Coated Rivet Dies: A Dramatic Improvement in Rivet Interference Profile

2016-01-2084
Published 09/27/2016

Curtis Hayes
Electroimpact Inc.

CITATION: Hayes, C., "Coated Rivet Dies: A Dramatic Improvement in Rivet Interference Profile," SAE Technical Paper 2016-01-2084, 2016, doi:10.4271/2016-01-2084.

Abstract

Successfully riveting aerospace fatigue-rated structure (for instance, wing panels) requires achieving rivet interference between a minimum and a maximum value in a number of locations along the shank of the rivet. In unbalanced structure, where the skin is much thicker than the stringer, this can be particularly challenging, as achieving minimum interference at the exit of the skin (D2) can often be a problem without exceeding the maximum interference at the exit of the stringer (D4). Softer base materials and harder, higher-strength rivets can compound the problem, while standard manufacturing variations in hardness of part and rivet materials can cause repeatability issues in the process. This paper presents a solution that has been successfully implemented on a production commercial aircraft. The application of a special coating on the stringer side die dramatically reduces interference at the exit of the stringer, which in some instances resulted in a reduction of over 38%. This allowed an increase in forming force to increase interference at the exit of the skin and made for a much more robust process. As well, variability of the process due to material and rivet variation was reduced. Comparisons of industry-standard uncoated, polished steel dies vs. the new, coated dies will be shown to illustrate the improvement in interference and process reliability.

Introduction

Two of the major challenges associated with riveting fatigue-rated structures are achieving the proper interference levels and developing a robust process. The required interference levels are defined by engineering specifications. However, as with all things, simply achieving the requirements once is not a solution. This is where a robust process comes into play. “Robust” being defined here as having the average interference +/- 2.5 standard deviations fall within the engineering-defined minimum and maximum levels for a particular rivet. Of the two challenges, obtaining a robust process can be the harder of the two. Having an average interference within range of the requirements is not enough if the standard deviation of the samples is too high. At some point, the process will go out of tolerance and there will be failures. Having a robust process means achieving the requirements with a high confidence in the repeatability of that process.

Developing a very robust process is critical because it allows for rivet interference sampling. Without sampling, every diameter and rivet grip length combination must be inspected prior to the machine being allowed in production on each panel. This inspection is very time consuming and, with ever-increasing production rates, has a significant impact on machine utilization and product flow. Sampling of rivet interference significantly reduces or eliminates machine down time due to this inspection process. Introduction of coated stringer side dies has resulted in significant improvements to the rivet interference profile and process repeatability and has allowed for rivet interference sampling.

Background

Rivet interference is defined as the amount the rivet expands the hole during the forming process. Since it is currently impossible to determine the amount the rivet has expanded while it is in the part, the standard industry practice is to install the rivet in a coupon that represents wing skin and stringer materials. The rivet is then cut out of the coupon and the diameter of the rivet is measured in up to five different locations, depending on the engineering requirements (Figure 1). These measurements are compared to the countersink and hole diameters to calculate the rivet interference. The required interferences are controlled by process specifications and vary depending on the airplane model being produced, the process used, the diameter and grip length of the rivet, and the location on the airplane (upper panel, lower panel, outboard wing, center section etc.).

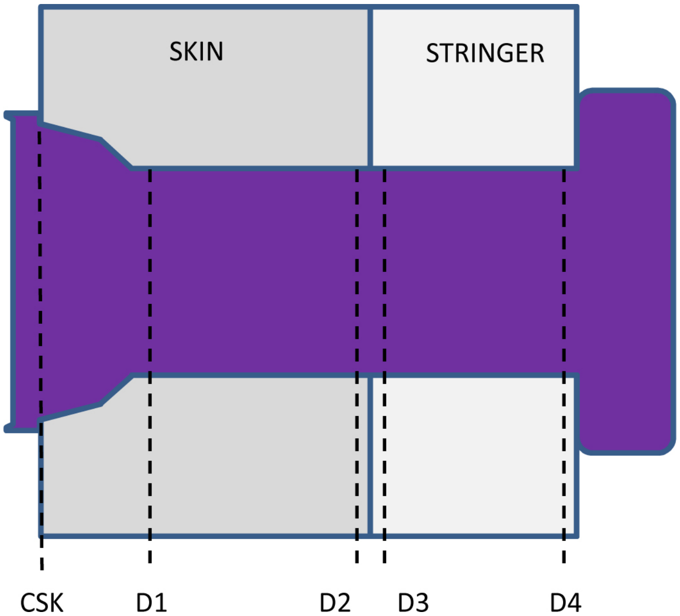

Figure 1. Rivet Interference Measurement Locations

During process development there usually is a struggle to achieve enough interference at the exit of the skin (D2) while keeping countersink interference and interference at the exit of the stringer (D4) from going too high. How difficult this is depends on the design of the structure (part thicknesses), skin and stringer materials, rivet material, and the engineering requirements. Two design features are very significant: total thickness to rivet diameter ratio (T/D ratio) and the ratio between skin and stringer thickness (skin/stringer ratio). In stacks where the thickness is large relative to rivet diameter (very high T/D) and/or the skin is much thicker than the stringer (very high skin/stringer ratio) it is difficult to achieve adequate D2 interference while keeping countersink interference and D4 interference from exceeding allowed maximums. Adequate interference at D2 is achieved primarily through force and changes to the rivet upset profile. As force is increased to achieve adequate interference at D2, the interference at both the countersink and D4 will increase to sometimes-unacceptable levels.

Problem

Difficulties with qualification were encountered while implementing a riveting machine on an existing commercial aircraft application. The structure skin/stringer ratio for some rivets was high, the rivets were being changed to a harder alloy, and the structure was lower-skin (2000-series) aluminum, relatively soft. These three things combined to make achieving proper interference values and low standard deviations very difficult. With much work process settings were developed that seemed to achieve the goals.

Despite valuable information and process knowledge being developed during qualification testing, it was not possible to test for all of the variables that arose once the machine entered production. During a trial implementation, it was quickly realized that the process was not robust enough to allow for sampling. While the average interference at the exit of the skin (D2) was above the minimum level, the standard deviation was too big, virtually guaranteeing a failure at some point. We found the same with the interference at the exit of the stringer (D4), where it was under the max value, but the standard deviation was such that we were likely to see a high failure. Of course, if the averages are far enough from the limits then high standard deviations can be withstood. Unfortunately, we were unable to achieve this.

To overcome the variation in interference levels, there was continual development of the process settings to help drive D4 interference down. Even with the variations of interference levels, the fatigue specimens that were run exceeded the required life levels. With this work, the system was able to enter production.

In these early days of production, a number of issues were identified that impacted the ability to achieve proper rivet interference and a small standard deviation. Examples include lot-to-lot variation of the rivets (hardness and shear strength), interference coupon variation (material and processing), drilling lubrication repeatability, and machine upset repeatability.

Discovery

During troubleshooting of a suspected contamination event, some oil was found in a part of the fastener feed system. The machine was experiencing large variations in interference at the exit of the stringer (D4). Some quite unexpected results were found during testing to determine if the oil was the cause of the variations. As expected, if the hole or the rivet were lubricated with the suspect oil then the rivets showed excessive interference. However, very unexpectedly, it was found that if only the tip of the rivet was contaminated then the interference at the exit of the hole actually dropped significantly while the interference at the exit of skin (D2) dropped only slightly or not at all. This indicated that if the die, and only the die, was lubricated, interference at the exit of the stringer (D4) would drop. This was quite unexpected because all of our experience has shown that lubrication is the cause of an increase in interference, never a decrease. To test this theory a small amount of Boelube was applied to the surface of the stringer-side die. This resulted in the same beneficial effect of a reduction in interference at D4 (Figure 2) as was seen in applying the contaminant oil to the rivet die. A drop of D4 interference to 50% of the expected level was an effect never previously seen.

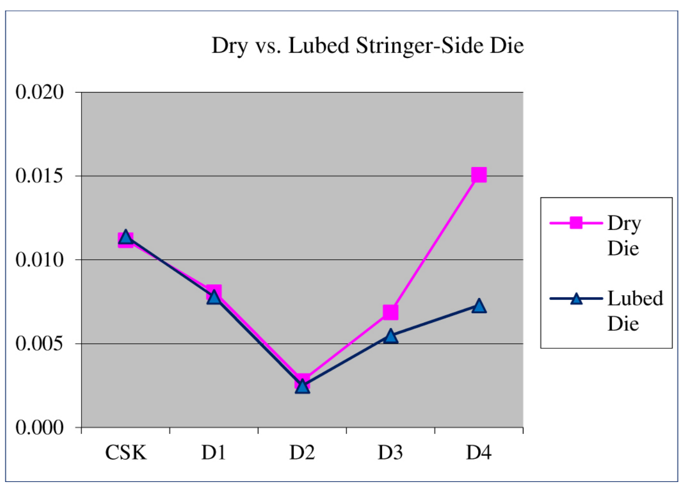

Figure 2. Dry vs. Lubricated Die

To check this result, we applied Boelube to the shank of the rivet, in one case, and the hole, in another. As expected, the interference was greatly increased in both tests. From this, we concluded that the benefit was achieved solely by reducing lubricating the stringer-side die.

We concluded that the effect of the lubricant was to reduce the coefficient of friction between the rivet and the die. The hypothesis is that reduced friction allows the tail of the rivet to more easily flow radially. With less radial constraint, the amount of force to expand the rivet in the hole at D4 is reduced, reducing the D4 interference level. The additional hypothesis is that there is no effect on interference at the exit of the skin (D2) because of friction down the length of the hole has already "locked-in" the D2 interference by the time the tail of the rivet is being significantly formed.

Because of the significant beneficial effect of a lubricated die, the effort turned to how to put this knowledge to our advantage. It was quickly decided that lubricating the die would be impractical. Besides the difficulty of implementing such a solution, there was a significant risk of contaminating both the rivet and the hole, which would negate the benefits of the lubricant on the die.

Since applying lubricant was impractical, would it be possible to find a coating that could be applied to the die that would have a very low coefficient of friction and serve the purpose of a lubricant? Coatings are used throughout industry on drills and tooling primarily to improve tool life by reducing abrasive wear. Rather than tool life, it was hoped a coating could be found that could improve the forming process through a reduction in friction.

DLC Coatings

During the initial investigation, it was quickly realized there are a very large number of coatings available. Most coatings in the metalworking industry are used to improve cutting performance and/or improve life. Low friction is not typically a constraint. Looking outside of the metalworking industry, one of us found that in the automotive racing industry, one coating in particular stood out as being a possibility: the DLC, or Diamond-Like Carbon, coating.

In top-level automotive racing (Formula-1, for example), DLC coatings are used to improve surface life through its extreme hardness and wear resistance, and to reduce frictional losses due to its very low coefficient of friction. Very high stress areas like piston pins and camshaft followers will often be coated. Surface stresses in camshaft followers are extreme and we considered that the condition might be similar to the stresses seen on a rivet die during forming. This led us to want to test the DLC coating.

A number of potential suppliers were found with a number of variations of the DLC coating. Most advertise a coefficient of friction value of 0.1 (friction coefficient against polished steel). There are at least seven different forms of DLC and multiple suppliers. Based on the urgency of the problem, rather than performing an extensive investigation, it was decided to start the investigation with one supplier's offering. For a variety of reasons, it was decided to try the coating with the highest hardness (to give the longest life), lowest coefficient of friction, and was the thinnest (to minimize marking effects if the coating flaked off). The hardest, strongest, and lowest-friction DLC coating is known as tetrahedral amorphous carbon, or ta-C.

Initial Results

Initial testing showed a significant improvement in a number of areas. First, and most important, was a dramatic reduction in interference at the exit of the stringer (D4) (Figure 3). The reduction in D4 interference was as much as 38% compared to an uncoated die. Second, the rivet process repeatability was significantly improved where the standard deviation between rivets was reduced by as much as 70%. Finally, the process showed a reduction in sensitivity to other variables. The process is now much less sensitive to rivet variation, coupon variation, and minor variations in lubricant supply. How much of the reduction in standard deviation was due to a reduction in sensitivity to these items is unknown, but it is suspected that this is the primary driver of the improvement in standard deviation.

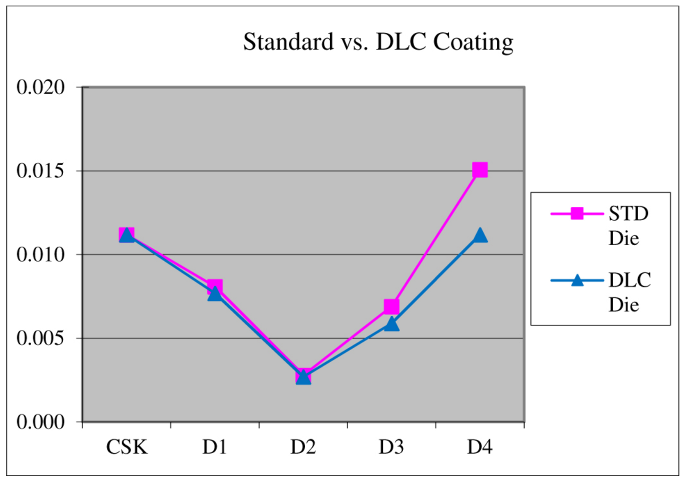

Figure 3. Standard vs. DLC Coated Dies

While the reduction in interference at the exit of the stringer (D4) was not as significant as that achieved with lubrication of the die, the reduction was enough to greatly improve the production capacity of the equipment.

Prior to production implementation, a series of fatigue tests were performed to make sure the changes in the process did not have a detrimental effect on the fatigue life of the airplane. In all cases, the fatigue life was comparable to the life achieved with the standard non-coated dies.

Additional Benefits

The significant reduction in interference at the exit of the stringer (D4) and the improved repeatability has allowed for changes in the process that improve interference at the exit of the skin (D2) and countersink interference. D2 interference was improved by increasing force and modifying the rivet upset profile without risking D4 interference increasing too high. In a few cases, the increase in force negatively impacted countersink interference (Figure 4). This was solved by changing the skin-side die geometries to reduce the countersink interference (Figure 5).

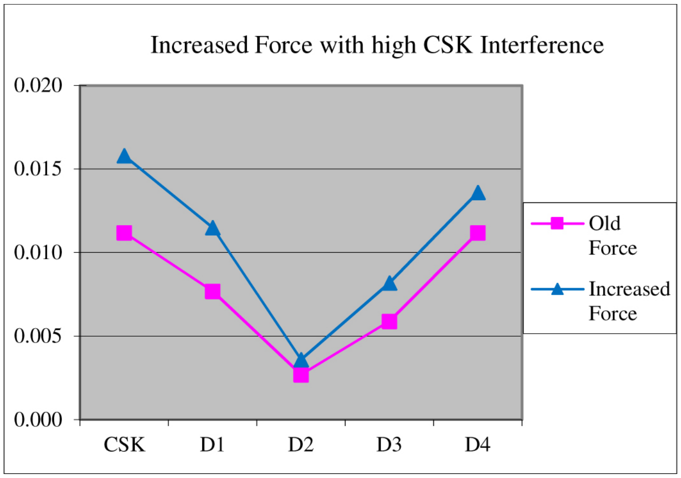

Figure 4. Improved D2 Interference

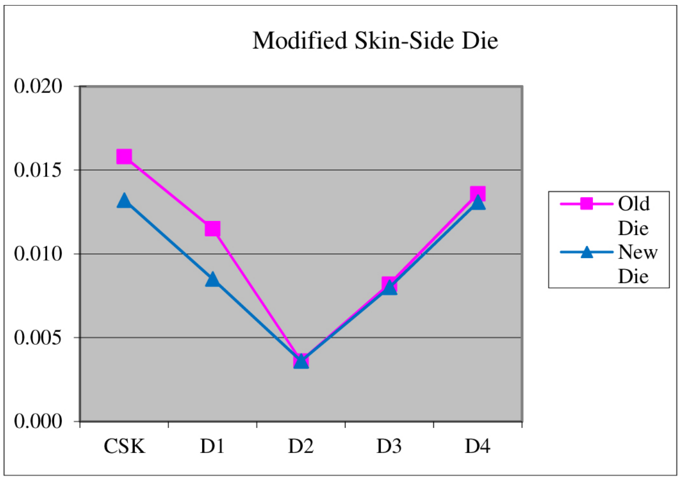

Figure 5. Improved CSK Interference

Other Issues and Significant Findings

Force vs. Benefit

An important finding was, in general, the greater the force, the greater the benefit. The dies showed the most improvement with the largest diameter rivets. This is important because this size is the hardest to achieve adequate rivet interference because of the very thick stacks called out by engineering.

Break-In Period

The initial tests were all completed with one test die. In order to determine if the results could be repeated with another die some tests were repeated with a new die coated from a different batch. Initial results were very concerning. When using the newly coated die the improvement in interference at the exit of the stringer (D4) was not as high as expected. Fortunately as more rivets were installed D4 interference dropped. It turns out the dies have a "break-in" period. The more the die is used the better it becomes. Most of the break-in occurs in the first 100 upset cycles, although there is a gradual improvement for the next few hundred upset cycles (Figure 6).

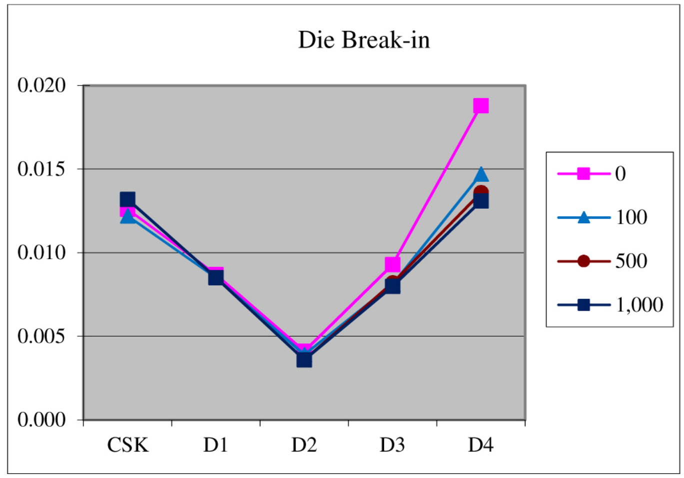

Figure 6. Break-in Period showing a reduction in D4 interference over the first 1000 cycles of use.

Unknown Die Life

At this writing, the impact on die life is unknown because it has not been necessary to remove any dies from production. As more upset cycles were put on the dies, the coating began to show signs of wear, particularly on the radius of the cup surface (Figure 7).

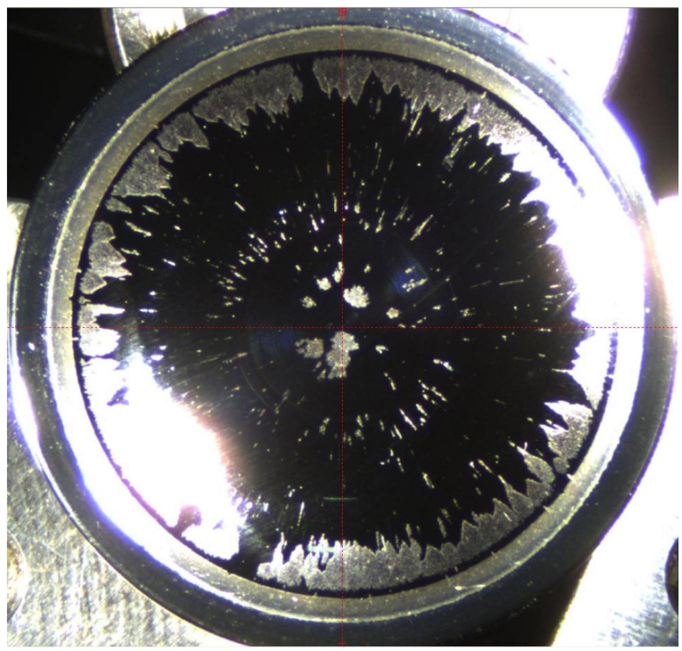

Figure 7. Coating Wear

At the time of removal, the rivet interference performance showed no signs of degradation. Because no dies have reached the point of failure, the failure mode of the coating is also unknown. Will the coating flake off? Will it continue to wear off? Will it last for the useful structural life of the die? All of these questions will be answered over time.

Skin-Side DLC Coated Die

Coating the skin-side die was also investigated and it was found to be unacceptable. The skin-side dies are shaped to penetrate the head of the rivet. The reduced friction of the DLC coating allowed the die to penetrate more resulting in a significant increase of countersink interference, which is undesirable.

Conclusion

Implementation of a DLC coating on the surface of the stringer-side upset dies has resulted in a significant improvement in the interference profile of installed rivets. There has also been a significant improvement in process repeatability and a significant reduction in process sensitivity to other process variables. These two improvements have allowed for the successful implementation of this system into high volume production.

Although a very satisfactory solution was found, there may still be a better solution because of the number of coating variations and suppliers of DLC coatings. Also, because this coating is being relied on to achieve acceptable rivet interference it is unwise to rely on a single supply source. Other DLC coatings and other coating suppliers are being investigated.

References

Contact Information

Curt Hayes
Electroimpact, Inc.
4606 107th ST SW, Mukilteo WA 98275, USA
CurtH@Electroimpact.com

Acknowledgments

The author wishes to acknowledge the following people who had significant contributions to the success of the DLC die effort: Tyler Kumley and Paul Haworth, both of Electroimpact. He would also like to thank the significant contributions of his customer to the success of this program.

Definitions/Abbreviations

T/D ratio - Total thickness divided by diameter of rivet

skin/stringer Ratio - Thickness of the skin divided by the thickness of the stringer

DLC coating - Diamond Like Carbon coating

Boelube - Metalworking lubricant from The Orelube Corporation

rivet upset profile - Shape of the upset load versus time. This is comprised of three stages, the ramp up of force, dwell time at the target forming load, and the ramp down.

rivet interference profile - Graph of rivet interference versus location on the rivet.

interference - The difference between the diameter at a particular location on a rivet and the diameter of the hole or countersink

CSK interference - Measurement in the skin material at the top of the countersink

D1 interference - Measurement in the skin material just below the bottom of the countersink

D2 interference - Measurement in the skin material just before the interface between the skin material and the stringer material

D3 interference - Measurement in the stringer material just after the interface between the skin material and the stringer material

D4 interference - Measurement in the stringer material just before the button of the rivet

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

http://papers.sae.org/2016-01-2084