

CDS Rolls Royce Bushing Bearing Blistering Analysis

Independent Project

5/9/2024
Bodycote LLC
David de Vall

OVERVIEW	3	PROBLEM STATEMENT.....	38
PROJECT PROPOSAL.....	6	IMPROVE	40
GANTT CHART	7	BLISTERING PREVENTION.....	41
DEFINE	8	BLISTERING DETECTION.....	44
PROJECT PLAN	9	FINALE FAILURE MODE AND EFFECTS ANALYSIS ..	45
OVERVIEW	9	CONTROL.....	46
<i>Problem statement/ Customer requirements .</i>	9	BLISTERING PREVENTION.....	47
<i>Project Objectives</i>	9	BLISTERING DETECTION.....	48
<i>Project scope</i>	10	REVIEW.....	49
<i>Voice of the Customer</i>	10	SUMMARY.....	50
<i>Prior research conducted</i>	11	MAJOR ISSUES	50
<i>Areas for Investigation.....</i>	11	MINOR ISSUES	51
<i>Affected Parties.....</i>	11	CONCLUSIONS AND RECOMMENDATIONS	51
<i>Additional resources needed.....</i>	11	REFERENCES	52
<i>Estimated results.....</i>	11		
<i>Potential risks.....</i>	12		
<i>Summary.....</i>	12		
PROCESS MAP.....	13		
MEASURE.....	14		
FREQUENCY RECORDING	15		
PRIMARY METRIC.....	15		
SECONDARY MEASURES.....	15		
BLISTERING DETECTION	22		
BLASTING VARIABLES	22		
FAILURE MODES AND EFFECTS ANALYSIS.....	23		
ANALYSE	24		
COLLECTED DATA.....	25		
PARETO ANALYSIS	25		
TIMELINE ANALYSIS	27		
COST/BENEFIT ANALYSIS	28		
LITERATURE REVIEWS	29		
SIX SIGMA PRINCIPLES.....	29		
DIP COATING.....	30		
<i>Advantages and disadvantages</i>	31		
Advantages.....	31		
• Disadvantages	31		
<i>Failure Modes</i>	32		
ELECTROLESS NICKEL PLATING	33		
BLISTERING IN METAL COATINGS.....	36		
ROOT CAUSE ANALYSIS.....	37		
FISHBONE DIAGRAM	37		
FIVE WHY'S	37		

Overview

Abstract

This report examines the effect of blistering failures on the production of Rolls Royce CDS parts. Blistering is a failure of a coating layer when produced or when subjected to mechanical or thermal stress, that in this circumstance results in a complete loss of the product. Blistering and other failure mode frequencies were measured over a period of nine months and pareto analysis was conducted to determine the impact of blistering and the requirement for correction. Analysis indicated that blistering was the primary source of failure and responsible for significant financial loss on the part of Rolls Royce, and research was undertaken into the cause of the failure mode and potential solutions.

Rolls Royce determined and implemented a solution individually, and analysis of the results was conducted to determine if the change was effective in preventing the issue and to determine what it may have been and what controls would be necessary. It was determined that the solution used was effective in reducing the frequency of blistering faults but has drastically increased the prevalence of pitting on CDS parts, leading to a slight increase in base material showing failures. In conclusion, the causes of the blistering fault were found and corrected, but more work will be needed to bring the CDS process within six sigma standards.

Introduction

I am a coating technician at Bodycote LLC, working in the Newport facility and studying at the University of Wales Trinity Saint David in Swansea. My current job role includes the grit blasting and thermal coating of bearing blanks for Rolls Royce aircraft engine fuel pumps.

Bodycote LLC is a company that provide heat treatment and specialist thermal processing services worldwide, including case hardening, stress relieving, isostatic pressing, and application of metallic and ceramic coatings.

The purpose of this project is to develop a solution to a pervasive problem withing the operations of the CDS-1 booth, which produces bearing blanks for Rolls Royce. During production, the core of the part is grit blasted, which can lead to a phenomenon known as blistering where the surface layer of the part peels away from the main body underneath. This can be minor or catastrophic, but always results in the failure of the part.



Figure 1: Two blistered components.

It will also be necessary to analyse other failure modes and their costs to determine if this project is the most cost-effective way to improve the CDS-1 process.

This project will be being approached as a DMAIC project, focussed on identifying and improving the processes undertaken at Bodycote and Rolls Royce in order to prevent the problem from occurring and improve the profitability; however, as Rolls Royce an employee of Bodycote I have limited capacity to obtain data from or instigate change at Rolly Royce, and therefore any Improvements or Controls that would need to be enacted at the Rolls Royce site and processes will be hypothetical in nature, as a planning process for what Rolls Royce could do to improve the process and eliminate these failure modes rather than a complete recording of what will actually be done.

Project Proposal

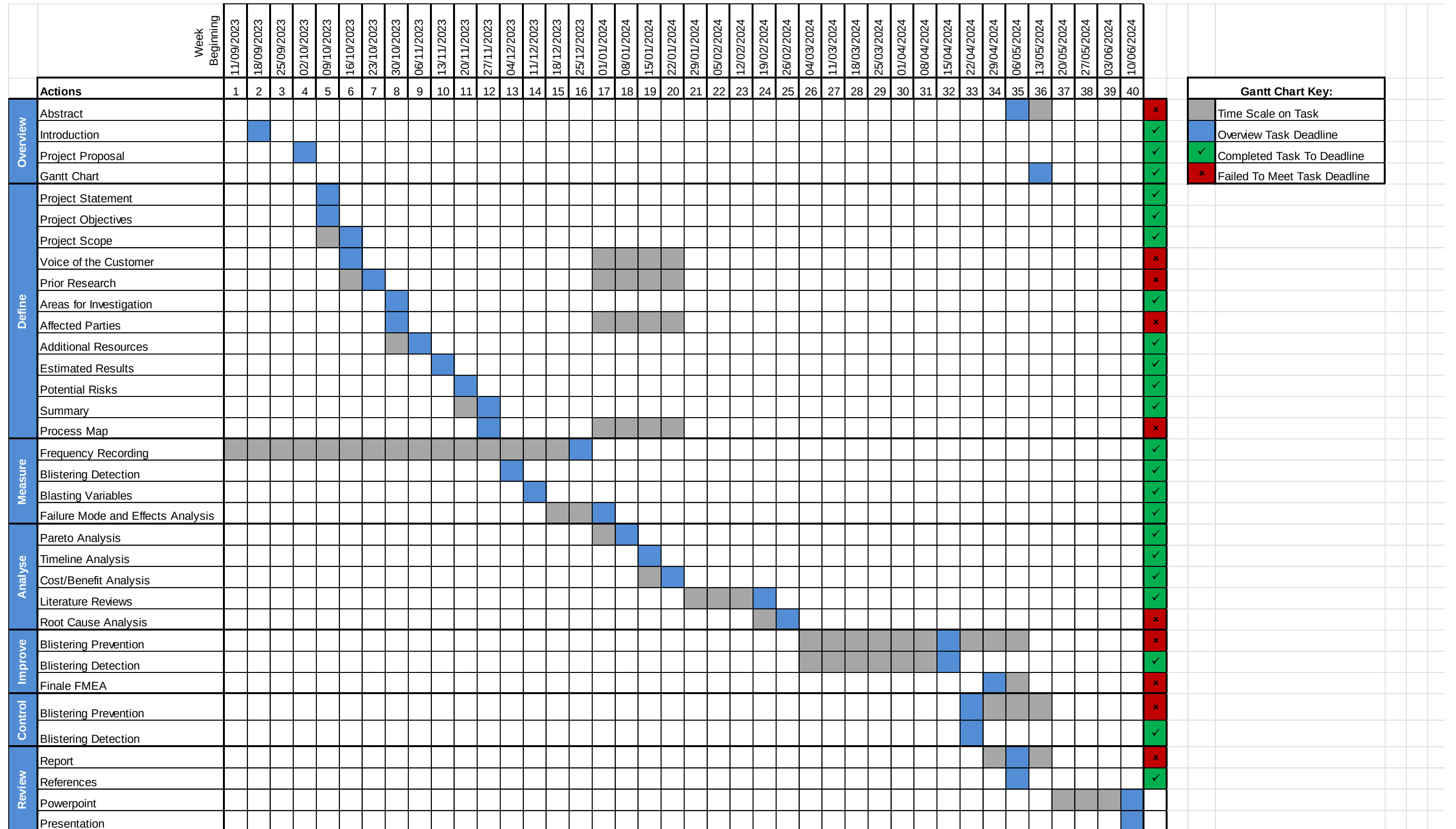
It is believed that blistering is the primary failure mode for CDS-1 parts and should be the primary area of study to mitigate failures. However, it has become clear that not only are failures too commonly occurring, but also that the detection method for failures is somewhat insufficient; parts have escaped detection until after they have been bond coated in some cases.



Figure 2: A blistered part that has been bond coated.

This indicates that improvement to the detection method following the blasting process could also use improvement, and this will also be investigated.

GANTT Chart



Define

Project Plan

Overview

Problem statement/ Customer requirements

Blistering is a failure mode of thin metal coatings in which the coating bubbles or ruptures away from the core part underneath. This failure can occur during the coating process or during later mechanical or thermal working. This results from localised adhesion failure (Corrosionpedia, 2019). The quantity of blistering failures occurring on Rolls Royce CDS parts seems excessive; it is not uncommon for one or more parts per 24-part batch to blister during grit blasting, which is drastically outside of ideal six sigma parameters.

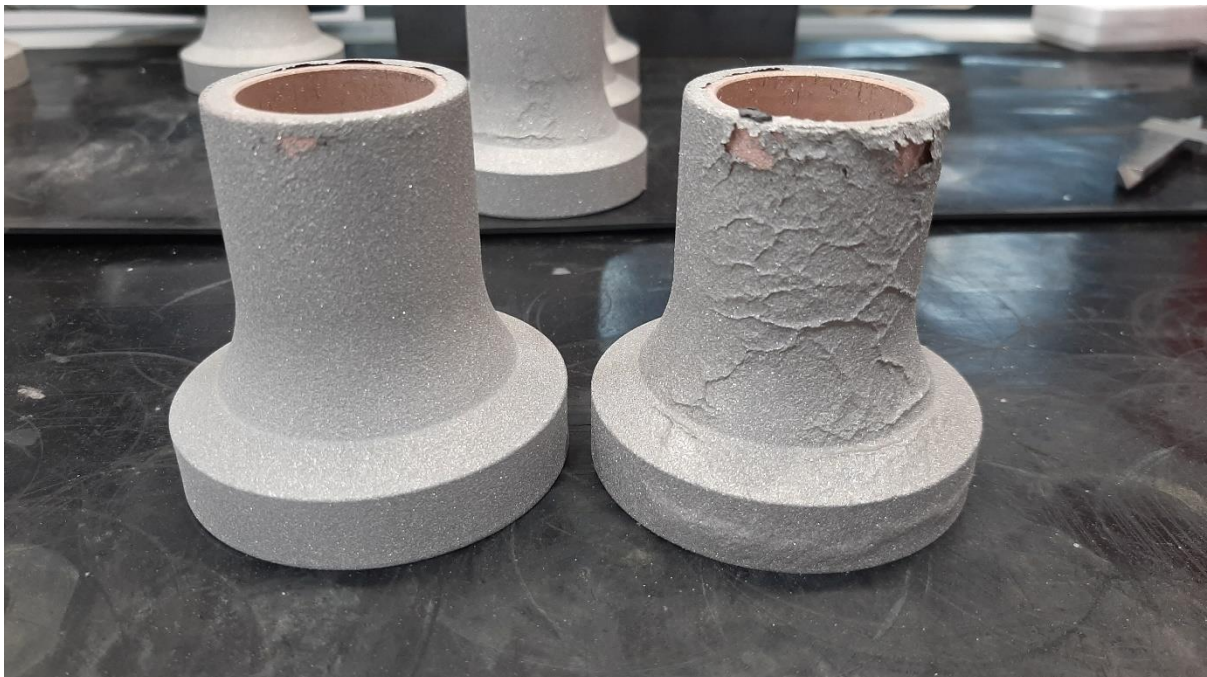


Figure 3: Two CDS parts exhibiting blistering failures.

The purpose of this project is to measure the frequency and patterns of blistering on the nickel coating surface of Rolls Royce CDS Bushing Bearing Blank parts, investigate the possible causal factors of this failure mode and its effects on the performance of a finished part, determine the financial impact on Bodycote and Rolls Royce in terms of wasted material, lost profit and unneeded transport costs, and investigate what cost-effective solutions are available in order to eliminate the failure mode.

Project Objectives

The first objective of the project is to determine a means of categorising and measuring blistering failure modes for CDS parts and measure the failure rate over a fixed timespan so that the impact of this failure mode can be properly assessed. The second objective is to research blistering failure of nickel coating in other applications and how it has been combatted, and to ascertain if any of those

methods are suitable for the CDS parts. The effectiveness of any implemented solution will be measured by repeating the sample taking from the measurement phase for a similar span of time and comparing the results to those from before the solution was implemented.

The project will ideally require no additional materials beyond those already possessed by Rolls Royce and Bodycote, if the failure is found to be derived from either the nickel dip process or the blasting process. It is unclear at the present time what the exact cause of the blistering may be, so research into this field and the mechanics of dip coating will be required. The closest time constraint for this project would be the desired completion date of May 2024; meeting this deadline will be reliant on the success of research into determining the cause of blistering.

Additionally, the FMEA analysis below suggests that the control procedure for identifying blistering and removing failed samples from the production process is not perfect. This has a serious issue in that from bond coating onwards, parts must be produced in pairs; if a blistered part is bonded to a non-blistered part, the non-blistered part is now also scrap, doubling the cost of the failure. If elimination of blistering cannot be achieved, a more reliable detection method must be established.

Project scope

This project will include:

- The measuring of blistering fail frequency over time,
- Investigation into the causes of blistering failures,
- Investigation into the mechanics and adhesion of nickel dip coatings,
- Design and implementation of a means of reducing or preventing blistering failures caused by the processes used,
- Design and implementation of a means of minimising detection failure.

This project will not include:

- Investigation into the failure modes of non-CDS parts,
- Redesign of the CDS parts to minimise risk of blistering failure,

The staff involved with this project primarily includes:

- David de Vall, Coating Technician
- Ryan Dugmore, Production Engineer
- Ian Jenkins, Production Engineer

Voice of the Customer

Rolls Royce would like the project to be completed and appreciate the investigation on Bodycote's end of the process. However, they are reasonably sure that the issue lies on their end, during the application of the nickel coating, and are reluctant to share industry data that we do not need to continue our current regular production. They have seen fit to inform us that:

- The core of the part is a lead-bronze alloy, although not what percentage or any other alloying additions,
- The coating is nickel, although not any specific alloy,
- The coating is applied by a dip coating process, although not what parameters are involved in this process,
- That parts are cooled indoors and regularly dispatched to Bodycote within a week of being made.

Prior research conducted

The initial research portion of this project has consisted primarily of interviews and discussion with Ryan Dugmore, revealing that Rolls Royce use “something like a dip coating process” to coat the parts in an undefined nickel alloy, which are then blasted at Bodycote.

Areas for Investigation

It is presumed by Rolls Royce and Bodycote engineers that the cause of the blistering is not a result of the blasting process, but rather the coating process undertaken at Rolls Royce. Initially online research indicates a common consensus that blistering is a fault of adhesion during the coating process; however, this seems to commonly occur as a fault before blasting occurs, making the situation with the Rolls Royce parts atypical. This merits further research into dip coating processes.

Affected Parties

The primary affected party of this project will be Rolls Royce; there is currently an agreement in place between Rolls Royce and Bodycote that, given that the apparent cause for failure is a flaw in Rolls Royce’s manufacturing process and not Bodycote’s, that Bodycote will not be held financially accountable for parts that fail and need rework due to any blistering failure.

Additional resources needed

It is unclear at this time what the solution to the project would consist of. However, suggestions for potential solutions include the like of a different grit blasting medium, adjustments to the alloy used for the nickel coating and adjustments to the dip coating solution. Should any of these be implemented, it would require the procurement of additional resources such as grit of a different size or material, different alloying additions for the nickel coating or different chemicals for the dip coating solution.

Estimated results

It is estimated that the results of this project will be a reduction in the failure rates of CDS parts due to blistering. This will have multiple benefits, including:

- Increase in direct profit due to more parts being successfully produced.
- Reduction of costs created by the need to rework faulty parts.
- Reduction in time costs created by delays as fewer parts than required from a given batch successfully finish production.
- Reduction in material costs as faulty parts that cannot be reworked do not need to be replaced.

Potential risks

Risks involved in carrying out this project include:

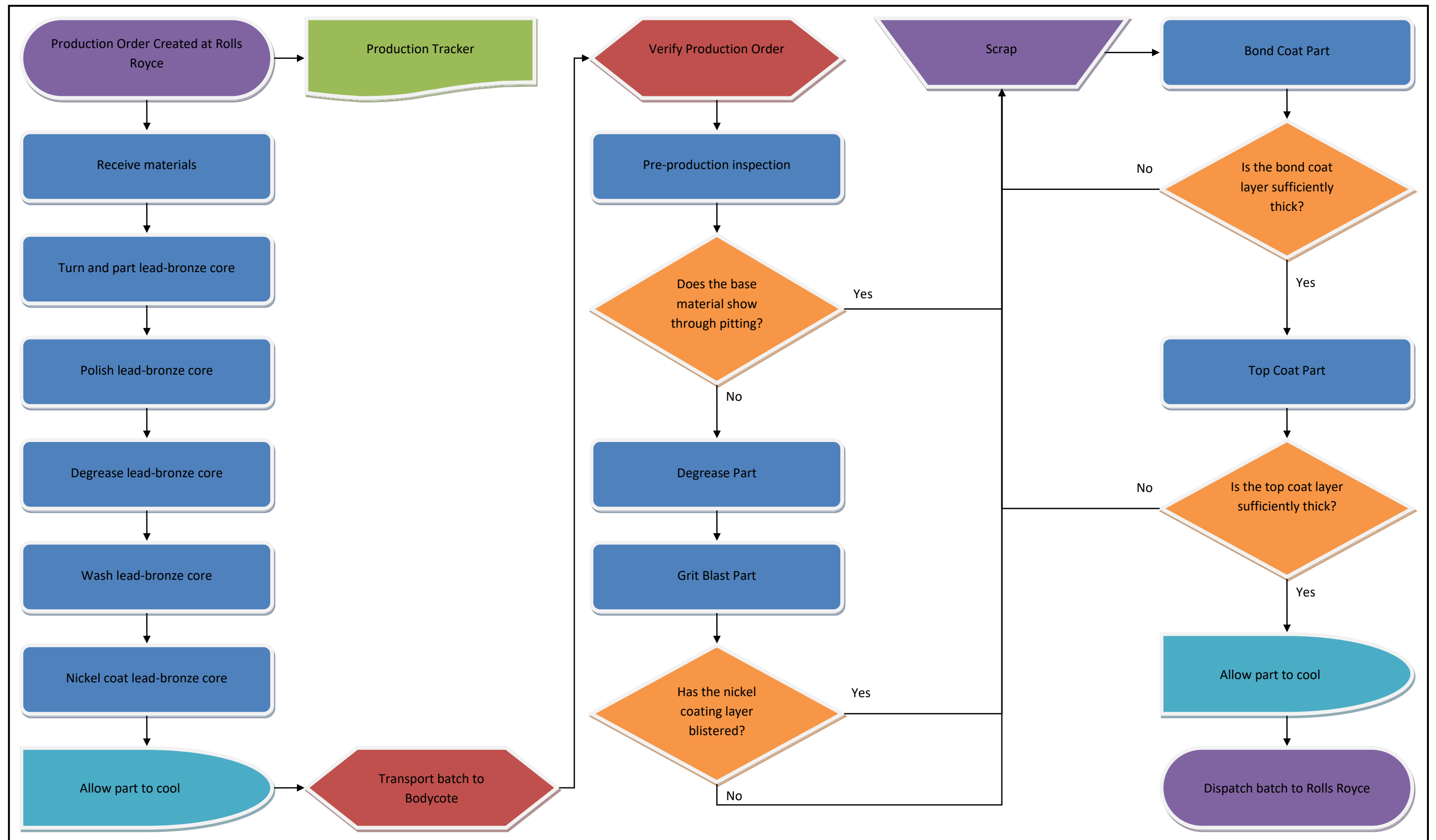
- Failure to determine the reason for blistering occurrences.
- Failure to identify a potential solution to rectify the cause of occurrence.
- Cost of correct solution being outside the project budget.
- Breakdown in communication between Bodycote and Rolls Royce.
- Denial of sharing critical information by Rolls Royce.

Some of these risks occurring could cause the project to fail, however investigation into the root cause of the problem and potential solutions to it will be able to continue as private research and reported here. A failure in breakdown between Rolls Royce and Bodycote does not present an immediate failure state for the project but could lead to ineffective implementation of solutions and difficulty ensuring correct control of the improved processes going forwards if both parties must be involved in/report on the modified process.

Summary

This project is being performed to reduce the rate of blistering failures on CDS parts at Bodycote after being nickel coated at Rolls Royce. It has a reasonable likelihood of success and a low chance of exceeding the project budget but relies on communication and cooperation between Bodycote and Rolls Royce to complete fully successfully. The research already conducted indicates that the project will require substantial research into the science of dip coating and other forms of nickel plating, but also that minimal resources may be required as the CDS parts should not need extensive redesign and instead minor alterations to the current standing coating process should be sufficient to correct the problem.

Process Map



Measure

Frequency Recording

The following data collection plan was produced to organise the recording of experimental data, to establish a starting point for this project's investigation:

Primary Metric				
Metric	Definition	Collection	Variables	Sampling Plan
Frequency of Blistering	The quantity of blistering failures that occur per X parts.	Visual analysis of parts for blistering failures under 1000 lux lighting.	Batch Number, Part Type, Number of Parts in Batch, Number of Blisters in Batch	All parts to be analysed and recorded due to low throughput
Secondary Measures				
Metric	Definition	Data Type	Collection	
Batch Number	The unique batch number for tracking purposes	Attribute	Recorded from production tracker	
Part Type	The part identification number of the batch	Attribute	Recorded from production tracker	
Number of Parts in Batch	The total number of parts to be processed	Variable	Visual count of parts to be blasted; not taken from production tracker to exclude parts that failed pre-production inspection	
Number of Blisters in Batch	The total number of parts that blister	Variable	Visual inspection and count of parts.	
Blister Severity	The number of parts for which the blistering was mild, forming a bubble, or sever, fully rupturing the coating.	Variable	Visual inspection of parts.	
Blister Location	The number of parts for which the blister was located on the vertical neck or curved shoulder of the part	Variable	Visual inspection of parts.	
Date	What date the batch was inspected on	Attribute	Recorded from Bodycote computer system.	

The sample size taken for the project was measured from 01/04/2023 to 14/12/2023, including all batches processed within that time. Blistering was divided into two regions, lip and shoulder, and two severities, minor and major.

- A lip blister is one that is limited to the narrow end of the part and does not spread more than 10mm away from it. A shoulder blister is one that affects the main body of the part past this 10mm limit, including any lip blister.
- A minor blister is one in which the surface of the nickel coating remains intact, and simply peels away from the base materials. A major blister is one in which the surface of the nickel coating tears, exposing the base material.



Figure 4: Minor Shoulder Blisters

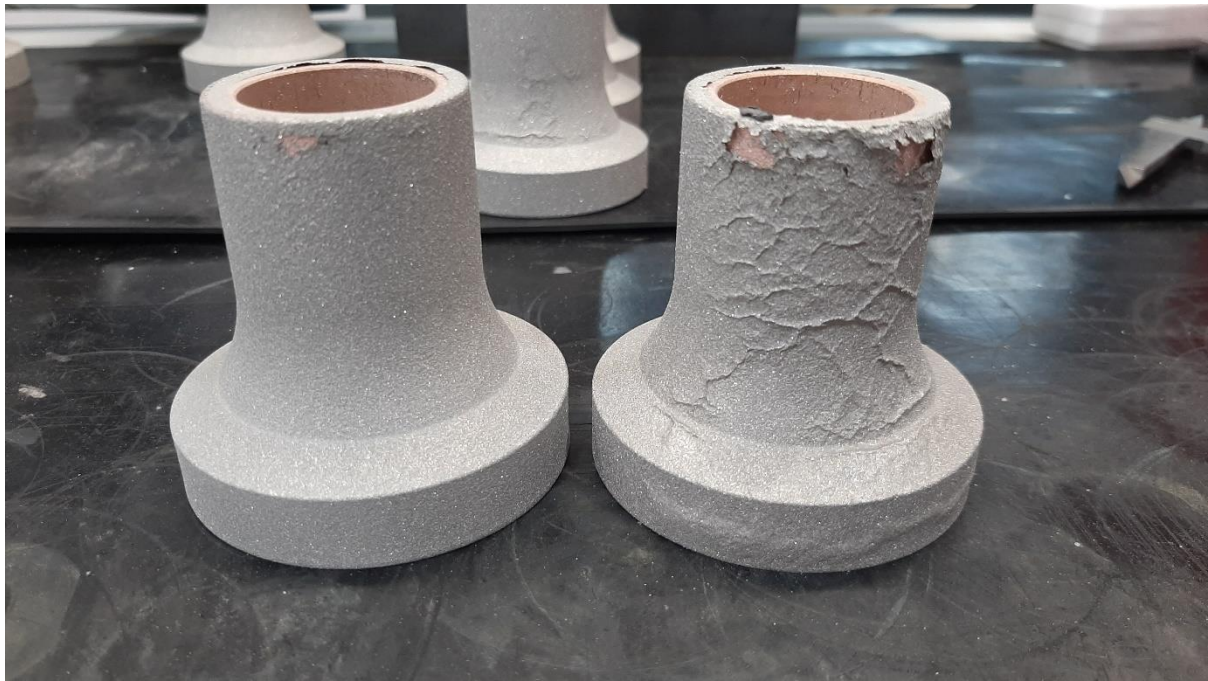


Figure 5: Major Lip and Major Shoulder Blisters

The full results of the measurement process are presented below: [improve readability]

Date	Batch	Part	Okay	Minor Lip	Minor Shoulder	Major Lip	Major Shoulder	Bond Undersize	Top Undersize	Out of Shape	Flameout	Bond Off-Colour	Rate of Blistering
03-Apr	201642	277	22										0.00%
03-Apr	201657	277	19			1							5.00%
04-Apr	201666	277	9			2							18.18%
04-Apr	201687	277	15	3		1	3						31.82%
05-Apr	201686	277	14	4		2		2	2				25.00%
06-Apr	201704	277	20										0.00%
11-Apr	201669	290	14	2						4			10.00%
11-Apr	201658	290	19	1									5.00%
11-Apr	201706	955	18										0.00%
12-Apr	201659	290	18										0.00%
13-Apr	201665	290	19		1								5.00%
15-Apr	201705	290	16						2				0.00%
17-Apr	201710	290	20										0.00%
17-Apr	201709	955	24										0.00%
18-Apr	201743	955	16										0.00%
18-Apr	201719	549	22										0.00%
19-Apr	201745	290	14	1	1		2						22.22%
19-Apr	201769	466	15	2	1							4	13.64%

20-Apr	201770	555	20											0.00%
21-Apr	201771	555	20					4						0.00%
24-Apr	201796	290	20											0.00%
25-Apr	201797	290	20											0.00%
25-Apr	201804	290	20											0.00%
27-Apr	201803	290	20											0.00%
02-May	201813	290	10	2										16.67%
03-May	201814	290	20											0.00%
04-May	201835	955	22											0.00%
04-May	201862	290	18											0.00%
05-May	201863	290	20											0.00%
09-May	201865	290	18											0.00%
09-May	201864	290	20											0.00%
10-May	201880	549	24											0.00%
11-May	201879	549	24											0.00%
12-May	201904	290	12	2										14.29%
15-May	201903	290	18											0.00%
15-May	201902	290	20											0.00%
15-May	201774	685	4	2	1		5							66.67%
16-May	201911	277	23			1								4.17%
16-May	201912	277	24											0.00%
17-May	201938	549	18						4					0.00%
19-May	201944	549	20											0.00%
22-May	201943	549	23	1										4.17%
22-May	201942	555	22											0.00%
23-May	201978	466	23											0.00%
23-May	201977	466	22											0.00%
24-May	201940	290	18											0.00%
25-May	201941	290	10	1	1									16.67%
25-May	201979	277	20											0.00%
30-May	201893	290	20											0.00%
30-May	201894	290	16						2					0.00%
31-May	201910	555	22											0.00%
31-May	202012	466	18											0.00%
01-Jun	201997	466	19	2		1		2						12.50%
05-Jun	201980	277	22											0.00%
05-Jun	201982	277	24											0.00%
22-Jun	201981	277	22						2					0.00%
23-Jun	201999	290	18	1	1									10.00%
25-Jun	201998	290	15					2						0.00%
26-Jun	202000	955	23	1										4.17%
27-Jun	202013	290	20											0.00%
27-Jun	202027	290	20											0.00%
28-Jun	202026	290	20											0.00%
28-Jun	202042	290	20											0.00%
29-Jun	202062	277	20											0.00%

15-Aug	202501	466	24											0.00%
16-Aug	202505	277	22											0.00%
16-Aug	202504	277	24											0.00%
17-Aug	202503	277	20											0.00%
17-Aug	202502	277	24											0.00%
22-Aug	202542	555	22						2					0.00%
23-Aug	202545	555	22						2					0.00%
24-Aug	202548	549	24											0.00%
24-Aug	202541	549	22											0.00%
29-Aug	202546	466	24											0.00%
29-Aug	202547	466	24											0.00%
30-Aug	202597	290	20											0.00%
31-Aug	202596	290	20											0.00%
04-Sep	202598	290	20											0.00%
05-Sep	202593	277	24											0.00%
05-Sep	202592	277	22						2					0.00%
06-Sep	202595	955	24											0.00%
06-Sep	202594	955	24											0.00%
07-Sep	202634	277	22											0.00%
08-Sep	202533	277	24											0.00%
10-Sep	202631	290	20											0.00%
11-Sep	202632	290	19											0.00%
12-Sep	202682	290	20											0.00%
12-Sep	202684	290	20											0.00%
13-Sep	202683	290	20											0.00%
14-Sep	202712	290	20											0.00%
14-Sep	202711	290	19											0.00%
18-Sep	202714	277	24											0.00%
18-Sep	202713	277	24											0.00%
20-Sep	202742	277	24											0.00%
20-Sep	202741	277	24											0.00%
22-Sep	202740	277	24											0.00%
25-Sep	202754	277	24											0.00%
25-Sep	202753	290	19											0.00%
25-Sep	202752	290	19											0.00%
26-Sep	202802	277	24											0.00%
27-Sep	202801	277	24											0.00%
28-Sep	202804	466	23											0.00%
04-Oct	202805	290	20											0.00%
05-Oct	202845	290	17	1										5.56%
09-Oct	202848	290	20											0.00%
10-Oct	202847	290	20											0.00%
10-Oct	202846	290	19	1										5.00%
11-Oct	202849	466	20											0.00%
12-Oct	202911	277	23	1										4.17%

15-Oct	202912	277	24										0.00%
17-Oct	202913	290	14	2				2					11.11%
18-Oct	202914	290	19										0.00%
18-Oct	202948	290	14										0.00%
19-Oct	202945	277	23										0.00%
23-Oct	202946	277	23										0.00%
23-Oct	202949	466	24										0.00%
24-Oct	202950	466	24										0.00%
26-Oct	202947	290	10										0.00%
30-Oct	202990	290	18										0.00%
30-Oct	202987	290	20										0.00%
31-Oct	202986	290	18					2					0.00%
31-Oct	202989	290	17	1				2					5.00%
04-Nov	202985	290	20										0.00%
06-Nov	202988	290	20										0.00%
06-Nov	203037	277	23										0.00%
07-Nov	203036	277	24										0.00%
08-Nov	203035	277	24										0.00%
09-Nov	203049	8	24										0.00%
13-Nov	203050	549	24										0.00%
13-Nov	203022	549	24										0.00%
13-Nov	203073	277	24										0.00%
14-Nov	203074	277	24										0.00%
15-Nov	203072	290	20										0.00%
15-Nov	203114	290	14										0.00%
15-Nov	203116	290	20										0.00%
17-Nov	203113	290	18										0.00%
18-Nov	203115	290	20										0.00%
20-Nov	203117	290	22					2					0.00%
21-Nov	203130	466	19		4	1							20.83%
22-Nov	203120	277	24										0.00%
22-Nov	203118	277	23										0.00%
22-Nov	203119	277	10										0.00%
23-Nov	203129	555	22										0.00%
27-Nov	203150	290	18										0.00%
27-Nov	203151	290	19										0.00%
27-Nov	203148	466	24										0.00%
28-Nov	203149	466	18	2									10.00%
29-Nov	203162	277	24										0.00%
29-Nov	203164	277	24										0.00%
30-Nov	203163	277	24										0.00%
30-Nov	203165	277	0		4		18						100.00%
02-Dec	203210	290	18										0.00%
04-Dec	203212	290	20										0.00%
04-Dec	203209	290	13		3	1	2						31.58%

05-Dec	203242	277	23	1										4.17%
06-Dec	203243	277	22						2					0.00%
06-Dec	203244	277	24											0.00%
11-Dec	203211	290	17	2										10.53%
11-Dec	203213	466	24											0.00%
12-Dec	203214	466	16											0.00%
13-Dec	203288	290	19											0.00%
13-Dec	203293	290	19											0.00%
14-Dec	203291	290	20											0.00%
	3975		3862	37	9	9	12	18	20	4	0	4		

As can be seen, a total of 3975 parts were studied, with a total of 113 failures between all failure modes. This represents a 2.3% failure rate.

Blistering Detection

The current requirement for checking for Blistering requires the part to be studied by eye under a light of minimum 1000 lux. This is readily achieved at the CDS-1 workbench. However, lighting levels in the blasting room are much lower: regular room lighting only achieves 362 lux of illumination, and the interior of the grit blasting cabinet receives only 141 lux even with a clear and undamaged sacrificial screen fitted. While this is still enough to see serious Blistering and abort blasting such parts early, it means that proper analysis can only be done at the workbench by the CDS-1 operator, even if there is a separate operator blasting parts for them.

Blasting Variables

The following variables have been identified in the blasting process at Bodycote:

- Grit Size, which is currently set to #20 grade grit, but #60 grade grit is available on-site,
- Air Pressure, which is currently set to 55psi,
- Blasting Time, which varies by part number,
- Distance between Nozzle and Part, which is currently 80-130mm,

Each of these variables will be investigated to determine if they have an impact on blistering of parts, and if adjusting them would resolve the issue without causing loss of performance in successful parts.

Failure Modes and Effects Analysis

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		
Blasting	Blistering	Scrap Part	10	Unknown	7	Visual inspection after blasting	5	350
Bond Coating	Part Undersize due to gun flameout	Scrap Part	10	Gun Flameout	3	Regular Gun Maintenance	2	60
Bond Coating	Part Undersize due to gun blockage	Scrap Part	10	Gun Blockage (Major)	1	Regular Gun Maintenance	2	20
Bond Coating	Part Undersize due to insufficient cycles	Scrap Part	10	Insufficient Cycles	1	Guideline on cycles required	1	10
Bond Coating	Part off-colour	None	1	Gun Blockage (Minor)	3	Regular Gun Maintenance	2	6
Top Coating	Part Undersize due to wire jam	Scrap Part	10	Wire Jam	2	Operator on-hand during spraying to prevent jams	3	60
Top Coating	Part Undersize due to insufficient cycles	Part Requires Further Spraying	5	Insufficient Cycles	3	Guideline on cycles required, additional tolerance for adding cycles	1	15
Top Coating	Part Out of Shape	Additional Milling Time	5	Program Incorrect	1	Dry run of program during setup	3	15

As can be seen from the FMEA, blistering during the blasting process is the currently largest problem due to having the largest RPN, because of having the highest severity and occurrence combined. This makes it a serious issue that must be addressed as soon as possible to reduce the number of failed components and their impact on the customer.

Additionally, the FMEA analysis indicates that the control procedure for identifying blistering and removing failed samples from the production process is not perfect, due to the high detection value. This has a serious issue in that from bond coating onwards, parts must be produced in pairs; if a blistered part is bonded to a non-blistered part, the non-blistered part is now also scrap, doubling the cost of the failure.

Therefore, while the original premise of the project was on preventing blistering failures from occurring, it is also necessary to investigate the detection method used and determine if any improvements can be made to this process.

Alongside this, the causes for bond and top coats being undersize are also very high in places, notably when due to gun flameout and wire jam. Investigation should be made into improving these processes later and should be a project to conduct soon in Bodycote’s continuous improvement program; however, they remain outside of the scope of this project due to having a much lower RPN than the blistering problem.

Analyse

Collected Data

Pareto Analysis

To determine the severity of blistering compared to other sources, pareto analysis was conducted, regrouping all blistering sources into one failure mode since all ultimately result in a scarp part.

Pareto analysis is a decision-making tool used to compare and fix problems strategically. It uses the Pareto principle, named after Italian economist Vilfredo Pareto. He found that many phenomena or trends follow the 80/20 rule, that being that 80% of the outcome can be linked to 20% of the causes. To conduct Pareto Analysis, similar outcomes are grouped, and the quantity of each group is compared, arranged from highest to lowest.

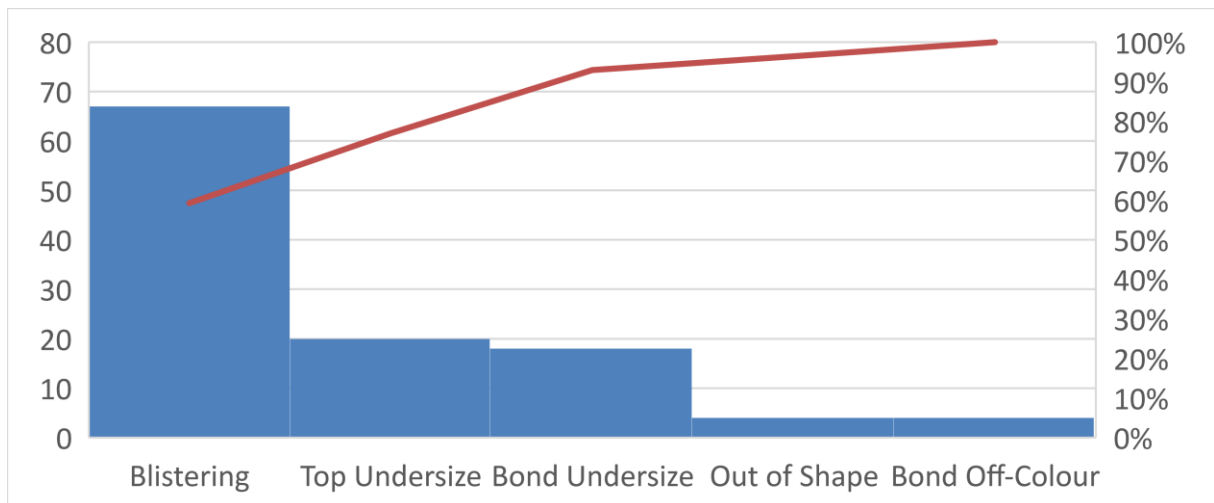


Figure 6: Pareto Analysis of Failure Modes

As can be seen, blistering does indeed account for roughly 80% of failures on CDS-1 parts, making it clear that resolving this problem will have the biggest impact in reducing failure rates and increasing profitability.

Next, Pareto Analysis was conducted to see if any part type was more vulnerable to blistering than any other, using the total number of parts that failed as the compared metric:

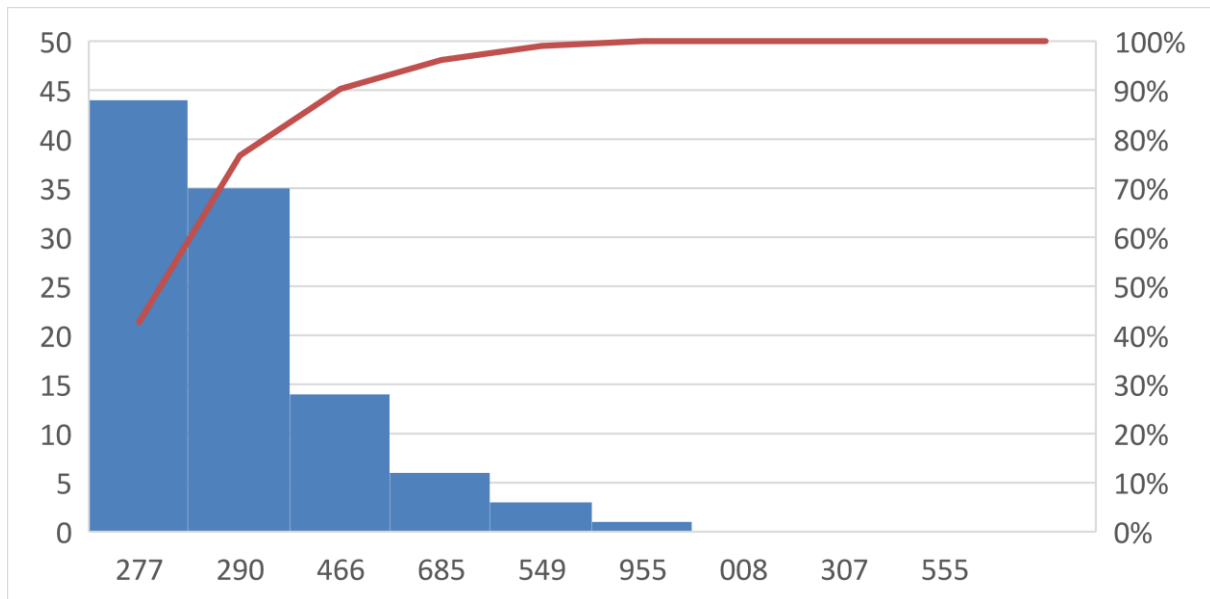


Figure 7: Pareto Analysis of Failures by Part (Frequency)

However, in the article “Pareto Principle and Rate Analysis”, it was demonstrated that “the method of recording the number of failures is insufficient if the opportunity to occur is not equal” (Radson & Boyd, 1997). This indicates that merely measuring the frequency of failures is a flawed practice, as a product that is produced more will logically show more failures whereas it might be less prone to failure per part; instead, Pareto Analysis should be performed by failure rate. This was done for the CDS-1 blistering failures, and the results are shown below:

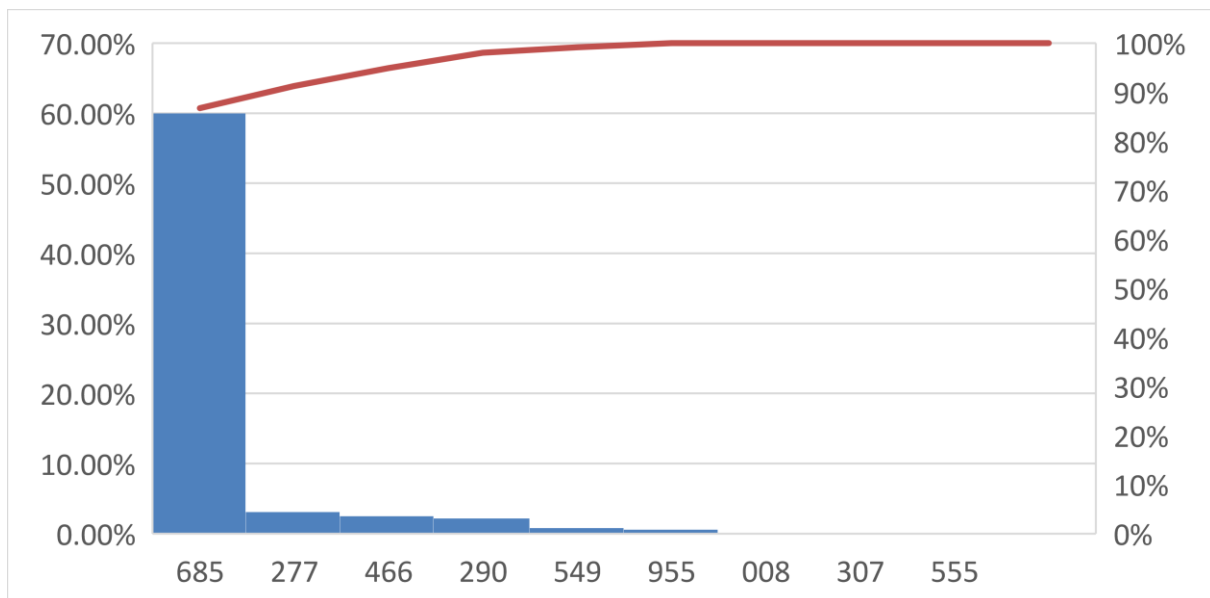


Figure 8: Pareto Analysis of Failures by Part (Rate)

As can be seen, part type 685 suddenly becomes a much more pressing issue under this revised study. However, as a grand total of 10 of them were produced during the study, they are a much rarer part and account for a lower percentage of lost profit and rework costs than other parts. 466s also become a slightly more pressing issue than 290s, giving weight to the argument that they should also be considered even though on frequency analysis the 80% mark was reached almost entirely just on 277s and 290s.

The last issue to consider during Pareto Analysis is that different parts are not costed equally; the study “Issues in Pareto Analysis and their Resolution” posits that incorrect criteria are often used, especially in maintenance of failure rate tasks; frequency of incident vs cost/downtime. (Sarkar, Mukhopadhyay, & Ghosh, 2012) This can have the complication of leading to misclassifying of vital few/trivial many, since a smaller number of much higher-cost failures might be worth more than a larger number of cheaper failures.

Unfortunately, applicability to this project is minimal as Rolls Royce will not release cost of failure stats at this time, so this complication cannot be accounted for. However, sales records indicate that parts are similarly priced, and thus the cost of failure likely deviates little between different part types, making the above concern a marginal issue.

Timeline Analysis

Following Pareto Analysis, the failure over time were plotted, resulting in the graph below:

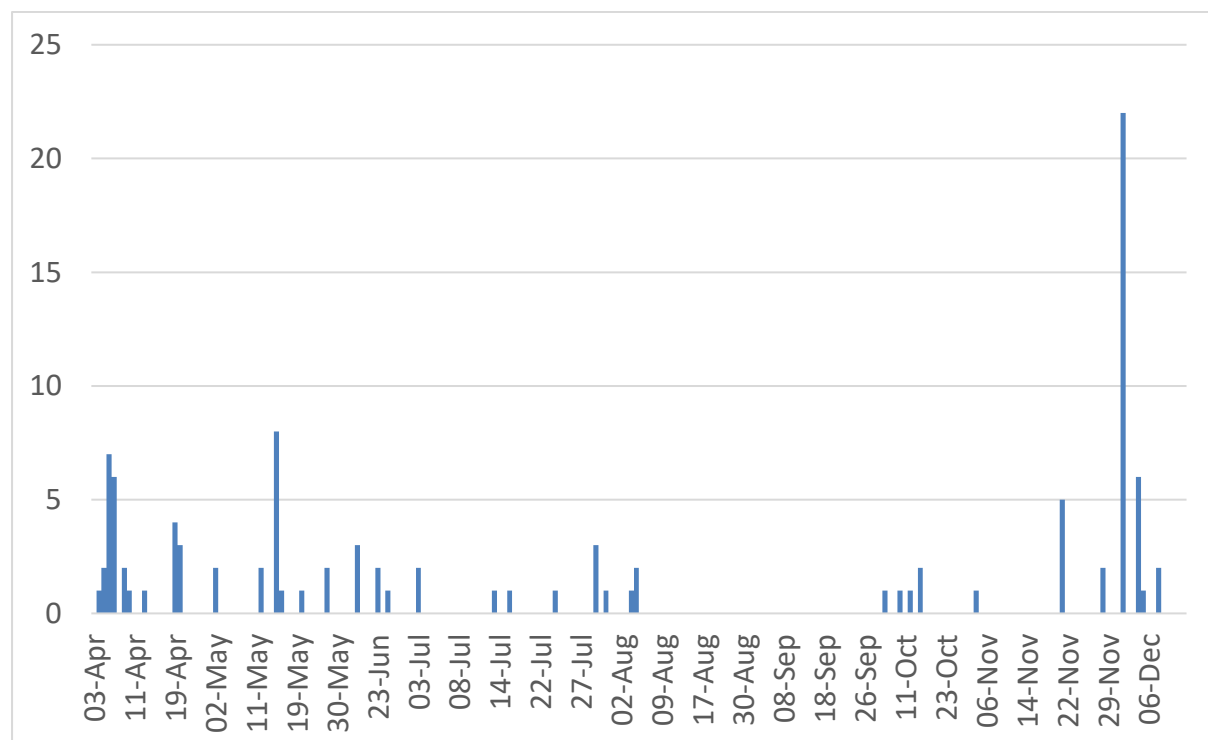


Figure 9: Failures over Time

It is immediately noticeable [no failures in august and September – hypothesise why]

that faults occur more frequently at the beginning and end of the measurement period, during spring and winter. This suggests a seasonal element to the fault, and so environmental conditions might be a factor.

However, discussion with Rolls Royce indicates that parts are dip coated and cooled in environmentally controlled conditions and dispatched to Bodycote for further processing within a week of being dipped. There is little chance for environmental conditions to play a large role in affecting the quality of parts withing this narrow timeframe.

Cost/Benefit Analysis

A proper cost/benefit analysis requires a process of improvement to have already been selected and a strategy to be priced. Unfortunately, at this stage it is unclear what strategy can be expected or precisely what improvement can be made.

However, the potential benefit can still be determined; the cost of failures to Bodycote and Rolls Royce can be determined, to give an expected maximum improvement if the blistering failure mode is eliminated entirely.

It is known that Bodycote charges Rolls Royce approximately £180 per part, and that because the reason for the failure is believed to lie with Roll Royce, they have agreed to pay Bodycote in full for any part that fail. Additionally, any part that fails is one less part that Rolls Royce have, requiring them to produce another part to replace it (by scratch or by reworking blistered parts). This means that they directly pay Bodycote £360 per blistered part. Multiplying this by the number of failures in the recording period gives us a figure of £24,120 for the recording period. This can be divided by the 255 day period and multiplied by 365 to give us an initial estimate of minimum loss to blistering per year of **£34,524**.

As the parts fail at the blistering stage, the cost to Bodycote is only the cost of running the vapour degreaser and operating the grit blaster until the blistering is seen. Since degreasing is an unmanned process done on 2-3 batches at a time and very little grit or time is needed per part blasted, these costs are negligible and easily covered by the compensation of £180 per part by Rolls Royce.

Transport cost is not an issue, as Rolls Royce typically send and receive multiple batches at a time, making transport cost per part negligible.

Other factors that Rolls Royce would need to disclose for a proper cost benefit analysis to be conducted would be:

- The price of producing the lead-bronze core (if a replacement is needed) or the price of stripping the nickel layer (if a blistered part's core can be reused)
- The price of applying the nickel plating (to include materials, chemicals, energy, staff wages and maintenance)
- The lost profit per part

Each of these factors would almost certainly push the cost of a blistering failure higher; however, the initial estimate of £34,500 still gives a very large effective budget to implement cost-effective improvement to the process.

Literature Reviews

Six Sigma Principles

Six Sigma is a methodology by which process improvement can be evaluated and managed by use of careful study of production variables. The general premise of the methodology is that variation in a given process creates room for error, and that rather than testing the final product of a process for deviation or defect, the process itself should be carefully controlled in order to guarantee that parts are fit for purpose (The Council for Six Sigma Certification, 2018). This has numerous advantages, saving both materials and the financial and time cost of production that would have previously produced a faulty product, further minimising time cost by reducing the number of quality assurance processes needed in the production cycle, and increasing customer satisfaction by minimising the risk of faulty parts being produced, passing QA and being dispatched to the customer only to be found unfit for purpose at their end.

The core principle behind six sigma methodology is also the reason for its name; one sigma is the unit used to quantify standard deviation, a measure of how many instances of a variable strays outside the accepted value. If a variable falls within six sigma, then only 3.4 parts in every million will be defective, resulting in a 99.99966% success rate for part production (The Council for Six Sigma Certification, 2018). As the CDS parts are currently experiencing 113 defects in 3975 parts, or a failure rate of 2.84277%, it clearly falls outside of this goal.

The key behind six sigma process control is to control variation within the process to ensure predictable results at the output of the process. Variations can be measured as common variations, which are internal to the process such as machine settings and timings, and special variations, which are external to the process and uncontrolled such as the weather (Gitlow, Melnyck, & Levine, 2015). To control the process, the former must be recorded, and the effects of different variations analysed, and the latter must be eliminated as factors to all reasonable extent. Unfortunately, many of the variables associated with the Rolls Royce side of the production have not been shared with Bodycote, and so it can only be speculated on what process controls they have in place and how improvements could be devised and implemented.

It is from Six Sigma methodology that we obtain the DMAIC process that is implemented in this project for process improvement, but it also informs the DMADV methodology for process replacement in the event that a process cannot be improved to an acceptable level (The Council for Six Sigma Certification, 2018).

Dip Coating

Dip coating represents the oldest form of thin film deposition that is commercially viable, with the first patent for this process being issued in 1939 (Geffcken & Berger, 1939). The process is split into three technical stages:

1. Immersion and dwell time, in which the part to be coated (the substrate) is immersed in a liquid solution of the coating to be applied (the precursor) and left immersed for a span of time sufficient to promote chemical interaction between the two systems,
2. Deposition and drainage, in which the coating is formed as the substrate is removed from the precursor, clinging to it via its liquid surface tension as excess liquid drains from it,
3. Evaporation, in which solution compounds evaporate from the deposited wet film, leaving behind a dry film consisting of the desired coating. This can be performed more rapidly via heated drying.

The coated piece might then be heat treated to remove residual materials or alter the crystal structure of the coating after processing (Brinker, 2013). This dry coating can be thickened further via repeated dipping, but the coating thickness per dip will also be affected by:

- Immersion time, forming a thicker film the longer the substrate is immersed up to a steady state value. This means that, assuming a safe steady state value, there is no failure that can occur from excessive immersion time, but an insufficient immersion time may create problems.
- Withdrawal speed, which is inversely proportional to film thickness; however, increased withdrawal speed also results in a decrease in surface porosity of the film.
- Substrate surface material and geometry.
- Concentration of precursor solution; as the concentration increases, so too does the film thickness.
- Temperature: Film thickness will increase as temperature decreases, as a hotter solution will contract more while cooling during the evaporation stage and have more internal energy to overcome its own surface tension making it adhere to the substrate.
- Technical practices: different modifications can be made to the dip coating process, such as dip draining (where the precursor is drained as the substrate is removed, resulting in a faster extraction rate) and angle-dependent dip coating (in which the substrate is dipped at an angle to give differing coating thickness on either side).

(Savita L. Patil, 2023)

Advantages and disadvantages

The primary advantages and disadvantages to using a dip coating process compared to other additive manufacturing methods are quoted below:

Advantages

1. Dip coating is highly efficient with minimal wastage.
2. It is simple and inexpensive technique.
3. Specific thickness can be obtained by controlling few preparative parameters.
4. Coating on flat and uneven surfaces as well as tubes is possible. Both side coating on flat surface also possible at a time.
5. Uniform coating with roughness in nanometres can be possible.
6. By varying withdrawal speed gradient coating also possible.
7. Fairly good adhesion

• Disadvantages

1. During the drying phase, wet film is affected by environmental condition such as turbulent air flow. To avoid this process can be done in a clean room.
2. Curved or flexible substrates difficult to coat.
3. When changing from liquid to solid layer, material shrinkage can lead to cracking in the film.
4. Light parts can float or fall from carrier and thickness of film can change from top to bottom.

(Savita L. Patil, 2023)

The notable points to take away from this are that the process is primarily selected because it is cheap and simple to execute, while coating the entire outside surface of the part. This will make suggestions of an alternate process such as thermal coating or electroplating unlikely to be considered, due to the high increase in cost those processes would bring in terms of energy consumption.

However, it is also noted that the process can have difficulty coating curved substrates, such as the bushing bearings. While most blister failures have occurred at the lip of the part and not inside the curved shoulder, it still stands to reason that this feature may be at fault for the failure, creating uneven stresses withing the nickel coating.

Most example of the dip coating process and the effects of its parameters in industrial use that could be found focus on electronic components or non-metallic substrates, and coating thicknesses measure in nanometres, so they make for poor comparison to the nickel dip coating process being investigated.

Failure Modes

Multiple failure modes exist for dip coatings, mostly resulting in inconsistent coating thickness. As this is not an issue that the CDS parts are experiencing, they will not be discussed here. However, one failure mode exists that may be relevant to the project, and that is cracking. This can be seen in films following post-deposition heat treatment, and is characterised by long, straight cracks in the film structure that become more prevalent as the coating thickness increases. There are three primary sources for cracking occurring:

1. Small particles on the film surface which create structural weak points, which create additional stress during heat treatment.
2. High loss of liquid during the evaporation process that causes uneven stress in the film that does not resolve properly when heat treated.
3. Mismatch of thermal expansion between substrate and coating causing sheer stress between the two during heat treatment.

(Dr. J. Griffin, 2021)

However, this failure mode does not correlate well with what is known of the Rolls Royce side of the CDS part processes, and the blistering failure mode; cracking occurs in straight line during heat treatment, while blistering affects randomised lines or areas, and Rolls Royce do not subject parts to a heat treatment process prior to shipping them to Bodycote. It may be propagated during the degreasing process at Bodycote but given that this process only reaches temperatures of roughly 125°C this seems highly unlikely; the recrystallization range of nickel alloys starts at 400°C (Baker, Chang, & Li, 2011). Coupled with the lack of industry examples of dip coating being used to apply metallic coatings, it calls to question whether this is the process that is actually in use at Rolls Royce, or if the current understanding of Bodycote engineers on Rolls Royce's process is incorrect. Fortunately, reading around the subject has revealed a more likely candidate for the process in use by rolls Royce, which is reviewed in the following section.

Electroless Nickel Plating

Electroless metal deposition is a process very similar in concept to electrolytic plating, however rather than an electric charge being run between cathode and anode in a solution, instead a chemical agent is used to induce oxidation of the substrate's metal surface (Bonin, Delaunois, & Vitry, 2019). This results in a much lower use of energy in exchange for the cost of additional solution materials, but also gives several other beneficial advantages such as a uniform coating thickness regardless of the structure of the part being coated; this makes it ideal for curved products such as the CDS parts being studied, creating a high probability that this is the coating method used at Rolls Royce, rather than a regular dip coating as was previously understood.

An electroless nickel plating solution will primarily consist of two components: a source of nickel ions, and reductants. There are three principal types of electroless nickel coatings based on what metallic ions are present:

- Pure metallic coatings, in this case consisting solely of Ni ions.
- Alloy and poly-alloy coatings, which consist of a single coating made from two metals. These metals may be two or more that can be electrolessly deposited from similar baths combined to modify their properties, or one metal that cannot normally be deposited by the autocatalytic mechanism instead being induced to co-deposit with a metal that can. Examples given from these include Ni-P, Ni-B, Ni-P-B, Ni-W-P, Ni-Cu-P, Ni-Co-P, Ni-P-Sn, and Ni-W-Cu-P.
- Composite coatings, which introduce non-metallic additives to affect the properties of any of the prior coatings. Typically, this will be to either increase the lubrication of the coating by introducing solid lubricants such as WS₂, MoS₂, PTFE and graphite, or to further increase the wear resistance of the coating by introducing hard particles such as WC, SiC, Al₂O₃, B₄C and diamond. Composite coatings have further issues with uniformity of additive distribution throughout the coating, though common preventative processes exist.

Additionally, there are two primary reductants:

- Sodium hypophosphite baths are the most common because they give higher deposition rates to achieve a thicker coating quickly and are simpler to understand and control.
- Sodium borohydride baths are more powerful, producing higher deposition of nickel per volume of reducing agent, making them more cost effective. However, they can produce nickel boride ions instead of nickel ions in an acidic or neutral environment; therefore, the pH of solutions must be held between 12 and 14 to entirely suppress the formation of boride ions and make the process more reliable.

(Sahoo & Das, 2010)

It is unknown at this time precisely what alloy Rolls Royce may have used for their components, or what composite additives they may have included to achieve different physical properties. It is also unknown which reductant Rolls Royce employs.

Another factor frequently present in electroless nickel plating processes is one or more complexing agents; these are typically organic acids or their salts, such as sodium acetate, acetic acid and sodium citrate, and are included to perform one or more of three functions:

- They exert a buffering action that prevents the pH of the solution from falling too fast, which is valuable as many factors of the product such as the deposition rate and the solubility of the Nickel Phosphate content are affected by this.
- They prevent the precipitation of nickel salts, e.g., basic salts or phosphates.
- They reduce the concentration of free nickel ions by forming meta-stable complexes.

(Mahdavi & Sarabi Dariani, 2022)

It is currently unknown what, if any, complexing agents are used by Rolls Royce. However, it is understood that not using a complexing agent is exceptionally rare, and so Rolls Royce likely use a form of complexing agent as a process control measure (especially if a sodium borohydride bath is used).

Surfactants should also be discussed, which are wetting agents included to lower the surface tension of the solution and improve the wettability and stability of the deposited metallic particles. This assists the nickel-plating process by increasing surface finish, hardness and, in Ni-P coating, corrosion resistance due to increased phosphorous deposits. Anionic surfactants will also increase the presence and even the distribution of additives to the coating such as aluminium oxide and carbon nanotubes, that can be used to further improve corrosion resistance by plugging pores in the coating (Chintada, Gurugubelli, & Koutavarapu, 2022). However, the use of surfactants by Rolls Royce seems unlikely as the surface finish and corrosion resistance of the part are not needed qualities, since the nickel coating layer is internal in the part.

It is also worth discussing the effects of other post-coating processes that can be used to modify the properties of the coating. Heat treatment is the most immediately apparent process to be considered, and in electroless nickel plating this will affect the thickness and hardness of the coating by allowing the nickel layer to recrystallise, at the expense of corrosion resistance (Sahoo & Das, 2010). It stands to reason that these properties would be desirable for the CDS-1 parts, as corrosion resistance is less important due to the internal position of the coating layer; however, this process cannot be undertaken, as the stated optimal heat treatment temperature is 400°C; a temperature too high for the lead-bronze core material, as the lead in it will melt and leech out of the alloy (a process known as lead sweat, which is also a consideration in the thermal spraying process). It is possible that a lack of heat treatment may be causing the blistering issue; however, it has already been shown that multiple other techniques for increasing the nickel coating hardness exist, so this seems unlikely.

The most important remaining factor discussed is the adhesion of the coating to the substrate; as following research into Grit Blasting will show, the primary cause of blistering during grit blasting is poor adhesion of the coating surface. The following quote accurately surmises the information that could be found on this matter: “In general, electroless nickel coatings have superior adhesion compared with the nickel electro-deposition method. This is due to the existence of a stronger metal-to-metal bonding during the electroless deposition. However, in case of coating non-ferrous

alloys such as magnesium and aluminium, the adherence of the electroless nickel coatings to the substrate is sometimes poor. Hence, the study of adhesion is mainly concentrated in studies using one of these alloys as substrates.” (Sahoo & Das, 2010)

The cited report goes on to discuss adhesion to aluminium and magnesium substrates in some small amount of detail, noting in both cases that adhesion is higher on alloy substrates rather than on pure metal substrates. Heat treatment is also cited as a means to increase adhesion of aluminium substrates, and zincating is noted as a process that increases adhesion between the nickel coating layer and the substrate alloy; unfortunately, all further investigation to see if the same process could be applied to lead-bronze as a means to increase coating adhesion of the Rolls Royce parts met a dead-end, as the current available literature regarding zincating focusses only on aluminium components. Additionally, no experimental data regarding adhesion of nickel coatings is directly presented in this report.

Blistering in Metal Coatings

Blistering and bubbling are two related failure types that occur in metal coating, with the distinction between the two being that blistering is caused by the movement of water into the space between the substrate and the coating layer by osmosis, and bubbling referring to any similar raising or tearing of the coating surface but formed by a non-osmotic process. Blistering can be caused by the presence of water-soluble salts or solvents in the coating process, and bubbling can be caused by environmental factors such as direct sunlight, humid weather, or cool temperatures creating uneven drying in the applied coating (Molegraaf, 2018). These factors do seem like they could be responsible for the cause of CDS part blistering, given the previously noted trend towards blistering in the winter months when humidity would be higher and temperature would be lower, with both factors possibly continuing into the indoors plant.

However, it is understood that with nickel coating specifically the cause of blistering is due to poor adhesion of the coating to the substrate surface as a result of poor control of the pre-treatment process before the nickel plating takes place, such as insufficient degreasing, formation and improper removal of metal soaps from polishing compounds, formation of silicic acid films and including of copper deposits beneath the nickel coating from contamination (Nickel Institute, 2022). This is supported by the quote:

“Lack of adhesion may be indicated by blistering, or by peeling when the plated component is subjected to mechanical deformation, heating or through failure to pass standard adhesion tests.”
(Nickel Institute, 2022)

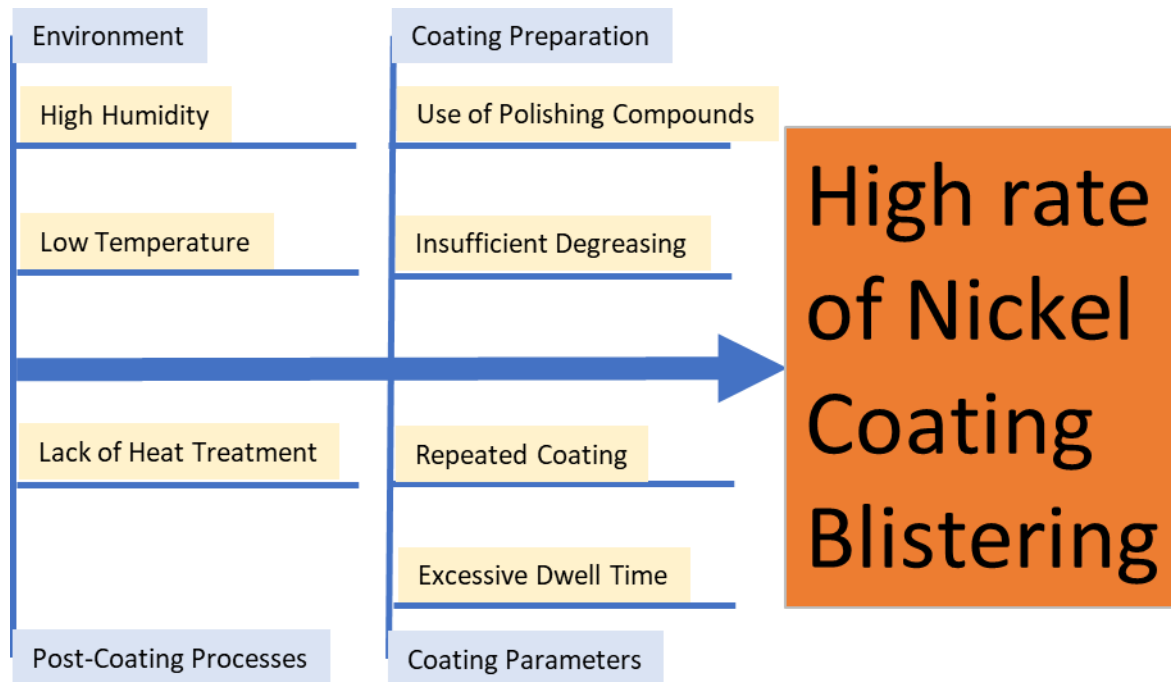
That the fault does not become apparent until the grit blasting process (a form of mechanical deformation) supports the notion that one of these factors is at fault for the blistering. The immersion of copper deposits seems unlikely, as the nickel coating is being applied to a lead-bronze substrate and the research on electroless nickel plating did not indicate the use of copper compounds in other factors of the process. Therefore, it can be presumed that the cause of the fault would be due to insufficient degreasing or cleaning of cleaning or polishing materials, or the formation of similar materials within the solution bath during the early stages of electroless coating.

The above report goes on to indicate that contaminants on the substrate may not always be the issue; if the part is repeatedly dipped to increase the coating thickness, there may be a lack of adhesion between nickel layers. While this is likely not the case for any severe blister, as the lead-bronze substrate becomes visible through the torn nickel coating, it may hold true for minor blisters.

Root Cause Analysis

Fishbone Diagram

The following diagram displays a summary of the potential reasons for blistering failure as discovered by the literature review:



Five Why's

The following chart has been constructed to organise the above data points and to help determine their possible causes. The proper purpose of a Five Why investigation would be to determine the cause present for a given factor by conducting actual investigation on-site; however, as contact with Rolls Royce has been restricted, the following chart instead organises the currently understood situation, and would be used as a tool to facilitate and expediate determining the actual cause/causes of the problem once investigation at Rolls Royce becomes possible:

Problem Statement

Blistering occurs during grit blasting process

Why?

Poor Adhesion of nickel coating

Why?

Residual grease on substrate during coating

Why?

Insufficient degreasing

Why?

Degreasing performed by hand

Why?

Inexpensive compared to running a vapor degreaser

Why?

Fault with vapor degreaser

Why?

Insufficient maintenance

Why?

Entrapment of residual polishing compounds/metal soaps

Why?

Insufficient cleaning following polishing

Why?

Unknown

Why?

Repeated coating

Why?

To incrementally increase coating thickness

Why?

To meet production targets without exceeding a maximum tolerance

Why?

High humidity / low temperature

Why?

Insufficient heating / environmental controls

Why?

Heater / air conditioning unit broken

Why?

Insufficient maintenance

Why?

Excessive thickness of nickel coating

Why?

Excessive dwell time

Why?

Poor process control

Why?

Improperly designed coating process

Why?

Lack of understanding of coating process

Why?

Operator negligence

Why?

Lack of recent training

Why?

Lack of heat treatment

Why?

Minimum heat of 400°C would destroy part

Why?

Causes sweat that leeches lead out of core alloy

Why?

Melting point of lead in core structure at 327°C

Improve

Blistering Prevention

The cause of blistering has been found and rectified without Bodycote's assistance, according to Rolls Royce. This seems to be correct, as the failure chart continuing into 2024 drops off dramatically:

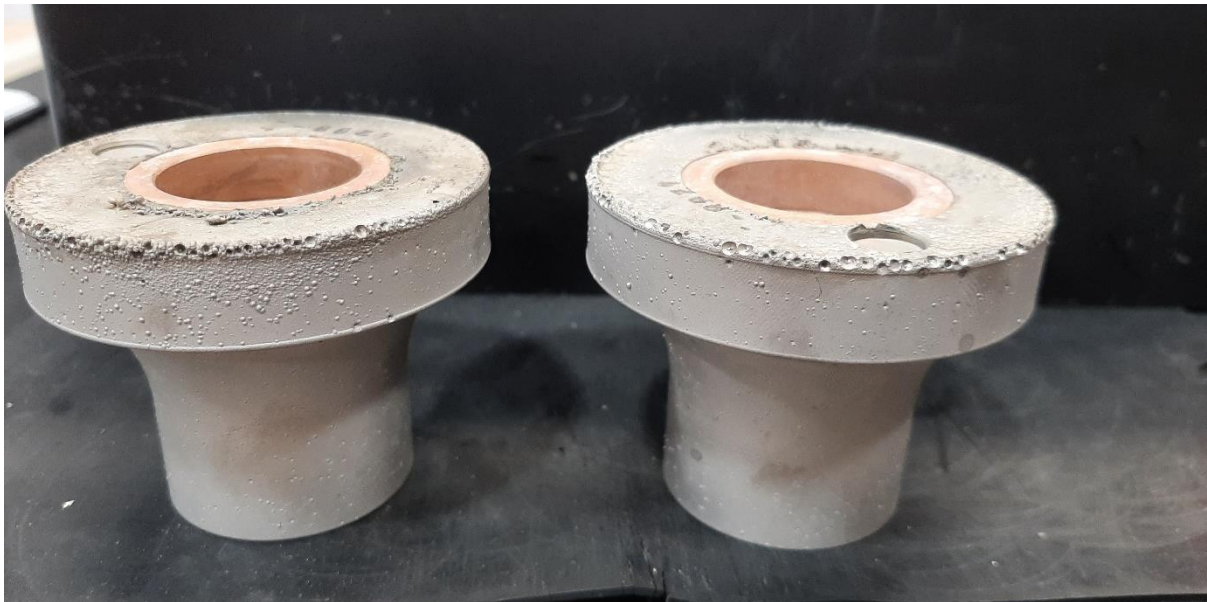
Date	Batch	Part	Okay	Minor Lip	Minor Shoulder	Major Lip	Major Shoulder	Rate of Blistering
25-Apr	203520	290	18					0.00%
29-Apr	203521	549	20					0.00%
29-Apr	203522	549	20					0.00%
30-Apr	203525	277	22					0.00%
30-Apr	203528	277	21		1			4.55%
			2281	5	3	0	0	0.35%

Row Labels	Sum of Okay	Sum of Minor Lip	Sum of Minor Shoulder	Count of Major Lip	Count of Major Shoulder
008	168				
277	372	1	1		
290	410	1	1		
308	24				
466	170				
549	617	2			
555	320	1			
955	200		1		
Grand Total	2281	5	3		

They have not given specific details on the improvement that they have implemented due to the confidential nature of their agreement with Bodycote preventing the sharing of precise details, but the source was found to be "something wrong with the dip coating solution". This suggests that the dip coating/electroless nickel coating procedures and parameters may have been correct, and a contaminant had been introduced such as grease or polishing compounds, but it is also possible that the concentration of reductant in the coating solution was too low, or that the pH of the solution

had risen too high due to insufficient presence or effectiveness of complexing agents. While these factors are understood to primarily affect the nickel deposition rate and their effect on adhesion of the coating layer has not been analysed in the literature review, it stands to reason that a decrease in deposition rate indicates a lower propensity for the nickel to bond to the substrate, which would logically create a subsequent loss of adhesion.

However, it has also been noticed that there has been a considerable increase in pitting in the surface coating of CDS parts; this is a failure mode characterised by holes or pock marks in the surface of varying size. These pits are almost always circular and are more prevalent on the shoulder of the part than on the lip. Thankfully, as the nickel layer exists primarily to assist with the bonding of thermally sprayed aluminium to the lead-bronze core, the surface finish of the layer is not at risk; the pitting is only a direct failure of the part if it causes a through hole and the lead-bronze substrate is visible through the nickel layer. This is much less frequent, although has increased; actual study of the increased failure rate is ongoing.



By studying the causes of pitting in nickel coating, it may be possible to infer what changes Rolls Royce have made to their nickel-plating process. Any change made to reduce blistering that increases pitting seems like a net positive at the current time; pitting is a preferable problem to have compared to blistering, since all blistering is a failure of the part, but pitting is only a problem if the base material is showing. However, additional measure may be required to minimise losses to pitting to counteract the effects of these performed changes.

There are five primary types of pitting based on cause, that have different characteristics:

1. Particle pitting, creating pits that are generally irregular in shape,
2. Gas pitting, which creates pits that are roughly circular,
3. Organic pitting caused by oil or pretreatment chemicals, which usually occurs in clusters and is flat-bottomed,
4. Heavy Metal pitting, which tends towards edges and can penetrate down to base metal,
5. Substrate pitting, which is caused by irregularities in the substrate shape.

(Aleksinas, 2007)

We can immediately discount substrate pitting out of hand as the substrate structure has not been changed. Similarly, Particle pitting seems unlikely as the pits are regular circles in shape, and organic pitting may be unlikely as pitting tends to be distributed and are not flat-bottomed.

Solutions to gas pitting include adding surfactants to lower surface tension of the liquid solution and agitating the solution, to promote the removal of trapped hydrogen gas from the substrate as it is liberated to enable the electroless plating (Aleksinas, 2007). Therefore, it may be the case that Rolls Royce have sought to combat the adhesion issue by decreasing the concentration of surfactants; this would be a practical thing to do, as the presence of surfactants was debatable to begin with due to their use primarily being to improve characteristics that do not seem important in the coating's role, such as surface finish and corrosion resistance. If this is the case, the agitation of the solution such as by vibration or stirring may be a good practice to implement to reduce gas pitting. This would be a reasonably cheap correction to implement and would retain the improvement to adhesion that the removal of the surfactant seems to have brought.

However, it seems far more likely that Heavy Metal pitting is the process occurring; "Alloys such as leaded steel and brass can also pit during EN plating due to presence of their alloying constituents at the surface." (Aleksinas, 2007). It seems logical to assume that the pitting is the result of lead from the lead-bronze substrate coming free of the main body of the substrate is the cause of this issue. This could indicate that Rolls-Royce have implemented a more thorough process for degreasing or polishing of the part before coating that is now liberating lead atoms from the primary structure of the substrate. It would follow that this mechanism is more prevalent on the outer rim of the shoulder region of the part than on the concave neck, as it would be easier to apply higher pressure to this region and create more abrasive action. It would also follow that degreasing and/or washing of the polished part by hand would be less effective for the same reasons, as demonstrated by the remaining blistering shown to be minor and focussed on the neck of the part much more prevalently.

While this correction has clearly had an improvement on the adhesion of the nickel coat if it is the one that had been implemented, a measure should be taken to mitigate the pitting issue. Ideally, the liberated lead molecules should not be allowed to enter the plating bath, which would require the parts to be cleansed more thoroughly before plating (Rudy, 2022). Additionally, the bath should be filtered for contaminants regularly; a 1µm or finer filter is suggested.

Overall, it seems that Rolls Royce's corrections to the process have been to more thoroughly degrease and surface polish the CDS parts, and/or to reduce the presence of excessive surfactants in the coating bath. These have been implemented successfully in terms of reducing the rate of blistering failures, and are inexpensive corrections to implement; however, they have not been brought in line with six sigma levels of variance, and a new issue has arisen in the form of pitting of the nickel coating; these issues will require further investigation, to determine if the taken course of action was correct, and to manage and mitigate the newly introduced failure mode.

By determining the new blister failures per day and multiplying that by the new day measured/365, we get a new cost of blister failure per year of **£8,760**. This means that, provided that the implemented solution costed less than £25,700 per year it was cost-effective. It is likely that adjustments made to the bath solution would be well within this boundary, especially if the concentration has been reduced rather than increase.

Blistering Detection

To combat the low detection rate for blistering, the decision was made to install a part analysis workbench inside the blasting room. This bench is fitted with a light that provides 1400 lux, which is much more than the 1000 lux required for proper part analysis. This allows for the blasting operator to check parts for minor blisters as well as the CDS-1 operator, if both are different. With two pairs of eyes instead of one, it stands to reason that the rate of detection failures for blistered parts will be halved.



Figure 10: The new inspection table.

To coincide with this installation, support technician Mark James had been trained in the visual inspection of CDS-1 parts for minor Blistering.

This installation has the additional benefit of providing the same increased detection power for CDS-2 parts. [Future Process Map if that has changed, revisit FMEA]

Final Failure Mode and Effects Analysis

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		
Nickel Plating	Pitting resulting in base material showing	Scrap Part	10	Entrapment of released hydrogen gas or lead molecules during plating	5	Visual inspection of parts	3	150
Blasting	Blistering	Scrap Part	10	Poor adhesion of nickel coating to the lead-bronze substrate	2	Visual inspection after blasting	2	40
Bond Coating	Part Undersize due to gun flameout	Scrap Part	10	Gun Flameout	3	Regular Gun Maintenance	2	60
Bond Coating	Part Undersize due to gun blockage	Scrap Part	10	Gun Blockage (Major)	1	Regular Gun Maintenance	2	20
Bond Coating	Part Undersize due to insufficient cycles	Scrap Part	10	Insufficient Cycles	1	Guideline on cycles required	1	10
Bond Coating	Part off-colour	None	1	Gun Blockage (Minor)	3	Regular Gun Maintenance	2	6
Top Coating	Part Undersize due to wire jam	Scrap Part	10	Wire Jam	2	Operator on-hand during spraying to prevent jams	3	60
Top Coating	Part Undersize due to insufficient cycles	Part Requires Further Spraying	5	Insufficient Cycles	3	Guideline on cycles required, additional tolerance for adding cycles	1	15
Top Coating	Part Out of Shape	Additional Milling Time	5	Program Incorrect	1	Dry run of program during setup	3	15

As can be seen from the greatly lowered RPN, the blistering issue has mostly been resolved. While examples of blistering occur and remain outside of six sigma standards, their occurrence has been greatly reduced and since the beginning of the year no examples have escaped detection prior to being coated thanks to the new inspection booth. Room for improvement still exists, but the more economic place for Bodycote to focus its improvement efforts would be on tackling the issues present in the bond and top coat.

The addition of the nickel-plating process to the FMEA chart, now that it is better understood, highlights that the presence of pitting is a serious issue that will need to be focussed on; however, as this process is entirely managed by Rolls Royce, all decision on how to proceed remains with them. Bodycote will continue to record and report data on this failure mode to help them make an informed decision.

Control

Blistering Prevention

It is currently unknown what control measures Rolls Royce have implemented to ensure that the issue with the nickel dip solution does not reoccur. However, control measures for the improvements they seem to have implemented are suggested as follows:

- Additional degreasing of CDS parts prior to coating may be either manual, using acetone and a cloth by hand, or automatic, using a vapour degreaser. In the latter case, the settings of the degreaser have presumably been adjusted to correct the blistering fault, and the control measure for the process will primarily be ensuring that the machine is in good maintenance and the settings are not tampered with; a productive maintenance and inspection program should be implemented, ensuring that the machine is brought back up to full and correct working order regularly. If the former, then staff will need retraining on a regular basis to ensure that they do not return to the previous standard of degreasing. Both implementations should already have a stamping and sign off process associated with them on the production tracker, to verify that they have been performed and who by before the batch progresses to coating.
- More thorough polishing than was already being performed will need to be verified to ensure that it continues to be performed properly. Staff will need retraining on a regular basis in order to ensure that they do not return to the previous standard of polishing and to identify and report concerns regarding the functionality of the polishing machine to maintenance, and a productive maintenance and inspection program should be implemented to ensure that the machine is kept at full and correct working order and the operator's concerns are investigated and corrective action taken where necessary. This process should already have an associated stamping and sign off process on the production tracker, to verify that it has been performed and who by before the batch progresses to coating.
- The process of washing parts after polishing needs to be regulated, especially if it has been or needs to be improved to remove excess heavy metal particles such as liberated lead from the substrate surface to prevent heavy metal pitting. Washing is likely done automatically, in which case the same procedures as above apply; regular inspection to ensure that the settings are correct once they have been established via testing, and regular maintenance to ensure that the washing machine is operating effectively. If washing is not already a regular part of the coating process, then it must be added to the production tracker as a stamped-against process to track that it is being completed.
- It was originally theorized that the quantity of reductant in the plating solution may have been too low, or that the quantity of complexing agents may be out of balance resulting in a raised pH which would dissuade nickel bonding (especially in a sodium borohydride bath). Additionally, heavy metals like lead can contaminate the nickel-plating bath solution. These factors together, along with the stated solution found being an alteration to the bath solution, indicates that the monitoring and adjustment process for the bath is insufficient; regular removal and replacing of this solution is advisable, to remove heavy metal particles that may be accumulating, as well as set the concentration of reductant and complexing agents back within acceptable levels. This latter purpose may also be able to correct by

adding additional materials to the existing bath if the lead accumulation is low enough due to a good washing process being implemented. Regular testing should be undertaken to determine a rate at which lead accumulates and the solution mixture degrades, and a rota established to organize top-ups of chemical agents and complete replacement of the bath solution. Both operations need to have responsible members of staff assigned, likely an organizing engineer, the coating bath operator and the maintenance team, and then appropriate intervals for top-up and replacement dated, with a calendar tracker and stamping required by operator and maintenance when the operation is performed.

- The coating bath equipment almost certainly has an existing maintenance schedule, and very little was found that could be at fault in the current system during the literature review. However, additions could be made that would help combat the newly apparent increase in pitting. Two methods exist for controlling this; the addition of a bath agitator such as a vibrator or work-rod agitator to reduce gas cling and prevent gas pitting problems, alongside filtering of heavy metal molecules from the bath. These solutions will require control measures; the agitator will be a mechanical component and require regular inspection for wear and fatigue, and regular testing to ensure that it is performing at the required strength. These processes should be added to the current maintenance program for the bath equipment and require stamping against to ensure they have been completed. A filtration system will also need to be devised if not already present, and regular filter replacement for the bath will need to be organized and added to the maintenance paperwork to be stamped against when maintenance is performed. Thankfully it should be easy to determine whether these control measures are being performed correctly; pitting is currently visible to the naked eye, and so after coating batches can be quickly studied to look for evidence of pitting, and these results recorded and plotted over time; if they start rising, it indicates that better control measures will be needed.

Blistering Detection

There is currently no direct control in place to ensure that the newly installed inspection table is being used as intended by Mark James. It is difficult to determine how the process could be made to absolutely require this step to be completed: however, a managerial control could be easily implemented, as an alteration could be made in the Manufacturing Route Card that accompanies each batch to include a post -blasting visual inspection as well as a pre-bonding one. This would be slightly complicated by two problems:

- The “Inspect and Clean Surface” process already directly follows the “Surface Activation” process. This could be tackled by denoting the two processes as “Inspect Surface - Blasting Operator” and “Inspect and Clean Surface - Bonding Operator.” However, this then lead directly into the second problem:
- It is frequently the case that no support operators are available, and indeed this is standard practice on afternoon shifts. This means that for half or more of all batches, the binging operator is also the blasting operator. While having one operator perform two visual inspections will still increase the detection chance, controlling the process to ensure this in these instances will be nigh impossible, especially during afternoon shifts in which no managers or engineers are on site.

Review

Summary

The purpose of this report was to investigate the possible causes for blistering on CDS parts during the grit blasting process, to quantify the failure rate of these parts and to devise a method to reduce these failures. Significant effort was placed into identifying the cause, which was determined to be a shortcoming in Rolls Royce's nickel-plating method. Information on the exact technique used was sparse, coming second-hand from Bodycote's Ryan Dugmore, but the explanation and extended literature review highlighted that electroless nickel plating was the most likely candidate. Further reading into this subject revealed multiple failure modes that could result in a lack of adhesion that would cause a blistering failure later in the production process, making the true cause of the failure difficult to determine.

The problem was finally resolved separately from the ongoing investigation by Rolls Royce themselves, but this had a knock-on effect of increasing another phenomenon in the parts that could lead to failure. This both highlighted how proper investigation and experimentation is important to prevent knock-on problems like this from occurring and provided a new avenue of research into determining the true cause of the now resolved blistering problem by cross-referencing causal factors of the new pitting problem. While multiple possibilities as to the cause still exist, it has helped devise a short list of potential control measures that Rolls Royce may need to introduce, and some notes on methods they could investigate to mitigate the new issue they have introduced.

With a significant reduction in blistering rate since the beginning of 2024, the goals of this project have been met on what is inferred to have been a very cost-effective budget. However, multiple complications arose during the undertaking of this project, and significant improvements must be made to the management of future projects to mitigate these.

Major Issues

The primary issue encountered during the project was Rolls Royce's refusal to share much information with Bodycote personnel. Nothing specific is known about the methods and parameters used by their nickel coating process, other than what information has been gleaned from Bodycote engineers during prior cooperation in years prior. This lack of information made the initial investigation stage of this project extremely difficult and any sort of final answer on the exact cause of the lack of coating adhesion and a proper solution to it impossible to obtain, resulting in the project requiring a lot more research and literature review to analyse and refine what little guidance Bodycote engineers could provide.

Additionally, Rolls Royce's insistence on minimal modifications to the process has resulted in a lack of experimental data on what could be done at Bodycote's facility. While all available literature does support the notion that the blistering problem is due to flaws in the plating process, tests such as varying the blasting time or changing the grit size might have yielded some further insight into the exact mechanics of the problems and assisted in determining what measures were needed. Instead, Bodycote were instead basically required to do nothing while the problem persisted and merely be content with being reimbursed for each failed part.

Furthermore, during the project a secondary issue arose with the CDS part known as join line separation. This consisted of the nickel-aluminium bond coating applied at Bodycote not adhering properly to the nickel coating that Rolls Royce applied. The exact cause for this is currently unknown; however, the issue was assumed to be a fault at Bodycote's facility despite no changes having been implemented in the CDS preparation or coating processes, and this soured working relationships between the two parties. Communication between the two became impossible on any other issue, resulting in no further possibility of acquiring information regarding the nickel dip process.

Minor Issues

Other issues were encountered besides those involved in working with a second company on this project.

Bodycote engineers were found to not have a good grasp of plating methods in use at Rolls Royce, or their definition or terminology; Bodycote itself is primarily involved with rotary thermal spray coating, grinding and polishing, and the engineers specialize in these fields. Electroplating and electroless chemical plating are not subjects that they are familiar with; this became apparent when the initial explanation of what Rolls Royce's plating process was involved the phrase "something like a dip coat", resulting in research into dip coating and not electroless nickel plating as was needed.

During the project my shift schedule was changed from a five days per week 6am – 2pm morning shift to a four days per week 2pm – 12 midnight evening shift. This did not significantly impact the amount of working time available for the project outside of working hours, and indeed opened the entirety of Fridays. It did, however, severely limit the amount of time that was available per week to discuss project matter with Bodycote engineers; as most Bodycote staff end their shift at 4pm, there became only two hours per day for any face-to-face discussion, in which they were regularly trying to conclude matters from the rest of their shift in readiness to go home.

Conclusions and Recommendations

The primary complications encountered in this project were due to working with an exterior company on a project that they had full control over, requiring little input from myself to plan and so having little incentive to share information. Additionally, the lack of expertise of myself and other Bodycote personnel was a significant issue, requiring a lot of reading on my part to more fully understand the situation and devise a solution.

Going forward, I will endeavour to choose projects that are either wholly or primarily controlled by the company I am directly involved with, and that I can understand the core sciences of or speak directly with another member of staff with good understanding. This will aid greatly in producing a more complete project.

References

- Aleksinas, M. J. (2007, 11 01). *Pitting on Thick Electroless Nickel Deposits*. Retrieved from Products Finishing: <https://www.pfonline.com/articles/lay-it-on-thick>
- Baker, I., Chang, H., & Li, J. (2011). Recrystallization Processing of Cold-Rolled Nickel. *Materials Research Society symposia proceedings*.
- Bonin, L., Delaunois, F., & Vitry, V. (2019). *Electroless Nickel Plating: Fundamentals to Applications*. CRC Press.
- Brinker, C. J. (2013). *Dip Coating*. Albuquerque: Springer.
- Chintada, V. B., Gurugubelli, T. R., & Koutavarapu, R. (2022). The Impact of Surfactants on the Properties of Electroless Ni–P–SiC Coatings. *Materials Chemistry and Physics*.
- Corrosionpedia. (2019, 08 12). *Blistering*. Retrieved from Corrosionpedia: <https://www.corrosionpedia.com/definition/166/blistering>
- Dr. J. Griffin, D. M. (2021, February 11). *Dip Coating: Practical Guide to Theory and Troubleshooting*. Retrieved from Ossila: <https://www.ossila.com/pages/dip-coating>
- Geffcken, W., & Berger, E. (1939). *Verfahren zur Anderung des Reflexionsvermögens optischer Glaser*. Deutsches Reichspatent.
- Gitlow, H. s., Melnyck, R. J., & Levine, D. M. (2015). *A Guide to Six Sigma Process Improvement for Practitioners and Students*. Pearson Education.
- Mahdavi, N., & Sarabi Dariani, A. A. (2022). The Effect of Complexing Agent on Electroless Nickel Sulphamate Coating on Brass Alloy: Structure Characteristics & Corrosion Behaviour. *Journal of Bio- and Tribo-Corrosion*.
- Molegraaf, K. (2018, May 23). *Do You Know What Is Causing Blisters In Your Coating?* Retrieved from Spear Industrial Coatings: <https://spearindustrial.com/know-causing-blisters-coating/>
- Nickel Institute. (2022). *Nickel Plating Handbook*. Nickel Institute.
- Radson, & Boyd. (1997). Pareto Principle and Rate Analysis.
- Rudy, S. F. (2022, May 12). *Electroless Nickel: Problems and Corrective Action*. Retrieved from Finishing & Coating: <https://finishingandcoating.com/index.php/plating/1107-electroless-nickel-problems-and-corrective-action>
- Sahoo, P., & Das, S. K. (2010). *Tribology of electroless nickel coatings – A review*. Kolkata: Elsevier.
- Sarkar, Mukhopadhyay, & Ghosh. (2012). *Issues in Pareto Analysis and their resolution*.
- Savita L. Patil, S. R. (2023). Dip Coating: Simple Way of Coating. In T. B. Deshmukh, *Simple Chemical Methods for Thin Film Deposition* (pp. 425-447). Springer.
- The Council for Six Sigma Certification. (2018). *Six Sigma: A Complete Step-by-step Guide*. Harmony Living.