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Laser-Cut Parts Engineering Evaluation

September 24, 2023

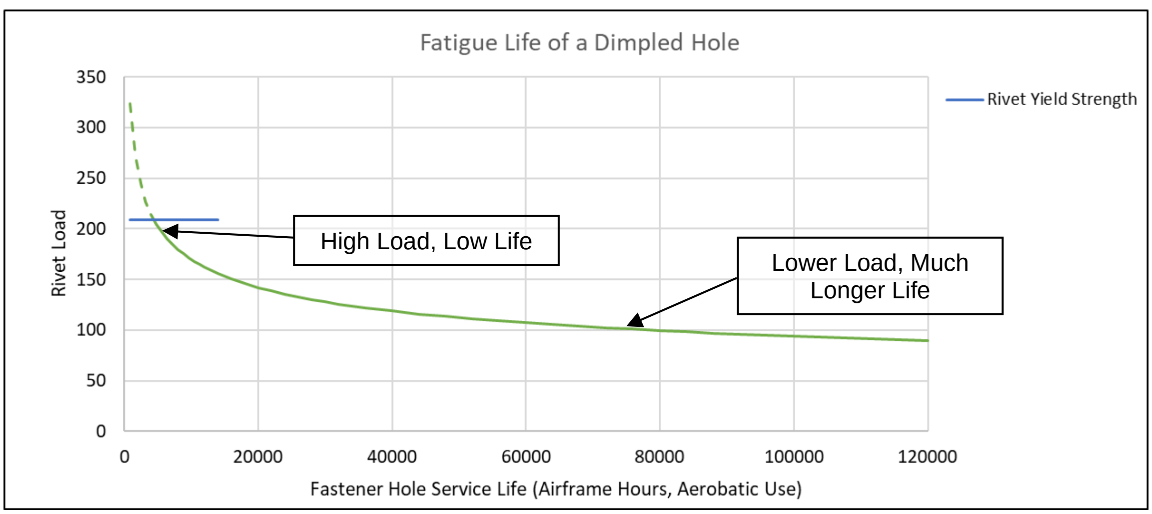
Introduction
Following reports from the field of irregular holes and cracked dimples in laser-cut sheet metal parts, an investigation was conducted to review the prevalence of these defects and the effect they have on the structure of aircraft parts and assemblies. The service-life of laser-cut structures has been evaluated through conservative analysis, computer simulations and mechanical testing of representative structural joints, sub-assembly details, and full assemblies. Based on the results of analysis and testing, Van's Aircraft has classified each part that was manufactured via the laser-cutting process into two categories: Parts that are Recommended for Replacement and parts that are Acceptable for Use. These classifications have been made out of an abundance of caution, and all parts classified as Acceptable for Use are functionally equivalent to punched parts.

From January 2022 through June 2023, Van's had certain parts manufactured using a laser-cutting process. These parts make up a portion of the internal structure, made of .040" aluminum or thinner, primarily: ribs, frames, and bulkheads. Note that skins, wing spars, and wing spar doublers were never produced using laser cutting. Rather, those parts were, and are, produced using the CNC punching or CNC machining processes that Van's has employed for many years.

Stress and Fatigue Life
The primary concern related to irregular holes and/or cracked dimples is what effect these have on the service life of a part through metal fatigue.

Fatigue is a phenomenon that affects <u>all</u> aluminum structures, regardless of stress level. Any amount of load applied to aluminum a sufficient number of times will eventually result in a fatigue crack. Fatigue life is finite, and a small portion of that part's life is used during every loading cycle, and is directly related to the magnitude of the stress developed. In any particular part the non-uniform application of load, the detailed design characteristics, and the nature of how that load is reacted will result in dramatically varied stresses. The point of highest stress will be the location where the fatigue life will be exhausted first, resulting in a fatigue crack.

In round numbers, a given reduction in stress increases the service life of a part exponentially; to the power of four. For example, for each 50% reduction in stress, the predicted service life of a part increases 16 times. The graph below illustrates this concept.



The dramatic relationship between stress and fatigue life drives the requirement that overall stress and any feature that creates a spike in local stress level is thoroughly examined. These stress spikes occur at features within a part (holes, cutouts, corners, defects, etc.) and are referred to as stress-concentrations.

Accelerated Life Testing

To analytically assess the quality of the laser-cut holes and their associated stress-concentrations, it is common practice to perform accelerated life testing using representative samples tested at high loads and cycle rates. This data can then be translated into airframe hours using conservative analysis that accounts for statistical variation, realistic loading and load cycles that are representative of the most demanding conditions for the aircraft - primarily aerobatics and flight training.

Test samples were constructed with representative defects following a review of laser-cut parts from different production batches. This review included all laser-cut part inventory in the Van's Aircraft warehouse, high-resolution photographs from customers, and parts that were returned to Van's for analysis. We used the worst-case laser-cut toolpath that creates a large heat affected area at every hole. Every dimpled hole in every sample included a crack developed from the dimpling process. The orientation was manipulated relative to the load and grain direction to evaluate the sensitivity of these variables and generate the worst-case fatigue properties.

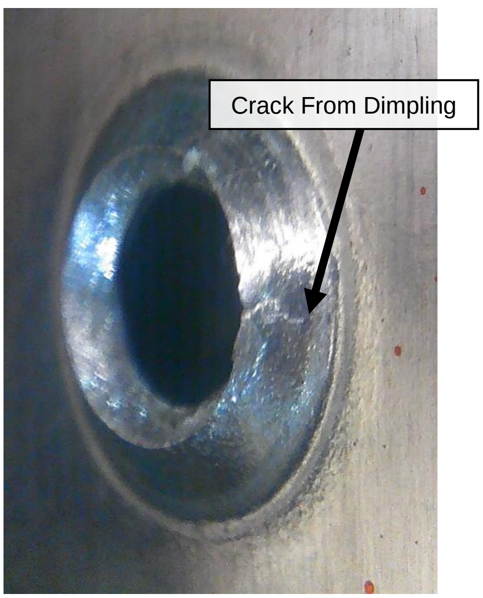


Photo 1: Test Sample Cracked Dimple

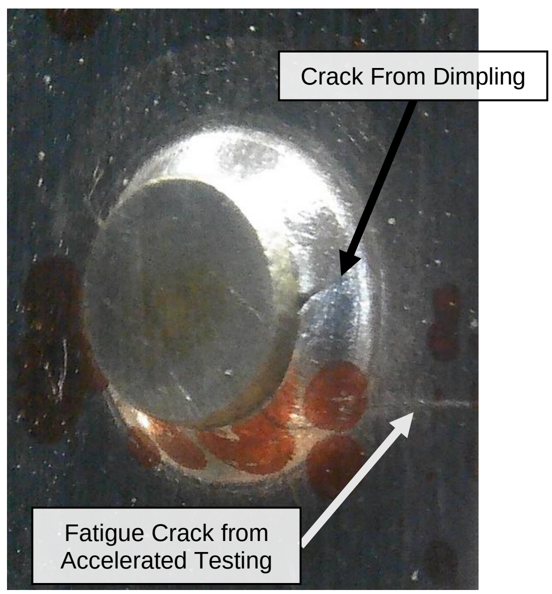


Photo 2: Test Sample after fatigue testing to failure.

A third-party company specializing in testing, material science, and structural durability was contracted to collaborate in the review of these laser-cut parts, providing guidance and oversight in the development and execution of the test and evaluation program. This company participated in physical testing of samples in their facilities (both unique testing and testing in duplicate to Van's), as well as the analysis and review of results. This expanded test capacity allowed for larger data sets and a greater combination of variables. These variables included:

- Fastener types
- Fastener diameter
- Material thickness
- Material types
- Installation configuration
- Material grain direction
- Defect orientation relative to the load
- Defect orientation relative to the material grain direction
- Single-shear joints

- Dimpled holes
- Machine-countersunk holes
- Non-dimpled holes
- Nested dimpled/countersunk holes

- Double-shear joints
- Non-reversing loads
- Reversing loads
- Combined shear and tension loads

Test samples were designed to highlight the worst-case fatigue properties for the laser-cut holes. Each sample contained multiple fasteners, and the failure of any hole would conclude the test. For example, a double-shear rivet test sample contains 8 rivets and is simultaneously testing 16 laser-cut holes. This conservatively establishes a sample life that is based on the worst of the group.

This partner company also provided detailed assessment of the metallurgy surrounding the laser-cut edges of dimpled and un-dimpled fastener holes.

Airframe Service Life Analysis
While analyzing the service life of an aircraft, criticality of the structure, stress levels, and the expected loading cycles were determined.

Structural assemblies were analyzed and classified as Primary Structure and Secondary Structure based on their application, relationship to flight loads, and criticality to the safe operation of the aircraft. Primary Structure is essential in maintaining the overall structural integrity of the airplane.

To identify high-stress locations and highly-loaded fastener holes, Van's Aircraft performed traditional mathematical analysis and computer simulations using Finite Element Analysis (FEA). This was done at the major assembly scale and refined to the smallest details. When analyzing stress levels, features such as relief notches between formed rib flanges typically exhibited the highest levels of stress, much greater than stresses observed at the fastener holes. Of note, fleet history has not indicated fatigue cracking occurs at these locations.

Many parts serve their function at stresses and loads far below that which would make them susceptible to fatigue damage. These are cases where the parts do not directly resist major portions of flight or ground loads and are often functioning to stabilize Primary Structure (typically the skins and spars of the airframe). This stabilizing structure is used to maintain shape and prevent buckling of another part, which increases that primary component's ability to resist compression or shear loads. At the mild stresses developed in these stabilizing parts, the laser-cut components are functionally equivalent to punched components, both have an unreasonably remote possibility of ever developing fatigue cracking in service.

To conservatively estimate the rate at which an aircraft would use the fatigue life of its most highly loaded components, an extreme use case was selected. Well beyond what is reasonable, and far beyond any known to Van's Aircraft, this was a theoretical aircraft spending 50% of flight time in flight-school operations, and 50% of flight time performing constant aerobatic maneuvers up to the design limits of the aircraft. This loading spectrum (load intensities and load cycle rates) was developed from real-world data (a survey of multiple RV's used in aerobatic airshow routines). The resulting aircraft model assumes a reduction of fatigue life at a rate more than 25 times that of an aircraft used in flight-school conditions alone.

Using this conservative aircraft model, an assessment was then made to determine at what stress level structures became susceptible to fatigue damage using the identified loading spectrum. Each part was then classified as needing replacement or acceptable for use.

Had we used a less conservative estimate of the loading spectrum closer to real-world use, the result would have been a dramatically longer life, proportional to the realistic use of the airplane. A review of a single flight where aerobatics are performed will typically include less than 10 minutes of actual aerobatic maneuvers (the airshow used to develop the conservative aircraft model lasts only 12 minutes). Takeoff, the standard climb and descent, the return to airport, and landing are all spent in a “normal” spectrum of flying. Next examine how often these aerobatic flights are performed and compare the small amount of time spent in aerobatic maneuvering to the total flight time. Consider the example airplane below:

<u>Aerobatic Flight Time per year</u>

Aerobatic maneuvering:	<10 minutes per flight *with maneuvers up to 6g limit of the airplane
Aerobatic “flights” per year:	<12 aerobatic flights
Total Aerobatic flight per year:	<2 Hours

<u>Total Flight Time per year</u>

Number of hours flown in a year:	~100 hours

This example aircraft would achieve a calculated service life at least 12 times higher than the very conservative airplane used in the classification of laser-cut parts. These are the same airframes, developing the same stresses in maneuvers, but the cycles and loads developed per flight hour are that dramatically different.

Residual Strength Testing
Industry testing standards also direct aircraft designers/manufacturers to assess the resilience and strength of aircraft structures in the event of various forms of structural failure. Therefore, additional conservative testing simulating a fully developed, undetected fatigue crack was performed on a complete RV-10 wing. A series of static tests under limit load was conducted, in which every main and nose rib was cut completely across the part in multiple locations, simulating failures at all elevated stress locations. Ribs were completely severed at the spar attachments, at relief notches, and out of fastener holes. This was a progressive test, starting with the most highly-stressed parts and progressing through the rest of the wing, including tank internal ribs and the tank baffle. This test simulated extremely unrealistic failures, well beyond that which could ever actually occur. This test demonstrated that the structure maintained its strength and function in an absolutely unrealistic and negligent scenario.

Parts Classification
Van’s Aircraft has conservatively classified – and recommends replacement of – laser-cut Primary Structure parts regardless of the magnitude of the stress found in the part, as well as parts that have any reasonable probability of being susceptible to fatigue damage. In addition, many components have been recommended for replacement due to their functional criticality alone, even though they are not particularly susceptible to fatigue damage. Examples of this can be found in flight control system support structure, such as the root rib on a RV-10 or RV-14 wing and the associated brackets which support the end of the aileron torque tube.

Parts classified as “Replacement Recommended” are somewhat susceptible to fatigue damage over the life of the aircraft, but pose no immediate risk to the safety of flight. The most conservative analysis, with statistical life reductions and evaluated at the highest-loaded rivets under near constant aerobatic conditions still predict that these parts have lives measured in thousands of hours. You may continue to fly your RV, and aerobatics are allowed.

Parts classified as “Acceptable for Use” have stress levels so low it is extremely unlikely that cracks will ever grow from the fastener holes. In the operational life of the airplane these are functionally equivalent to punched parts.

All customers, building or flying, should plan to replace the components marked for replacement in the laser-cut part list, or install additional parts developed by Van's as alternatives to replacement. In some instances, the Van's Engineering team will develop alternate solutions that may be installed instead of a complete part replacement. These alternate solutions will reduce workload significantly while also addressing any potential issues.

For flying aircraft, Van's Aircraft will provide further guidance including a time limit for part replacement after further testing and analysis has been conducted.

Quickbuild Kits
Several customers are waiting to receive quick build kits. Some of those kits are located in the Van's Aircraft warehouse and others are still in transit from our quick build assembly facilities. We intend to update these kits before shipment to the customer. This will involve replacing the parts that are recommended for replacement and/or installing alternate engineering solutions. The large number of kits to be reworked, combined with limited manpower, will result in extended lead-times. In addition, we are pursuing alternate resources to rework kits to help reduce lead times. This process will take time and we will communicate updates to quickbuild customers.

Many quick build kits require limited rework and a small number of parts that will need to be updated. If desired by the customer, to reduce lead time Van's will deliver those kits requiring limited rework to a customer along with the punched replacement parts. In instances where parts are complex to replace, the preferred solution will be to install parts developed to simplify and reduce the level of disassembly necessary. Please review the laser-cut parts list and your kit to become familiar with how involved a repair may be.

RV-12 Update
Fatigue testing has shown a lifespan of RV-12 parts that is significantly beyond the expected life of an airplane. A full aircraft sub-assembly with laser-cut components was tested through an accelerated life test representative of 30,000 hours of flight training use. This test was concluded with no deformation, failure, or detectable change to the assembly.

Accelerated life testing using representative samples, of various configurations, has shown a very long service life can be expected. This testing of highly-loaded rivets demonstrates that the rivet will fatigue before the hole, regardless of whether the fastener hole was punched or laser-cut. Lightly-loaded fastener holes will fatigue before the rivet, but have a dramatically longer fatigue life that is many multiples of the life of an aircraft. For these reasons, we determined that there is more than sufficient life for RV-12 aircraft utilizing laser-cut parts.

We have evaluated and classified the laser-cut components of the RV-12, and out of an abundance of caution we recommend the replacement of the following trim system components: F-1211D, F-1287A-1, F-1287D, and HS-1220. Service information along with a life limit for these parts will be forthcoming. For now, you may continue to fly your aircraft. The Laser Cut Parts List has been updated to include these RV-12 parts.

Summary
To reiterate, laser-cut parts have been classified using conservative assumptions and with an abundance of caution. Once the parts that Van's has recommended for replacement are addressed, the remaining laser-cut parts are secondary structure or lower, are functionally equivalent to punched parts, and are acceptable for use.

The analysis of fatigue life in these remaining parts is based on peak stress, from test data that uses worst-case outliers and statistical offsets. The calculated expected life is much greater.

It is very unlikely a fatigue crack should ever develop. However, should that happen RV structure will allow for ample time to inspect and correct. This will not alter the useful life of the aircraft.

Annual inspections of structure provide an opportunity to detect fatigue cracks, which can be corrected (typically stop-drilled), allowing the aircraft to remain in service. In addition, residual strength testing has demonstrated that in the rare case fatigue cracks ever develop in secondary structure there is minimal risk.

Revisions

9/29/2023 – Added information to the **Accelerated Life Testing** section, Paragraph 2.

References

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