Minimization of In-Process Corrosion of Aerospace Gears

Son Nguyen, Ali Manesh, Jim Reeves and Danny Mahan

Factors	Level = "+"	Level = "-"
A Condition	Virgin	Reclaimed
B Alloy	Pyrowear 53	9310
C HT Condition	Carburized	Core Material
D Exposure Time	90 Minutes	30 Minutes
E Coolant Concentration	8%	1%
F Coolant Temperature	150°F	70°F
G Coolant Type	Synthetic	Soluble Oil

A	B	C	D	E	F	G	E*G	Hours to Initiation	
-1	1	1	1	1	1	-1	-1	1848	
-1	-1	-1	1	1	1	-1	-1	1848	
-1	1	1	-1	1	1	-1	-1	1847	
-1	-1	1	-1	1	1	-1	-1	1847	
-1	1	-1	-1	1	1	-1	-1	1847	
-1	-1	-1	-1	1	1	-1	-1	1847	
-1	1	1	-1	1	-1	-1	-1	1843	
-1	-1	1	-1	1	-1	-1	-1	1843	
-1	1	-1	-1	1	-1	-1	-1	1843	
-1	-1	-1	-1	1	-1	-1	-1	1843	
-1	-1	1	1	1	-1	-1	-1	1842	
-1	1	-1	1	1	-1	-1	-1	1842	
-1	1	1	1	1	-1	-1	-1	1801	
-1	-1	-1	1	1	-1	-1	-1	1801	
1	-1	-1	-1	1	-1	-1	-1	1395	
1	-1	1	1	1	-1	-1	-1	1394	
1	1	1	1	1	1	-1	-1	1392	
1	1	-1	1	1	1	-1	-1	1392	
1	-1	-1	1	1	1	-1	-1	1392	
1	1	1	-1	1	1	-1	-1	1392	
1	1	1	-1	1	1	-1	-1	1392	
1	1	-1	-1	1	1	-1	-1	1392	
1	-1	-1	-1	1	1	-1	-1	1392	
1	-1	1	1	1	1	-1	-1	1338	
-1	-1	1	1	-1	1	-1	1	1319	
-1	-1	-1	1	-1	1	-1	1	1319	
1	1	1	-1	1	-1	-1	-1	1224	Treatment Run Example
-1	-1	1	1	1	1	-1	-1	1220	
-1	-1	1	-1	-1	1	-1	1	1204	

Figure 1—Partial Experimental Matrix With Screening Analysis.

Introduction

Carbon steels have primarily been used to manufacture aerospace gears due to the steels' mechanical characteristics. An alloyed low carbon steel is easily case-hardened to obtain a hard wear surface while maintaining the ductile core characteristics. The microstructure achieved will accept the heavy loading, shocks, and elevated temperatures that gears typically experience in applications. The carbon steel machinability allows for general machining practices to be employed when producing aerospace gears versus the more advanced metal removal processes required by stainless and nickel-based alloys.

As a consequence of using non-stainless steel for gears, in-process corrosion (rust and chemical attack) of gears is possible during the manufacturing process. Surface corrosion of carbon steel gears and shafts can lead to unacceptable stress risers in the material if action is not taken to remove the surface pitting and neutralize the cause. Once the corrosion effect begins, it will continue to attack the grain boundaries of the material. The result is reduced mechanical properties of the alloy that can lead to component failure at performance levels well below typical operating conditions.

Prior to this project, the corrosion problem was minimized by the use of oil-based preservatives and rust-inhibiting machining coolants. However, as the negative effect on exposed production workers and the environment was better understood, and with disposal costs escalating, the gear manufacturing industry changed to water-based coolants and degreasing agents. This

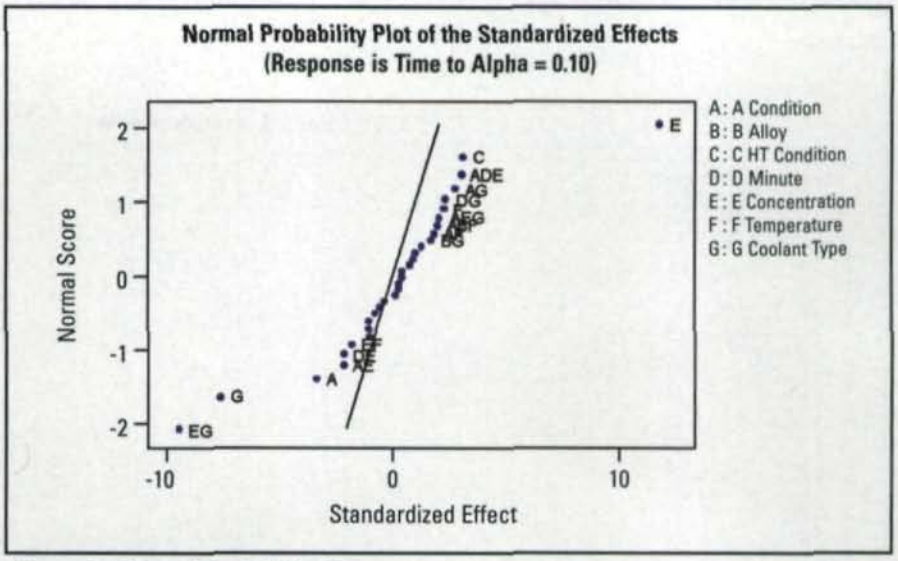

Figure 2—Normal Probability Plot.

shift was immediately followed by an increase in rust. The result was more costly gears from increased rework, scrapped gears, increased preventative activities and manufacturing flow inefficiencies due to out-of-sequence processing. The replacement of corroded gears created additional delays. Corrosion of gears in the manufacturing environment continued to plague the entire gear industry; therefore an investigation to minimize the corrosive effect was warranted.

Objectives

The objectives of this project were to identify the root causes of the observed in-process corrosion of gears and to develop preventative practices to mitigate its occurrence during the manufacturing of gears.

Specifically, the objectives were:

- Utilize advanced manufacturing tools, such as statistically designed experiments, process flow charts, and failure modes and effect analysis (FMEA) to systematically study the potential causes of the in-process corrosion.
- Evaluate the impacts of chemical attack and residual coolant on corrosion, including the investigation of an adapted on-line Digi-Galv probe as a predictive tool.
- Identify and implement preventive practices to reduce in-process corrosion.

Approach, Scope, and Methodology

This project was conducted in two phases: Phase I was to identify root causes of in-process corrosion by conducting a comprehensive study, using manufacturing process bench marking, at two gear production facilities. The Phase I study was augmented by controlled laboratory experiments. The desired end product of Phase I was to understand the sources of corrosion on gears during the manufacturing process and to identify solutions to minimize the corrosion problem. Phase II was to implement the identified solutions to a restricted area of the manufacturing floor to test them in a production environment.

Phase I involved defining the boundaries of the gear making process, developing detailed process maps that describe all of the steps required to produce the gears, verifying the actual inputs at each process step, and performing the failure mode and effects analysis (FMEA) to assess priority of the process parameters. After the process conditions that could potentially be contributing to corrosion initiation were identified and prioritized, the design of experiments were planned and performed.

For the process mapping, the boundary of the study was established from raw material handling through final inspection of the part. Typical manufacturing process steps for gears included turning, cutting, hobbing, deburring, grinding, heat treating (Cu plating, carburizing, stripping), lapping, shot peening and inspection. Three gear parts (spur, helical, and planetary pinion) were selected from two separate gear manufacturers as a result of the process mapping described above. These parts provided the basis for detailed evaluations of the significant manufacturing steps that were likely to initiate in-process corrosion. In addition, parts selected were made out of common base materials that are widely used in the aerospace industry to manufacture gears. The materials selected were 9310 (AMS6260, AMS6265) and Pyrowear X-53 (AMS6308) steels.

When the part selection and verification of the manufacturing steps were completed, the FMEA was used to evaluate the process inputs. The FMEAs allowed the team to prioritize process inputs that could contribute to corrosion initiation. Process control charts and the FMEA were used to identify and rank the suspect inputs to be tested.

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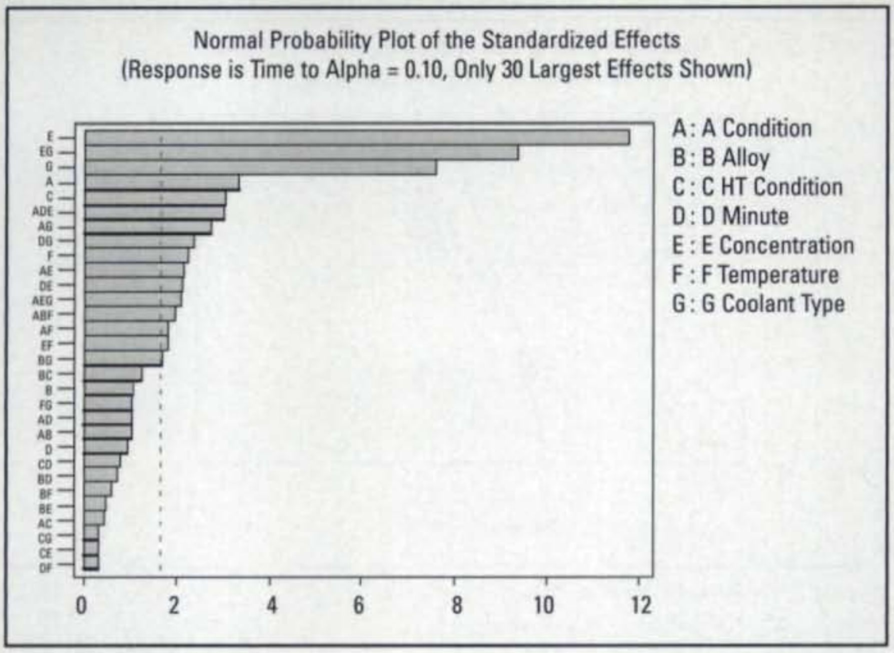


Figure 3—Pareto of Effects.

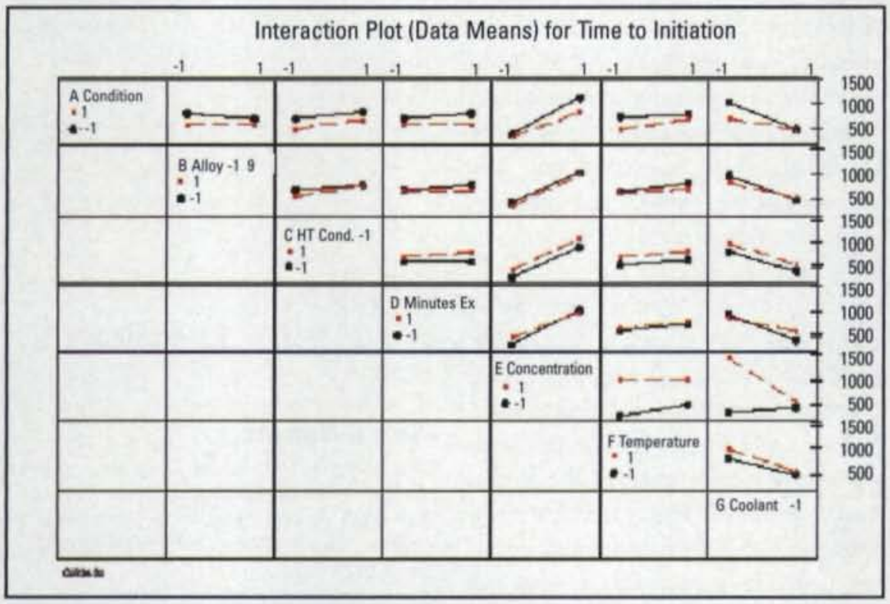


Figure 4—Interaction Plot.

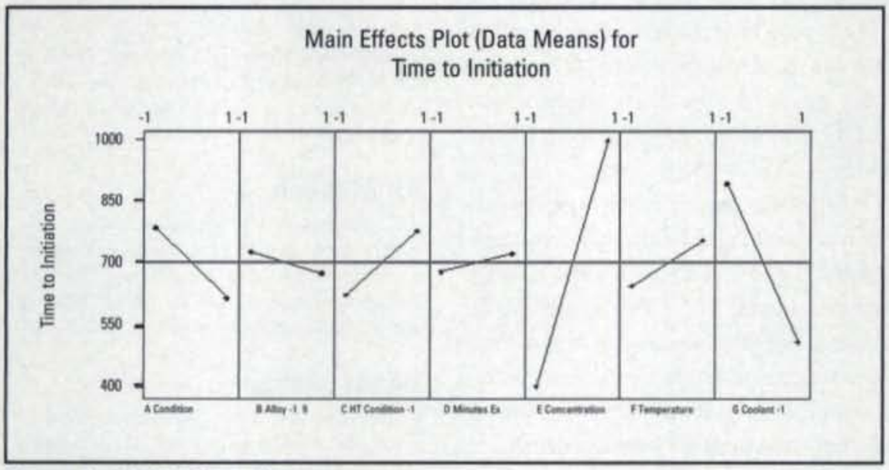


Figure 5—Main Effects Plot.

After a comprehensive investigation, the coolant was identified as one of the key process inputs that may be contributing to corrosion initiation. Multiple potential failure modes were identified for the coolant along with multiple possible interactions. Key factors identified after control chart and FMEA analyses were: coolant concentration, coolant temperature, exposure time, coolant type, coolant contamination and material heat treat condition.

Once the team had narrowed the list of potential corrosion initiation factors, the first DOE design strategy began. The strategies for the design and factor level settings are detailed in Figure 1. Factors selected for testing are: (A) coolant condition (virgin and reclaimed), (B) specimen alloy (Pyrowear X-53 and 9310), (C) specimen heat treat condition (carburized and uncarburized), (D) exposure time to coolant (90 and 30 minutes), (E) coolant concentration (8% and 1%), (F) coolant temperature (150° and 70°F), and (G) coolant type (synthetic and soluble oil). Refractometer readings were used as a measure of coolant concentration.

Phase II commenced in parallel with the DOEs as information became available from Phase I to speed up the verification of benefits resulting from implementation of the identified solutions. Examples of the success of this approach were the implementation of a new coolant in one gear facility and the resolution of the chemical attack problem noted on the gear line.

Discussion of Results

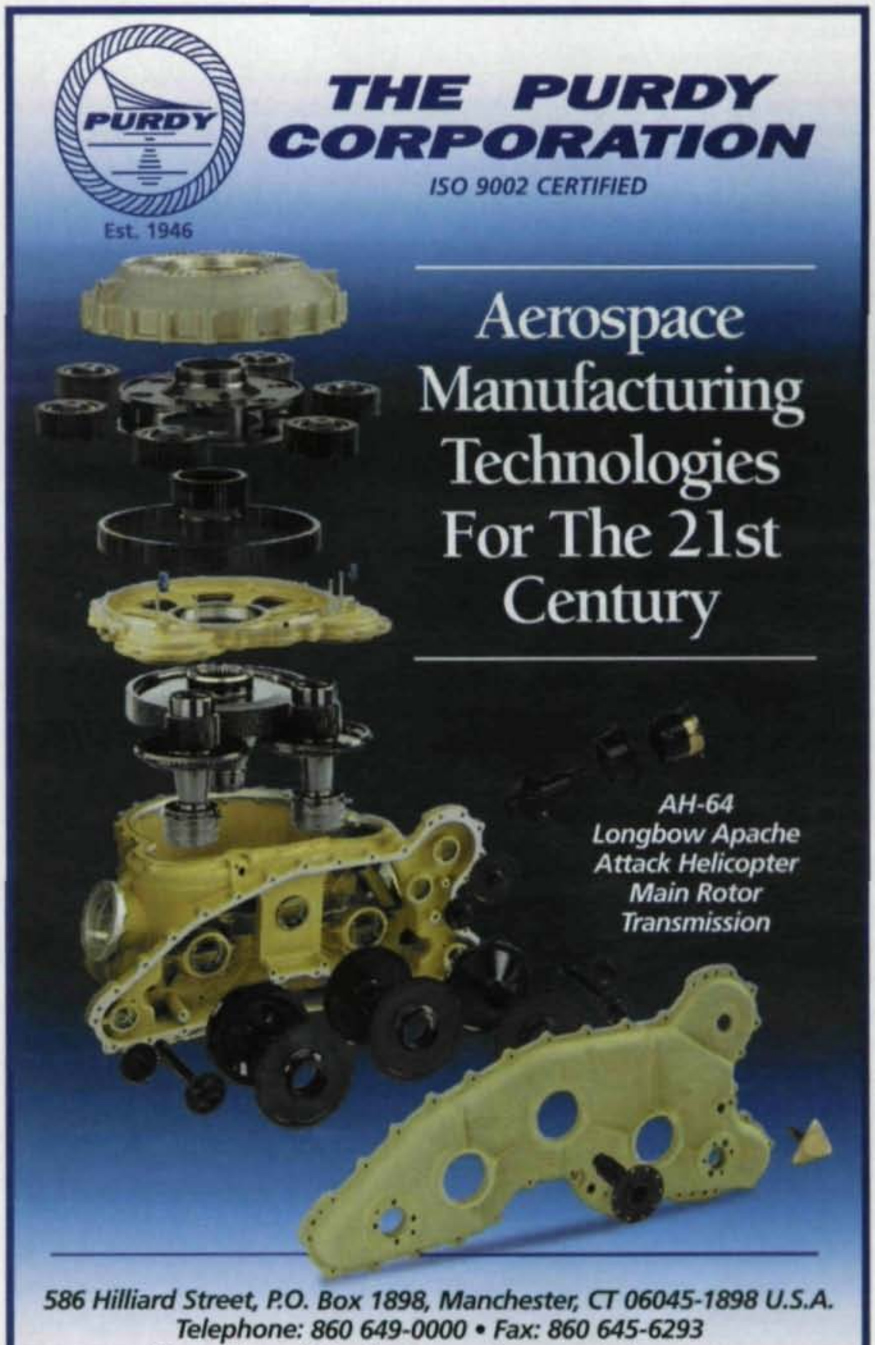
The DOEs were conducted at Honeywell Engines & Systems facility. The steel specimens were subjected to prescribed conditions identified in Figure 1. An example of a treatment run in the matrix was to soak a carburized Pyrowear X-53 specimen in an 8% concentration virgin soluble oil coolant at 70°F for 30 minutes. The specimens were then loaded into a humidity chamber that was set at 80°F and a relative humidity level of 70%. These samples were monitored twice daily for corrosion initiation. When corrosion initiation (response) occurred, the time (hours) to initiation was recorded and used for the experimental analysis.

Upon establishing the hours to corrosion initiation on the specimens, analyses of the experiment results were performed. A screening analysis was performed by sorting the hours to initiation in ascending order and evaluating the experiment matrix for any patterns. The visual pattern shown in Figure 1 that appeared to be significant is: coolant type, coolant condition, and an interaction between coolant concentration and coolant type. A statistical analysis was next performed. The normal probability plot and the Pareto of effects shown in Figure 2 and Figure 3 respectively, identified the same factors as being significant. Figure 4, the interaction plot, showed the coolant type by coolant concentration as the most significant interaction in the model. The main effects plot, Figure 5, indicated that coolant concentration and coolant type had the greatest effect. An analysis of variance (ANOVA) confirmed the results reported above as statistically significant. Based on the data, virgin and low concentration coolants are predicted to initiate corrosion more quickly than reclaimed and higher concentration coolants.

Heat treat condition also affected the initiation of corrosion in that high carbon (carburized) surfaces were more resistant to initiation as compared to core (uncarburized) surfaces. It was also synthesized from the data set that used/reclaimed coolants offered better corrosion resistance than the virgin mix in both synthetic and soluble oil coolants. The data also supported using the soluble oil coolant as the preferred cutting fluid. As a result of the experiment, the soluble oil, water-based coolant was implemented in the gear production area as part of Phase II work.

Based on the results of the first DOE, the strategy for the second experiment was developed. The factors selected for this experiment were: coolant concentration (3% and 6%), base material magnetism (0 gauss and 10 gauss), specimen surface finish (6 Ra and 36 Ra), iron particles in coolant (clean coolant and particles added), specimen raw material heat lot (heat lots 1 and 2), specimen heat treat condition (carburized and uncarburized), specimen alloy (9310 and Pyrowear X-53), degreasing solvent condition (virgin and used), and preservative oil application (four-minute soak application and spray application). At the suggestion of manufacturing personnel, the additional factor that was added to the DOE was the method of preservative oil application. Previous process mapping analysis revealed that a typical lot of gears could go through the preservative soak cycle 24 times. If the soak cycle could be replaced by a spray or quick immersion with the same result, significant savings in cycle time and cost could be realized.

With the factors and level settings established, the DOE was executed as described previously. However, there was no corrosion initiation observed on the samples after six months. The experiment indicated that the factors tested would not initiate corrosion, provided a coating of preservative oil was applied, regardless of



Run Order	Copper oz/gal	pH	Exposure (min.)	Attack
7	1	1	-1	1
1	-1	1	1	1
2	1	1	1	1
6	-1	1	-1	1
8	1	-1	-1	2
4	-1	-1	-1	2
5	1	-1	1	3
3	-1	-1	1	3

Factors	Level = "+"	Level = "-"
pH	10.3	8.6
Copper oz./gal.	9.9	6.3
Exposure time (min.)	90	45

Figure 6—Alkaline Strip Experiment Matrix.

Figure 7—PCI-Win Probe System.

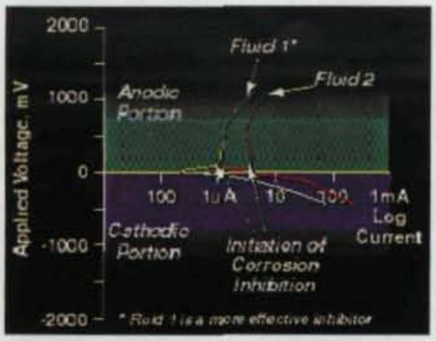


Figure 8—PCI-Win Sweep Output.

application method. Based on this result, the manufacturing specification was modified to only require a quick immersion in lieu of a four-minute soak. The practice was quickly implemented in Phase II.

Chemical Attack

During the project, a large quantity of gears were exhibiting a pitted condition at the machining operations in various areas. After metallurgical examination, it was determined that the pits were a result of chemical attack/corrosion. Since the machine cutting fluids, cleaning and preservation factors had been previously tested in Phase I, they were quickly dismissed as the root cause. This allowed the team to focus the investigation in the plating facility. The key factors were identified through a thought process mapping exercise. Possible initiators of the attack were alkaline pH, exposure time, and the ounces of copper in the alkaline strip solution. An experiment was designed to test these factors on 9310 steel specimens as shown in Figure 6. Analysis of the experiment identified pH as the factor with the highest significance. Data also indicated when the pH level was greater than 10, chemical attack did not occur.

For phase II implementation, the team installed a controller on the alkaline strip tanks to maintain the tank pH levels above 10.3, by automatically adding anhydrous ammonia when the pH level dropped below 10.3. It was noted that during the anhydrous ammonia addition, an exothermic reaction occurred, heating the solution to temperatures above 100°F. The problem identified with the elevated temperature was that when the alkaline stripping solution reached temperatures above 77°F, it became corrosive to carbon steels. The team installed a chilling unit in the stripping tanks to stabilize the solution temperature at 60°F. After installing the chiller and maintaining stable pH levels at 10.3–10.7, no chemical attack on an entire lot of gears has occurred due to pH imbalance as a root cause.

Residual Coolant

Early in the project, it was determined by extensive laboratory testing that water-based machining coolant was an effective corrosion inhibitor. Low carbon alloy gears coated with a film of in-process coolant did not corrode after two months in the high heat and humidity test chamber.

The results of this testing were:

- Used coolant is not a corrosion enabler.
- The coolant solution's ability to form a protective film barrier on the surface of the part determined its ability to inhibit corrosion. Whether this film came from virgin or in-process coolant was irrelevant.
- If a film was not left on the part by the coolant after the machining operation and it was not properly treated with a preservative oil, then corrosion was enabled. Such corrosion resulted in increased manufacturing costs and lead times.
- A corrosion-protective film could be formed after processing through either the coolant or preservative solution typically applied during the manufacturing process.

Test results indicated that residual coolant would leave a short-term corrosion inhibiting film on the gears similar to the ones resulting from immersion in an oil bath. This residual film could reduce the incidence of corrosion even if the preservative oil was not applied. If the proper fluid attributes could be measured and maintained, not only would costly corrosion initiation be greatly reduced, but the corrosion prevention steps (preservative baths) could also be decreased or eliminated.

On-line PCI-Win Probe

A significant barrier to relying on residual coolant as an effective short-term corrosion inhibitor is determining if the coolant has the proper attributes. Standard corrosion testing takes too long to give usable information in an on-going production environment. For example, this testing procedure would take approximately 48 hours to complete at added cost for coolant analysis. The team's goal was to find a tool to provide real time sump-site testing to predict the coolant's corrosion inhibiting properties.

After further research, the team decided on the use of an adapted Digi-Galv probing system, PCI-Win Probe, similar in operating principle to the ones used in the oil pipeline monitoring industry. The probe has the potential to provide quick indications of a coolant's corrosion-inhibiting capabilities.

The PCI-Win Probe system shown in Figure 7, consists of a small test cell (specimen housing and electrode), a digitally controlled dual range precision instrument unit, and a standard Pentium desktop PC with the AMPLICON PC30AT card and associated software installed. In addition, three accessories are added: a glass sleeve sample vessel, a constant temperature water bath with tubing to allow flow through the glass sleeve, and a pump to provide circulation of the sample. The accessories create a testing environment that simulates the actual conditions under which the coolants perform in the metalworking machines.

The PCI-Win Probe effectively measures the electrical resistance between the probe and metal specimen while both are submerged in the coolant being analyzed. The resistance represents the film formed by the coolant on the specimen. The higher the resistance, the more complete the coverage and the thicker the film. This resistance is measured and graphed by the PCI-Win Probe system, in the form of a "sweep" shown in Figure 8. The sweep consists of two parts, cathodic and anodic. The anodic portion (above the X-axis, or positive voltage values) of the sweep indicates the rust preventative (RP) packages of the fluid. The longer the curve remains in the vertical upswing, the better RP packages in the fluid. Also, the further to the left that the inflection point occurs, the better RP in the fluid. In general, an inflection point at or to the left of 10 µA indicates a fluid that is considered to be a good inhibitor of rust. As the RP package weakens, the sweep tends to trail off toward the right. If no inflection point occurs at all, and the sweep continues flatly toward the right, it demonstrates that the fluid's RP properties have depleted and are providing very little, if any, rust protection.

Using two common gear materials, laboratory testing of five water-based metalworking coolants and validation testing of two coolants were completed. Sample testing was done at Honeywell Engines and Systems. Ten machines were strategically selected to provide a broad range of machining processes and coolant conditions. In total, 10 weeks of tests were run with the two conditions for 9310 alloy and three weeks of tests were run with the two conditions for Pyrowear X-53 alloy. The purpose of the test was to validate previous results and to directly correlate the data gathered in the sweeps (location, initiation of inhibition) to the daily concentration, pH, bacteria, and total dissolved solids (TDS) levels.

The results obtained in the lab did agree with the Phase I results. In comparing the PCI-Win sweeps, it was evident that the FUCHS PT-97 soluble oil coolant was a better corrosion inhibitor than the ChemTool CT-757 synthetic coolant. Not only did the coolant type make a difference in sweep location and shape, the type of alloy was also a factor. For the Pyrowear X-53 alloy, the sweeps were shifted far to the right. In the DOE phase of this project, metal coupons made of Pyrowear X-53 and 9310 were placed in a humidity chamber and monitored for the initiation of corrosion. The Pyrowear X-53 coupons exhibited corrosion initiation before the 9310, which correlated to the PCI-Win findings. Additionally, it was clear that routine concentration, pH, bacteria, and TDS testing did not predict performance of rust inhibiting packages in coolants.

The PCI-Win Probe system did show an ability to differentiate between the two fluids' corrosion inhibiting performance. However, in its current form, the PCI-Win system is best suited for a laboratory envi-

ronment. Additionally, because of several equipment stability issues, the team decided that it was not robust and precise enough to implement for production floor use. More testing and evaluation were required. As further research and development is conducted, it is expected that this technology could become a useful predictive tool for both lab and production environments

Conclusions

When corrosion occurs during the manufacturing of gears, production costs associated with scrapping or rework escalate, and product delivery delays are likely due to the disruption of work flow within the product lines. Based on this project, the key parameters and preventative practices to minimize corrosion during the manufacturing of aerospace gears have been identified as follows:

- Coolant condition, type, and coolant concentration are the major factors effecting the initiation of in-process corrosion. In this project, low concentration and virgin coolants will initiate in-process corrosion more rapidly than higher concentration and reclaimed coolants.
- With respect to inhibiting in-process corrosion, soluble oil coolant performed better than synthetic coolant.
- Carburized surfaces are more resistant to corrosion initiation than uncarburized surfaces.
- Corrosion protection results are similar, regardless of the preservative oil application method, quick immersion or several minutes' soak.
- The alkaline strip step in the plating process is a major source of chemical attack. Maintaining pH levels between 10.3–10.7 and fluid temperature at 60°F maximum in the alkaline strip tank will minimize the potential for chemical attack on gears.
- Residual coolant can be an effective short-term corrosion inhibitor, thereby eliminating the time-consuming and costly oil preservative steps during the manufacturing of gears. The key to implementing this practice is to have a reliable method of monitoring the coolant conditions.
- The PCI-Win Probe system has the potential of characterizing the corrosion inhibitor characteristics of a coolant.

Recommendations for Future Work

Additional work on developing the PCI-Win Probe system as an online coolant tester is recommended. Once the coolant's corrosion inhibitor property is ascertained through online testing, the possibility exists to eliminate the preservative oil altogether and rely solely on the residual coolant as an effective short-term corrosion inhibitor. Suggestions for improvements to the PCI-Win Probe system include the following:

- The calomel electrode should be manufactured to a tighter tolerance.
- A calibration method must be developed for the PCI-Win Probe system to improve accuracy.
- The probe assembly should be repackaged to be more rugged and portable.

Acknowledgment

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