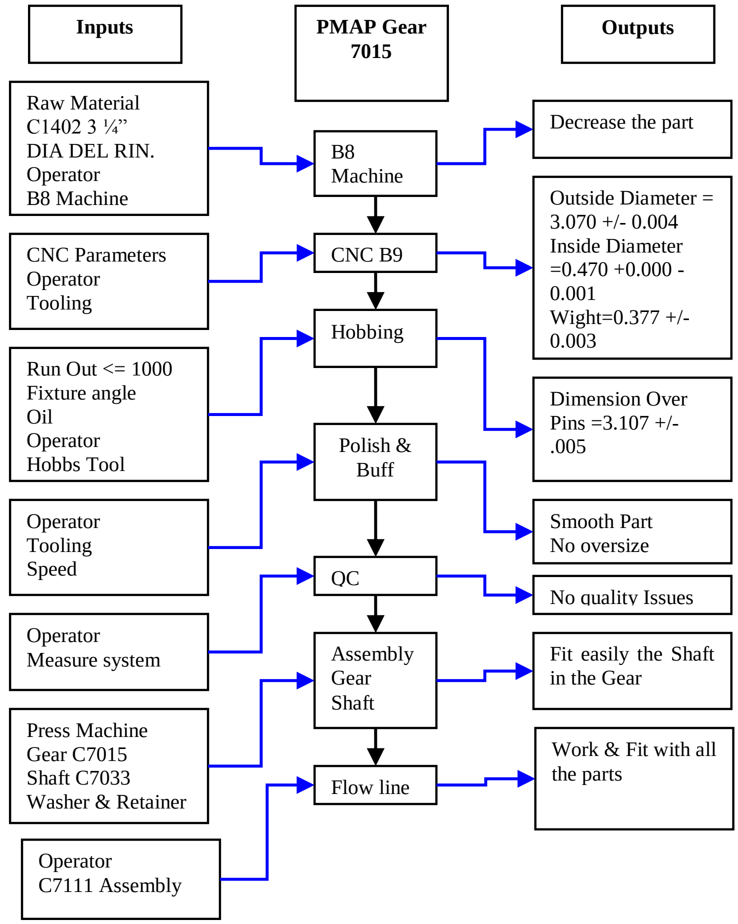


Table 18 Process Map of Gear, Del Rin with a part number C7015



Line No.	Process Function / Requirements	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Class	Potential Cause(s) / Mechanism(s) of Failure	OCC	Current Process Controls Prevention (P) Detection (D)	DET	RPN	Recommended Action (s)	Responsibility & Target Completion Date	
15													
16	Hobbing machine	Incorrect angle	Interference between gears	8		Error Operator	4	Red Line machine	3	96			
17													
18		Run Out	Egg Shape	8		Arbor vibration	4	Dial indicator	9	288			
19													
20		sharpening to much > 1 inch	Broke the hobb	7		Do not check the width of the teeth	9	Visual	9	567	Implement a gage to measure the width of the teeth of the hobb.		
21													
22		Sharpening at wrong angle	Interference between gears	8		Error Operator	4	Red line machine	3	96			
23													
24													
25		Incorrect handle	Hobb Broken	8		No trained	7	NONE	9	504			
26													
27													
28	key machine	4 flu	To loose (2 times) some curve (1 time)	8		Many flu take off too much material	10	Caliper	9	720	Identify which are the critical variables and put it in control		
29													
30		2 flu	2 times ok 0.187	8		Don't take enough material	10	Caliper	9	720	Identify which are the critical variables and put it in control		
31													
32		move dimension	deeply way	6		wear out	7	caliper	9	378			
33													
34		forget key way on the part	already welded	7		Error Operator	2	NONE	9	126			
35													
36													

Figure 9. Part of the PFMEA that was performed at Company

The possible causes are divided in Setup, Operator, End Milling, and Machine. For the setup, the variables to control are the center of the cutter and the feed rate, but only the feed rate effects directly in the width of the keyway. If the feed rate is too slow, the cutter is too hot and it breaks. If the feed rate is too fast, the durability of the cutter is less and the milling is not perfect.

For operator, this is a variable that can be controlled with training to the operator. There is only one operator, and he has many years in the same position, but the operator is confused about the correct cutter to use in the C7034. The operator uses two types of cutter; Carbide cutter and High steel speed cutter.

For the End Milling factor, there are three variables to control: the wear out, type of cuter, and the number of flute in the cutter. The wear out could cause imperfections in the keyway and there is not an estimate time to change the cutter, this is only changed when it is broken. The type of cutter could be Carbide or High Steel Speed, the differences in the performance on the shaft is unknown and the effects on the keyway also.

For the Machine factor, the variables to control are: Holder of shaft, the cleaning machine, and the head machine has to be perpendicular to the arm of the Bridgeport. The holder of shaft has a lock to hold the shaft but it is dependent of the operator. The cleaning is done by the operator but there is not a maintenance program. The head machine is critical factor but it is pretty locked and 90 degrees to the arm for long time without any problem.

After the analysis of the fish bone, some important factors to consider in the keyway process are:

1. The Milling process consists of the use of a vertical End Mill to make the keyway on the shaft. The material type of the cutter can be High Speed Steel (HSS) or Carbide. This cutter can have 2 or 4 flutes.

2. The RPM of the Vertical End Mill can vary according the type of material used in the cutter. It can be 1750 rpm or 2720 rpm, these speeds are constant in the machine "Bridgeport" and these can be modified by the operator.

Figure 11 shows the recommended cutting speeds for the different types of material of the cutter. For the Feed Rate Calculation, The Chip Load per Tooth is 0.005, the Feed Rate for the following type of material in the End Mill cutter are:

Carbide End Mill cutter:

Feed Rate (in/min.) = 2720 * .005 * 2 = 27.2 in/min

With the rpm suggested:

FR = 3053 * .005 * 2 = 30.53 in/min

FR = 4071 * .005 * 2 = 40.71 in/min

High Speed Steel cutter:

Feed Rate (in/min.) = 1750 * .005 * 4 = 35 in/min

The above results are the optimal feed rate speed for the vertical End mill machine.

Material	Milling Machine Cutting Speed (CS)			
	High Speed Steel Cutter		Carbide Cutter	
	Ft./Min	M/Min	Ft./Min	M/Min
Machine Steel	70-100	21-30	150-250	45-75
Tool Steel	60-70	18-20	125-200	40-60
Cass Iron	50-80	12-25	125-200	40-60
Bronze	65-120	20-35	200-400	60-120
Aluminum	500-1000	150-300	1000-2000	150-300

Figure 11. Milling Machine Cutting Speed from the Machinery's Handbook

3.4 Process Capability Analysis for Width

After defining the problem, the Numeric Evaluation Metric was developed. The purpose of the Numeric Evaluation Metric is to understand the measurements and see the variance in the current process. The following data was taken from a sample of 30 pieces, and all were considered "good". All the dimensions are inches.

MINITAB was used to graph the data in the following control graph and to have a better understanding of the between variation, the within variation, and the variation through the time. Figure 12 shows that the width chart is out of control, and the bell curve is too wide. In the case of the Figure 13 for Length, the bell curve is beyond of the limits. The length is the shaft diameter dimension plus the key dimension.

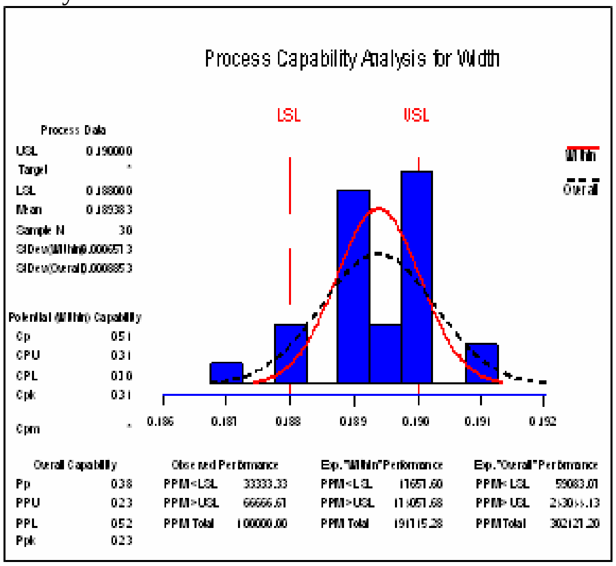


Figure 12. Process Capability Analysis for Width

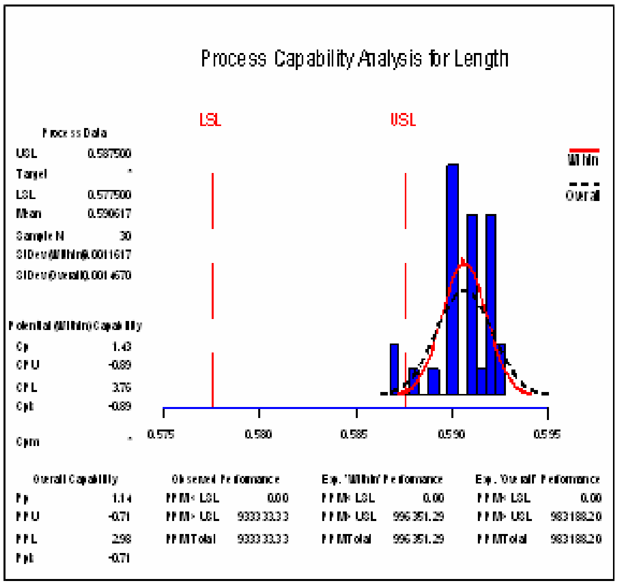


Figure 13. Process Capability Analysis for Length

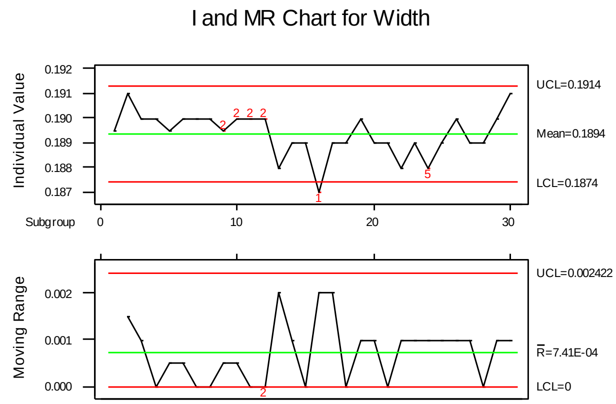


Figure 14. I and MR chart for width

Figure 14 shows the variance through the time (Individual Value), and the moving range chart is helpful to see the presence of special causes. The results are indicating that the process is out of control and the average has been moving through the time.

Results of I/MR for Width

Test Results for I Chart

TEST 1. One point more than 3.00 sigmas from center line.

Test Failed at points: 16

TEST 2. 9 points in a row on same side of center line.
Test Failed at points: 9 10 11 12

TEST 5. 2 out of 3 points more than 2 sigmas from center line

(on one side of CL).

Test Failed at points: 24

Test Results for MR Chart

TEST 2. 9 points in a row on same side of center line.
Test Failed at points: 12

Figure 15 indicates that the length performance is out of control. There are some measurements out of the limits of control and also in the moving average graph there is a high difference between some means.

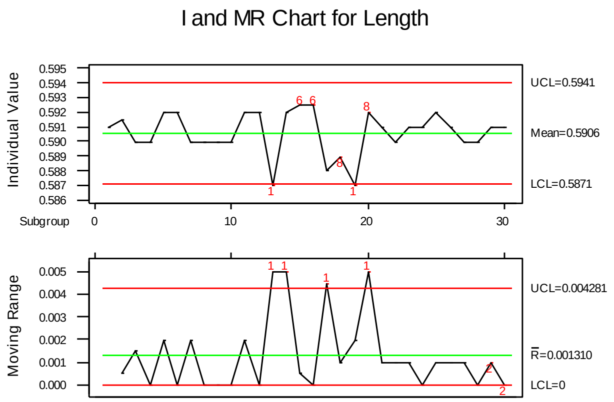


Figure 15. I and MR chart for length

Results of I/MR for Length

Test Results for I Chart

TEST 1. One point more than 3.00 sigmas from center line.
Test Failed at points: 13 19

TEST 5. 2 out of 3 points more than 2 sigmas from center line
(on one side of CL).

Test Failed at points: 19

TEST 6. 4 out of 5 points more than 1 sigma from center line
(on one side of CL).

Test Failed at points: 15 16

TEST 8. 8 points in a row more than 1 sigma from center line
(above and below CL).

Test Failed at points: 18 19 20

Test Results for MR Chart

TEST 1. One point more than 3.00 sigmas from center line.

Test Failed at points: 13 14 17 20

TEST 2. 9 points in a row on same side of center line.
Test Failed at points: 29 30

Graph R is presented in the Figure 16. It helps to understand the variance within the groups. As mentioned before, this graph will show the variance within the subgroups of the process. The question is: Is the variation constant in the measurements within the subgroups? Normally the measurements within the subgroup are consistent when it is in control. The subgroup size used in these graphs is 3.

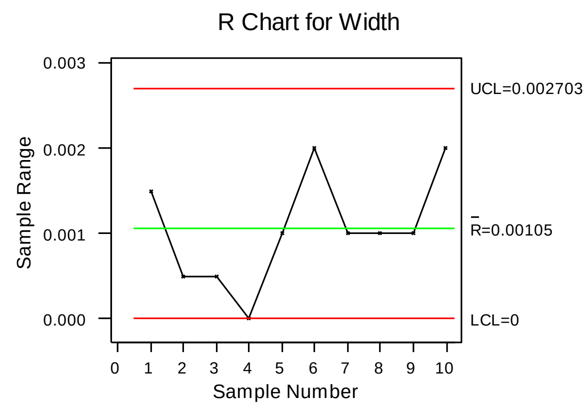


Figure 16. R Chart for width

As we can see in the above graph, the variation within the subgroups is inside of the limits, so the changes within the subgroups are not big. It is almost the same behavior in the subgroups. For the Length, the measurements within the subgroups is not too critical, it is within the limits as shown in Figure 17.

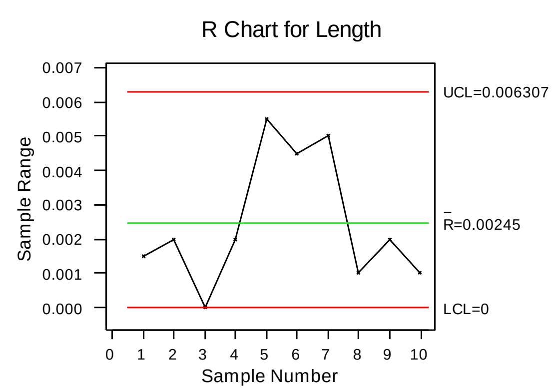


Figure 17. R Chart for length

Figure 18 shows the graph X-Bar, it is the variation between subgroups means. If the graph X-Bar is in control, the variation "Between" is lower than the variation "Within". The X-Bar Chart for length does not have any errors. The graph shows a good control between the subgroups as indicated in the Figure 19.

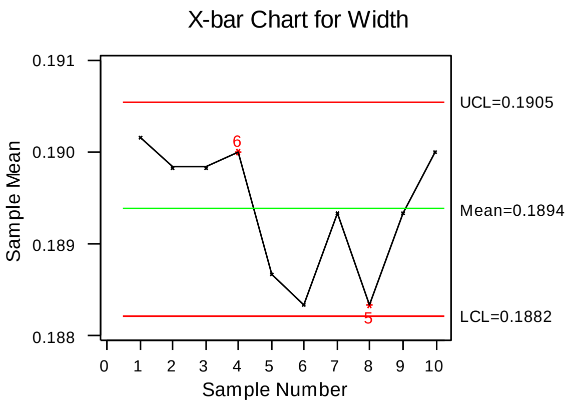


Figure 18. X-Bar chart for Width

Results of X-bar Chart: Width

TEST 5. 2 out of 3 points more than 2 sigmas from center line
(on one side of CL).

Test Failed at points: 8

TEST 6. 4 out of 5 points more than 1 sigma from center line
(on one side of CL).
Test Failed at points: 4

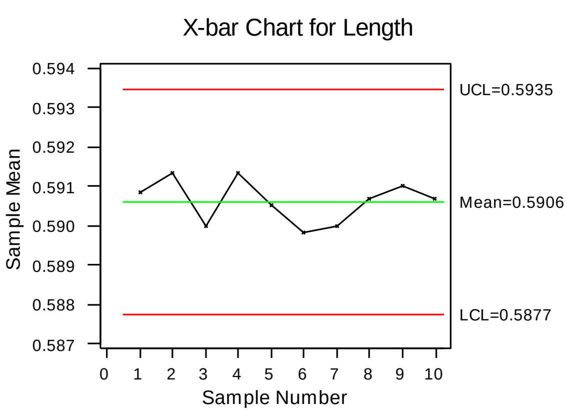


Figure 19. X-Bar Chart for length

3.5 Evaluation of the Measure System

All of the last measurements were taken with a measurement system. Sometimes the measurement system has errors in the measure or it is not accurate. In order to identify the error in the measurement system, I will proceed to make a measure system evaluation.

The result of the MSE is presented in the Figure 20. This chart shows that the biggest variation comes from part to part. The R graph indicates that both operators have errors in the repeatability of the measures. The Xbar indicates that the average of each measure is almost the same in both operators but it is too open and it is not within limits.

Results of Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.21E-08	**17.64**
Repeatability	9.00E-09	**13.15**
Reproducibility	3.07E-09	4.49
Operator	0.00E+00	0.00
Operator*Part	3.07E-09	4.49
Part-To-Part	5.64E-08	**82.36**
Total Variation	6.84E-08	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.10E-04	5.66E-04	42.00
Repeatability	9.49E-05	4.89E-04	36.27
Reproducibility	5.54E-05	2.86E-04	21.19
Operator	0.00E+00	0.00E+00	0.00
Operator*Part	5.54E-05	2.86E-04	21.19
Part-To-Part	2.37E-04	1.22E-03	90.75
Total Variation	2.62E-04	1.35E-03	100.00

Number of Distinct Categories = 3

The GR&R performed show that only the 17.64% of the variation is due to the measure system, the 13.15% of 17.64 is problem of repeatability and the rest of the problem is reproducibility. The biggest variation is in the parts with 82.36%.

4. DESIGN OF EXPERIMENTS

The following data was used in the DOE in order to learn the main effects of Variables Vs Width. The variables analyzed are the RPM of the vertical end mill and the number of flute of the End mill

The analysis phase consists of the development of capacity study and the DOE concepts applied in the problem. In this case the capacity study is on the width and the variables to analyze are: RPM and the number of flute in the cutter.

The following design is a **two-factor factorial design** with two factors. The factors are Flutes and RPM, each factor has 2 levels, and 10 replicas for each combination.

We were determined to understand the effects of variables on the width. Basically the test is performed with changes in RPM.

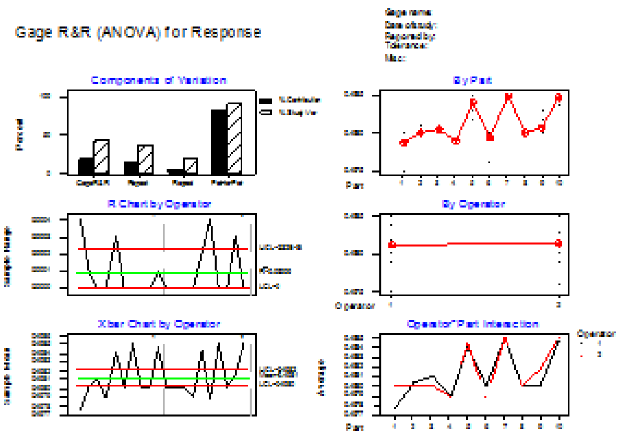


Figure 20. MSE Results

From 1750 to 2720, and changes of cutter from 2-Flute to 4-Flute. There are 10 replicates for each combination.

In this problem, we wanted to answer the following questions using the DOE in Table 19:

1. What effects do RPM and FLUTE have on the width of the keyway?

2. What is the best setup to perform the keyway?

Is there a choice of cutter that would give uniformly width regardless of RMP?

Table 19. Width Data (in Inches) for the keyway Design Experiment

Cutter Type (Factor A)	RPM (rev. per min.) (Factor B)	
	1750	2720
2 Flute	0.189 0.188 0.196 0.187 0.189 0.188 0.190 0.190 0.188 0.190	0.190 .187 0.187 0.188 0.186 0.188 0.188 0.187 0.187 0.190
4 Flute	0.195 0.195 0.192 0.197 0.197 0.196 0.195 0.196 0.195 0.194	0.194 0.192 0.194 0.194 0.193 0.194 0.193 0.194 0.193 0.193

Statistical hypothesis: H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$

H_1: at least one $\mu_I \neq \mu_j$

Where:

Low RPM = 1750 rpm

High RPM = 2720 rpm

μ_1 is the mean flute 2 and low RPM

μ_2 is the mean flute 4 and low RPM

μ_3 is the mean flute 2 and high RPM

μ_4 is the mean flute 2 and high RPM

The following table shows the data collected with the different combination of RPM and Flute number.

$F_{0.05,\,2,\,36} = 2.84$

Fo = 74.54

If Fo > $F_{0.05,\,2,\,36}$ then we reject Ho, in this case the Ho is rejected. There is a significant effect in the Flute and RPM.

In the normal plot of the effects, Figure 21, points that do not fall near the line usually signal important effects (Minitab Soft., 2001). The point A is the most distant in the graph, and the point B is closer to the line than the point A, this means that the point A has a bigger effect than the point B. Unimportant effects tend to be smaller and centered on zero.

The Pareto Chart, Figure 22, displays the absolute value of the effects, and allows looking at both the magnitude and the importance of an effect. Any effect that extends past this reference line is potentially important (Minitab, 2001). The most important effect in the chart is the amount of Flute.

Cube plots shown in Figure 23 can be used to show the relationship between up to eight factors. In this case, the main effect of factor A (Flute) can be calculated with the difference between the average response at the low level of A and the average response at high level of A.

$$A = ((0.1952 + 0.1934) / 2) - ((0.1894+0.1875)/2) = 0.00585$$

That is, increasing factor A from the low level to the high level causes an average response increase of 0.00585 units. Similarly, the main effect of B is

$$B = ((0.1875+0.1934)/2) - ((0.1894+.1952)/2) = -0.00185$$

The interaction plot is shown in Figure 24.

Effects Plot for Width

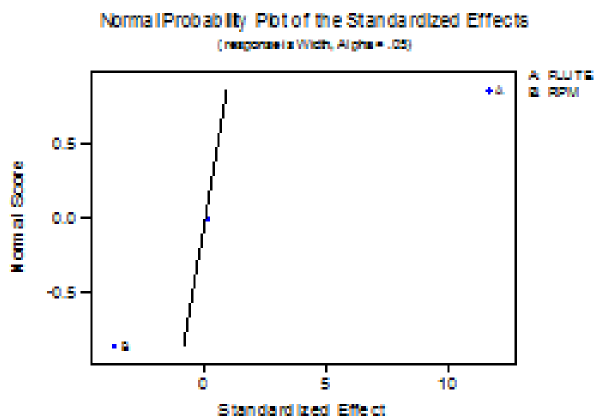


Figure 21. Normal Probability Plot of the Standardized Effects

Effects Pareto for Width

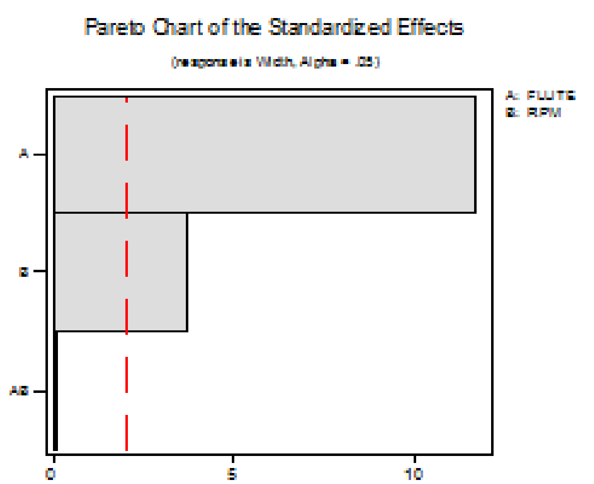


Figure 22. Pareto Chart of the Standardized Effects

Cube Plot for Width

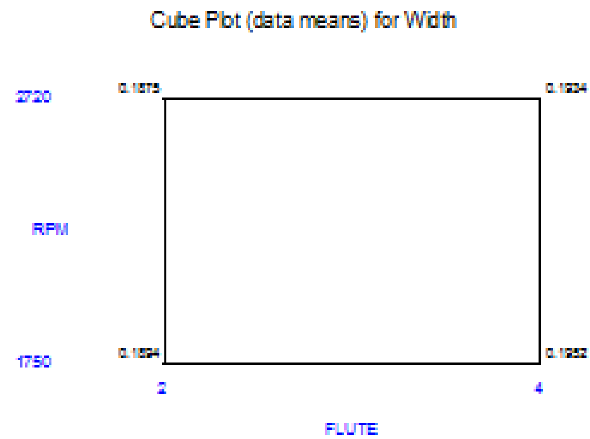


Figure 23. Cube Plot for Width

Interaction Plot for Width

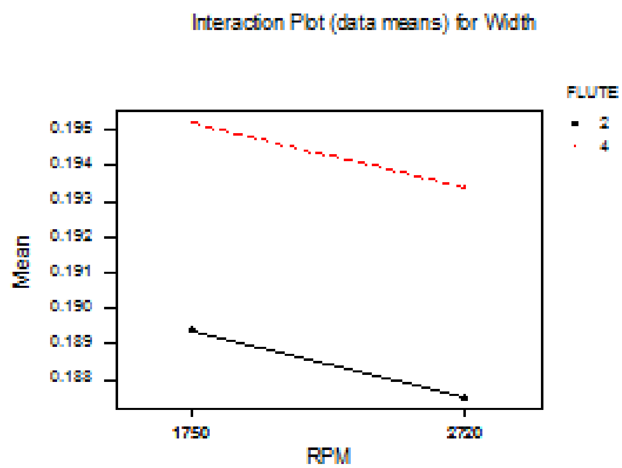


Figure 24. Interaction Plot for Width

An interaction between factors occurs when the change in response from the low level to the high level of one factor is not the same as the change in response at the same two levels of a second factor. That is, the effect of one factor is dependent upon a second factor (Minitab, 2002).

Main Effects for Width

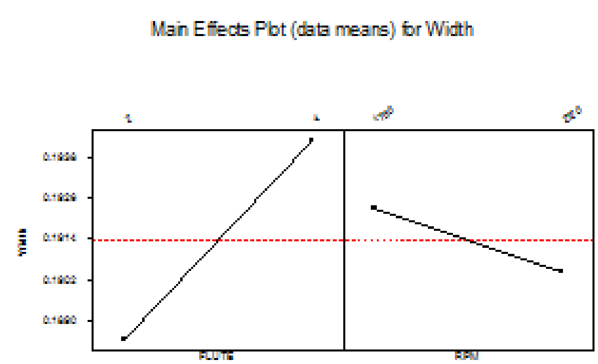


Figure 25. Main Effects for Width

A main effect plot is a plot of the means at each level of a factor (Minitab, 2002). Minitab plots the means at each level of a factor ad connects them with a line. Center points and factorial points are represented by different symbols. A reference line at the grand mean of the response data is drawn (Minitab, 2002).

The Figure 25 shows that the RPM is not affecting too much the width in the keyway, and the flute factor is the main variable to control in order to have the correct width in the keyway. The width increases when the flute is changed from 2 to 4 or vice verse.

5. IMPROVE PHASE

We can see that the best performance is 2 flute with a high RPM, and the feed rate should be (in/min.) = 2720 * .005 * 2 = 27.2 in/min.

In this phase I run some pieces with the 2-flute cutter, RPM = 2720, and the recommended feed rate. Also there are some metal particles inside the keyway that affect the measurement. In order to have accurate measurements, I will polish the edges of the keyway with a sand paper.

With this improvement, the operator will know the best setup to the vertical end milling machine and we will perform a close specification part.

Other recommendation is to use a different polish tool to eliminate all burrs within the keyway. The polish operation on the shaft generates several burrs and spikes around the keyway, which causes that the key does not fit within the keyway.

6. CONTROL PHASE

To control the dimension of the keyway is necessary to have a good 2-flute cutter, if we use a used cutter, we can generate problems in the keyways and we should rework the parts. The leader person should monitor the start date of a new cutter and how many pieces can be made with the same cutter.

7. DISCUSSION OF RESULTS

The following questions can be answered by analyzing the two factors (RPM and Type of cutter) and can be discussed by the graphs indicating for improving with some recommendations.

1. What effects do RPM and FLUTE have on the width of the keyway?

The two main variables to control are the end milling machine speed (rpm) and the type of cutter used; this is carbide or high speed steel. These two factors were analyzed in a Design of Experiments with the help of MINITAB, and the results indicate that the biggest effect is caused with the changes of cutters. In the Figure 25, the biggest impact is in the FLUTE section, any change from Flute-2 to Flute-4 makes a change of 0.0048 inches, this is almost 2.5% of 0.188 inches, the requirement indicated in the datasheets.

Another helpful graph is Figure 21, this shows that the FLUTE point is further from the line than the RPM point.

2. What is the best setup to perform the keyway?

The “Bridgebort” machine needs to be setup to mill the shaft, some important factors to consider in the setup are: the RPM of the milling, the surface feet per minute, and the feed rate.

According with the Equations 1, 2 and 3 in the page 54, the recommended RPM to carbide cutter is from 3053 rpm to 4071 rpm. This is considering a cutter flute-2 and following the Milling Cutting speed rules in the Figure 11.

As the “Bridgebort” machine has only two speeds, the feed rate was calculated with a RPM of 2720 rpm, this gave us a feed rate of 27.2 in/min.

3. Is there a choice of cutter that would give uniform width regardless of RMP?

The Figure 25 shows that the mean in width with 2720 or 1750, the results did not change significantly; this means that the flute-2 should not have any problem with variations of rpm in the “Brigdebort” End Mill Machine.

8. RECAPITULATION

The objective of my research was to analyze the elaboration of the keyway in shaft C7034, the principle is the same for other shafts used in the Series 7000. Milling the shaft uses the Vertical End Milling Machine “Bridgebort”, and the factors to consider in the analysis were the cutter and some variables to be controlled in the machine setup.

This problem was chosen because it was in the top RPN of the PFMEA developed in the plant. The operator did not know which form was the best to mill the shaft and have the most keyway in specification.

The first step was to develop the SIPOC of parts to have a full view of the manufacturing process and the requirements to achieve from each step in the process. The SIPOC was developed in all the gears and shafts that form the Series 7000, but the problem to analyze was in shaft C7034.

The second step was to develop the PMAP and a PFMEA, the PMAP to identify the critical variables to each part of the process, and to learn the outputs of each phase of the process. The PFMEA was a helpful tool to notify to the company the importance of the case, and involve the whole team in the same problem.

In the analysis phase, the cooperation of engineers and operators was so valuable, the fish bone was done to identify the possible causes unless the people already know that the problem was the tooling used in the Milling machine.

A brief research was done to identify the formulas to calculate the RPM in the Milling machine, and the adequate feed rate to the type of cutter. Before beginning collecting data, the GR&R was performed to know the variability in the measurement system and the part. Ten pieces were measured by two people with three trials for each one.

The last part of the analysis was concluded with the Design of Experiments, this shows that the means of the different factors are not equal, and the graphs shows a better view to demonstrate which factor has the bigger effect in the keyway.

9. CONCLUSIONS

The application of Six Sigma is a very efficient methodology to apply to manufacturing operations which are out of control. The engineering group defined the problem and narrowed down the topic requiring analysis. During the measurement phase, the evaluation of the measurement system was of significant importance to proceed with the sampling of data. In this phase two operators were used in the GR&R since only one operator who was using the Bridgebort machine.

In the analysis phase, the DOE was considered as two-factor factorial design; this is two factors and two levels. The results from the DOE rejected the hypothesis that there is a significant difference between the four means. With the MINITAB software, graphs were developed to show the interaction and effects of the factors versus the width of the keyway. As a conclusion, the design of experiments and the Six Sigma methodology made an excellent team together to prevent and solve quality problems that affected the productivity at a company.

The results obtained from the analysis of the data collected indicates that the best result is to use the carbide cutter with two flutes that gives a constant reading in the width of the keyway. For the setup, unless the Bridgeport is an old machine without indicators in the feed rate, the feed rate for this tooling should be 27.2 in/min.

One of the problems that caused the four flutes is the insufficient amount of carbide cutters, the lead man can use an inventory system to mark when it is necessary to order the cutters and avoid using the high speed steel cutter.

During the manufacturing process, the gears and shafts are exposed to many different processes that can generate burrs inside of the keyway; these small particles can cause problems in the assembly of the key. The recommendation is to polish inside the keyway and be sure to have a clean surface inside the keyway. During the polishing process where the shafts are exposed to the part, some speak burrs may intrude in the borders of the keyway, this narrows the width of the keyway and makes the assembly of the key difficult.

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