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Authors
Ball, Dale L
James, Mark A
Bucci, Robert J
et al.

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A Detailed Evaluation of the Effects of Bulk Residual Stress on Fatigue in Aluminum

Dale L. Ball[1,a *], Mark A. James[2,b], Robert J. Bucci[2], John D. Watton[2], Adrian T. DeWald[3], Michael R. Hill[3,c], Carl F. Popelar[4], R. Craig McClung[4,d]

[1]Lockheed Martin Aeronautics Co., P.O. Box 748, Fort Worth, TX 76101, USA

[2]Alcoa Technical Center, Alcoa Center, PA 15069, USA

[3]Hill Engineering LLC, Rancho Cordova, CA 95670, USA

[4]Southwest Research Institute, San Antonio, TX 78238, USA

[a]Dale.L.Ball@lmco.com, [b]Mark.A.James@alcoa.com, [c]mrhill@hill-engineering.com, [d]craig.mcclung@swri.org

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Abstract. The fully effective utilization of large aluminum forgings in aerospace structures has been hampered in the past by inadequate understanding of, and sometimes inaccurate representation of, bulk residual stresses and their impact on both design mechanical properties and structural performance. In recent years, significant advances in both computational and experimental methods have led to vastly improved characterization of residual stresses. As a result, new design approaches which require the extraction of residual stress effects from material property data and the formal inclusion of residual stresses in the design analysis, have been enabled. In particular, the impact of residual stresses on durability and damage tolerance can now be assessed, and more importantly, accounted for at the beginning of the design cycle.

In an effort to support the development of this next-generation design capability, the AFRL sponsored Metals Affordability Initiative (MAI) consortium has conducted a detailed experimental and analytical study of fatigue crack initiation and fatigue crack growth in aluminum coupons with known, quench induced residual stresses. In this study, coupons were designed and manufactured such that simple 'design features,' such as holes and machined pockets, were installed in locations with varying levels of bulk residual stress. The residual stresses at the critical locations in the coupons were measured using multiple techniques and modeled using detailed finite element analysis. Fatigue crack initiation (FCI) and fatigue crack growth (FCG) tests were performed using both constant amplitude and spectrum loading and the results were compared against computed FCI and FCG lives.

Forging Process Modeling

Over the past ten years the Alcoa Technical Center has been developing a forging-specific computational tool for residual stress and machining distortion modeling [1], [2]. This capability is used today to predict the post-quench residual stress, the post-cold-work residual stress, and the residual stress in a finished machined part. It has been extensively employed to improve the management of bulk residual stress through the improvement of quench practices and the development of Alcoa's Signature Stress Relief (SSR™) cold work process. It is a key Alcoa proprietary tool that elevates forged-part stress-relief from an art to a science and is the foundation of Alcoa's strategic advantage for forged parts.

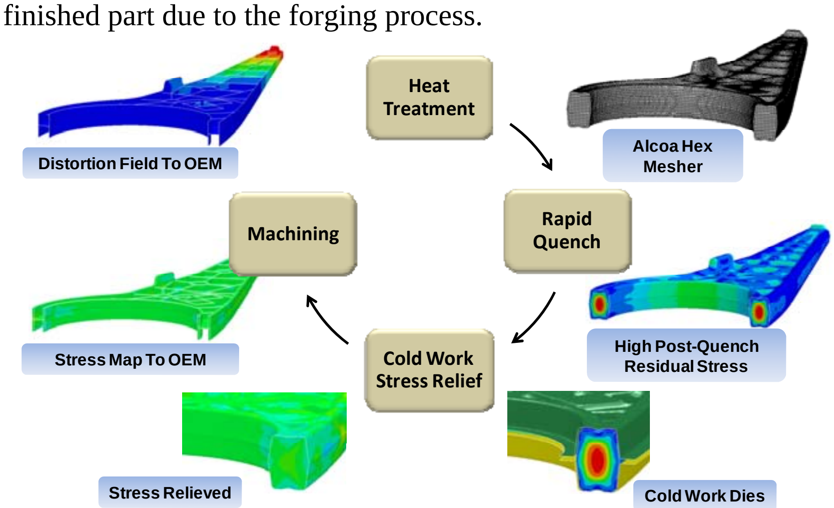
The Alcoa forging business has used the process model to design and optimize for consistent low residual stresses. As shown in Fig. 1 the process model simulates four important processing steps:

1. The heat treatment of the forging. This involves elevating the meshed forging geometry to the solution heat treatment temperature (~895°F for most aluminum alloys).
2. The rapid quench process to about 100-140°F. The quenching causes high tensile stresses in the core of the forging (shown in red) and high compressive stresses on the surface (shown in blue).

3. The cold work stress relief process. This involves a specially designed die set that squeezes the forging at room temp. Alcoa's process is trade marked as Signature Stress Relief (SSR^{TM}).

4. Machining. This step simulates the extraction of the finished part from the forging through the removal of all elements from the FE model that are not within the machined part profile. While this does not simulate the machining process per se, it does capture the bulk residual stresses and distortions that are left in the finished part due to the forging process.

Figure 1. Alcoa's forging process model: 1) solution heat treatment, 2) quench, 3) cold work stress relief, 4) artificial aging, and 5) machining. The capability includes material models for 7050 and 7085.



Experimental Program

A detailed, coupon level test program was conducted in order to quantify the impact that bulk residual stresses have on both mechanical properties (like strength, toughness and fatigue crack growth rate) and spectrum fatigue performance, including both crack initiation and crack growth. A large set of flat, rectangular coupons were manufactured from a 7085-T74 billet that was produced by Alcoa. As shown in Fig. 2, the billet was cut into a total of eleven 'logs', which were quenched and aged individually. Each log was left in the as-quenched state (i.e. no post-quench cold work was applied) in order to ensure that the level of residual stress in the test coupons was large enough to measurably affect performance.

Using the methods described above, Alcoa computed the full field residual stresses and strains in a typical log resulting from the quench and age process used for the log fabrication. These results were then used to calculate the residual stresses present in 16x4x0.25 inch coupon blanks cut from six different stacking positions within a log. See Fig. 3. The test specimens were designed to allow explicit examination of the interaction of bulk residual stresses (quench and age process induced) with simple, yet typical structural details (like holes and pockets) that introduce stress concentrations.

Four types of 'design feature' (DF) coupons, as well as simple flat panel coupons, were manufactured. The configurations for each specimen type were: DF0 – a featureless panel, DF1 – a centered open hole, DF2 – an eccentric open hole, DF3

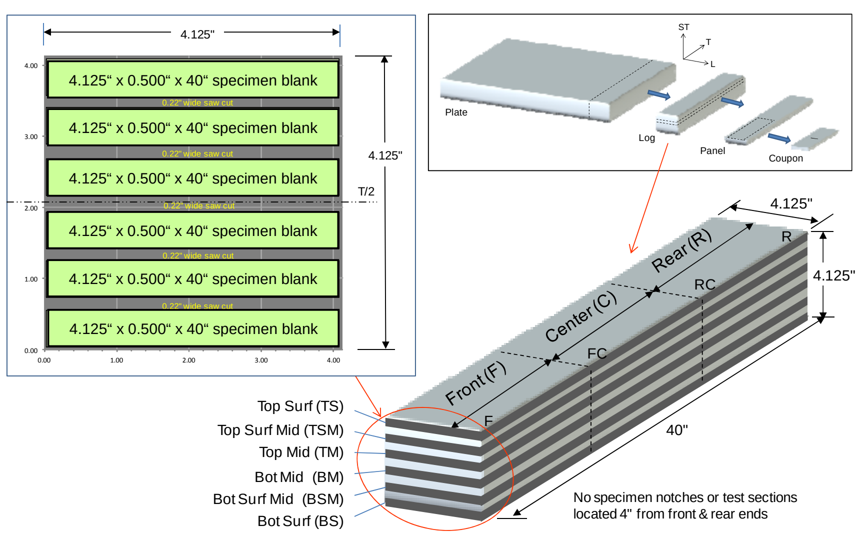


Figure 2. Log, panel and specimen blank positions within

– a centered, machined pocket, and DF4 – a pair of eccentric machined pockets, respectively. Specimen types DF0, DF1 and DF2 were nominally 0.25 inch thick and could be extracted from any of the six through-the-thickness stacking positions: TS=top surface, TSM=top surface middle, TM=top middle, BM=bottom middle, BSM=bottom surface middle, and BS=bottom surface (see Fig. 2). Specimens DF3 and DF4 were nominally 0.5 inch thick and could only be extracted from the TSM, TM, BM and BSM positions.

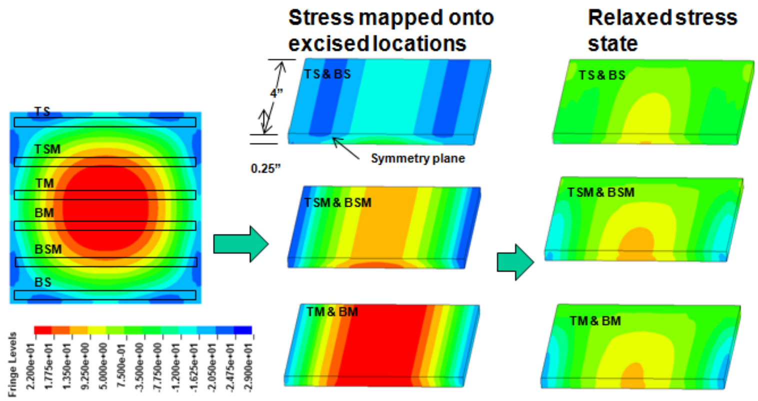


Figure 3. Alcoa analysis of quench and age induced residual stresses in coupon blanks extracted from six different positions in a 4.3 inch x 4.3 inch 7085-T74

Residual Stress Determination. Internal residual stress distributions were calculated and/or measured for each of the five DF coupon configurations at four of the log positions: BS, BM, TM, and TS. Each of the specimen blanks was shown to have a residual stress gradient across its width that ranged from compression at the edges to tension near the centerline, with nearly uniform variation through the thickness.

Alcoa computed the residual stresses in the DF0 coupons by modeling the quench and age processes for the log, and then modeling the extraction of a blank from each of four locations within a quenched log. Alcoa also conducted a large number of residual stress measurements on DF0 coupons (blanks) using the slitting method [3]. The measured stress component is the one in the longest dimension of the logs and coupons. Each of the profiles shown in Fig. 4 represents the average of slitting measurements from three separate coupons, as well as averaging from left to right. (The left to right averaging was done in order to force the RS profile to be symmetric about the coupon centerline.)

Upon comparison of the calculated RS fields with the slitting measurements, it was found that the predictions deviated from the slitting data, especially at the BS location. As a result, the averaged slitting data (rather than the FEA results) were used for the subsequent determination of the residual stress distributions in the design feature coupons. In order to calculate the residual stress profiles in the DF1 through DF4 coupons, Alcoa mapped the residual stress profile from the specimen blank at the appropriate log position onto a finite element model of the DF coupon, and then calculated the relaxation due to the removal of the material occupied by the design feature (i.e. the hole or the pocket(s)). As shown in Fig. 5, installation of a design feature, in this case a centered open hole, produces a concentration of the residual stress in the vicinity.

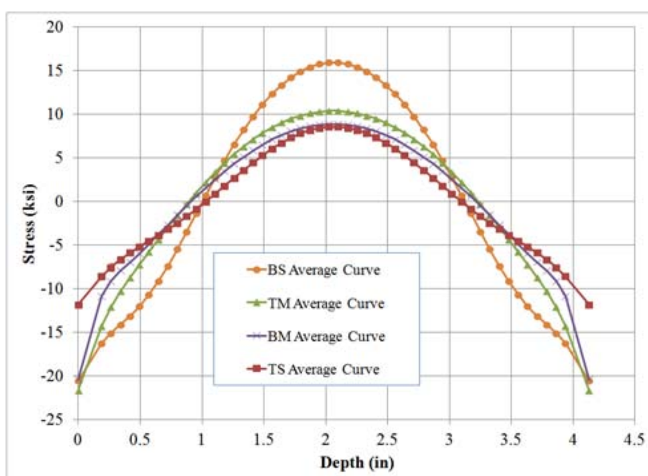


Figure 4. Measured DF0 stress versus log position using the slitting method.

In an effort to evaluate the averaged slitting data for the DF0 coupon, as well as the calculated RS profiles for the DF1 through DF4 coupons, Hill Engineering, LLC performed contour measurements [4] on one cross-section (the anticipated critical cracking plane) for each of the five coupon types for each of the four log positions; this resulted in a total of 20 measurements. An example set of comparisons between contour measurement results and calculated RS data for the DF2 coupons is shown in Fig. 6.

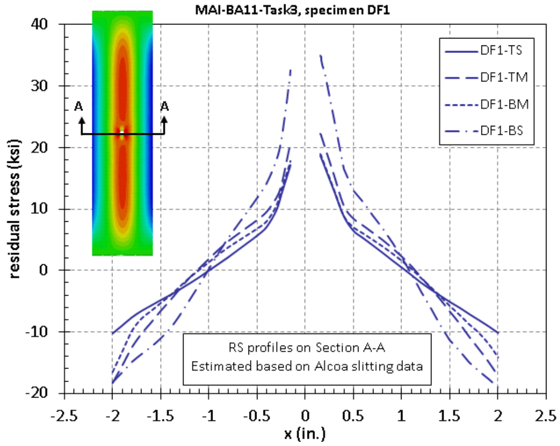


Figure 5. Calculated residual stress profile for DF1 coupons.

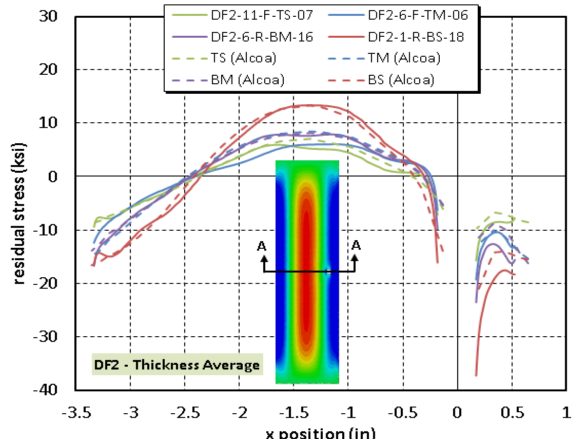


Figure 6. Line plots of thickness-averaged measured residual stress for DF2 coupons compared with estimates from Alcoa.

Fatigue Test Program. Both fatigue crack initiation (FCI) and fatigue crack growth (FCG) testing were conducted by Southwest Research Institute (SwRI). As noted above, the DF specimens were designed specifically to address potential interaction between a design feature and the bulk residual stress. For specimen DF1, the crack initiation site at the edge of the hole was in a tensile residual stress field, for DF2, it was in a transition or compressive field. Likewise, for specimen DF3, the crack would form in either the top or bottom fillet radii and would be growing in a tensile residual stress field, while the same crack in DF4 would be growing in a transition or compressive residual field.

The test program included both constant amplitude (CA) (R=0.1) and variable amplitude (VA) loading profiles. All of the VA tests were conducted using the same spectrum. This spectrum was based on an F-35 STOVL design wing bending moment history that was truncated sufficiently to reduce the load sequence to approximately 20000 cycles (40000 turning points). For FCI, two tests were conducted for each log position with DF1 and DF2 coupons, while one was conducted for each position with DF3 and DF4 coupons, for a total of 24 tests. The same matrix was employed for the FCG tests, along with an additional eight DF0 coupons for a total of 32 tests. An example of measured crack length vs cycles for two DF3 coupons subjected to spectrum loading is shown in Fig. 7; a photograph of a DF3 fracture surface is shown in the inset.

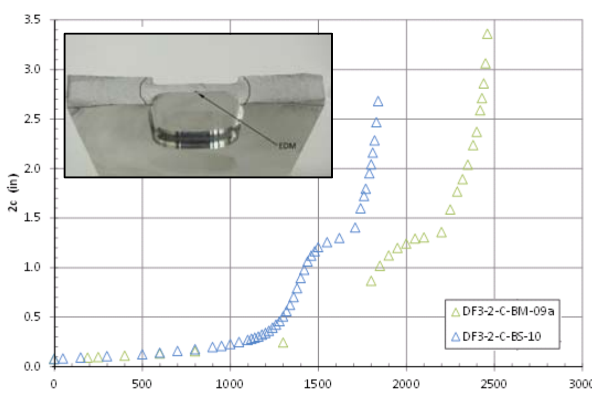


Figure 7. DF3 Spectrum fatigue crack growth results.

Fatigue Life Analysis Methods

As stated above, one of the major objectives of this program was the validation and further development of a residual stress modeling technology that calls for the extraction of the confounding effects of bulk residual stresses from material property data, and then the explicit reintroduction of those effects during design structural (strength, durability and damage tolerance) analyses. In the fatigue life modeling task, both fatigue crack initiation and fatigue crack growth methods were addressed. In general, industry standard methods for the inclusion of residual stress effects were evaluated and then modified as required.

Detail Stress Analysis. One of the prerequisites for both crack initiation and crack growth analyses is an accurate representation of the stresses and strains at the critical location(s) within the body being analyzed. For nominally elastic behavior, it is typically sufficient to calculate the stress-strain response for a unit condition and then scale the result as required for each of the stress (or load) values in the applied fatigue spectrum. In the case of the DF coupons, the p-version finite element code, StressCheck [5], was used to calculate the full field elastic stress distribution resulting from the application of a unit, uniform tensile stress at the specimen end. The results for the DF4 coupon (which is 1/8 symmetric) are shown in Fig. 8.

Fatigue Crack Initiation Analysis. Fatigue crack initiation (FCI) analyses were performed using the strain-life approach [6]. In the standard model, Neuber's rule is used to estimate local, stress-strain response based on applied, elastic stress. The effects of residual stress were incorporated in this analysis by using them to define the initial stress-strain conditions from which the hysteresis loop tracking begins [7]. During cyclic elastic-plastic response, and depending on notch acuity, it is possible and even likely that both forward and reverse plasticity will alter the residual stress-strain state. For each DF coupon, the applied stress versus crack initiation life relationship was calculated for each RS profile (log position). An example of this is shown in Fig. 9 for the DF1 coupon subjected to spectrum loading. Parametric analyses of this type were used to estimate the applied stress (and therefore load) required for each of the DF coupon FCI tests.

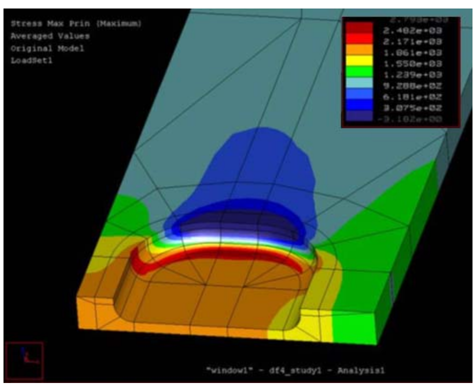


Figure 8. Solid FEA analysis results for DF4 Coupon, Calculated

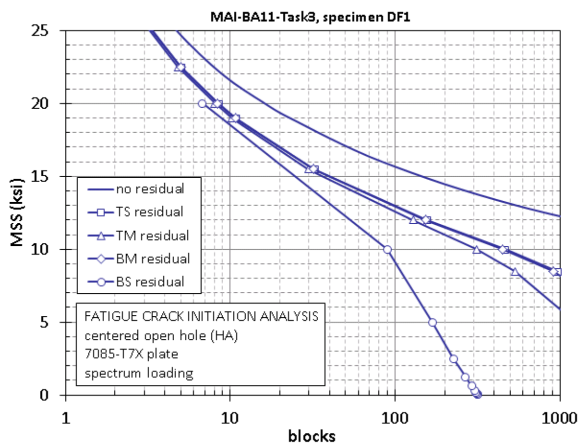


Figure 9. Calculated applied stress vs. FCI life relationships for DF1 coupons

Fatigue Crack Growth Analysis. In the case of crack growth analysis, the effects of residual stress are incorporated using the traditional LEFM approach [8], [9]. This approach calls for the calculation of the initial residual stress field in the uncracked body and makes the assumption that this stress field remains essentially unchanged during the subsequent fatigue crack growth. With the additional assumption that the bulk material response is elastic, both stresses and stress intensity factors may be superimposed. In particular, the stress intensity factor (SIF) due to the residual stress field and those due to the applied cyclic stresses may be summed to determine the appropriate total SIF at each cycle of the analysis. The preferred methods for the determination of the residual SIF are the weight function or Green's function methods [10], [11] since they can accommodate the arbitrary stress distributions which are typically encountered in residual stress problems. These methods are well established and widely used in the aerospace industry and they will not be discussed here. The specific Green's functions that were used in the current study are described in refs. [12] and [13]. The total SIF is used to calculate fatigue crack growth rate which in turn is integrated to obtain the crack growth life. With these assumptions, the only additional requirements for the analysis of crack growth are the initial residual stress field and the corresponding residual stress intensity factor vs. crack length relationship.

Using this approach, FCG lives were calculated for each of the DF coupon tests in the experimental program. Comparisons of computed crack growth lives for the DF2 specimens are shown in Figs. 10, and a summary of all of the correlation results is given in Fig. 11.

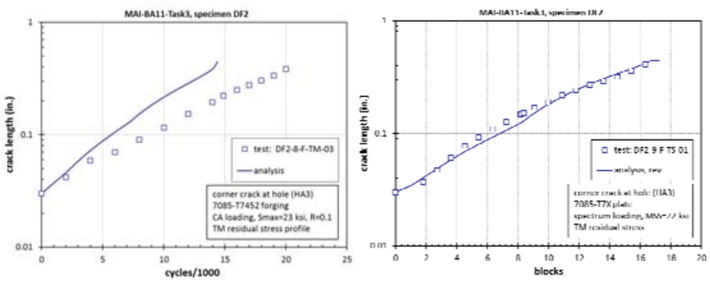


Figure 10. Comparison of calculated vs. measured FCG lives for DF2 coupons.

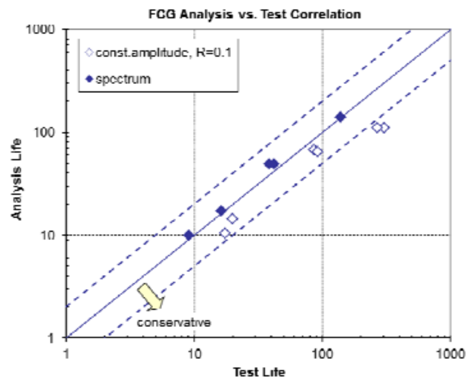


Figure 11. FCG analysis vs. test correlation summary.

Conclusions

Recent advances in the computational simulation of the quench, cold-work and machining processes for large aluminum forgings are opening the way for a new paradigm in the design, manufacture and sustainment of aircraft structures. This new paradigm requires the explicit inclusion of forging process induced bulk residual stresses in the fatigue analyses used to design and certify the airframe; however, it will not see widespread acceptance until both the residual stress and fatigue life models have been thoroughly validated. The current program shows that the effects of residual stress on fatigue can be simulated with reasonable accuracy for the conditions studied. This in turn suggests that the "next-generation" design/structural analyses which will rely on these models may be achievable.

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