THE EFFECTS OF RESIDUAL TENSILE STRESSES INDUCED BY COLD-WORKING A FASTENER HOLE

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ABSTRACT

During a spectrum component fatigue test performed at IAI, a crack initiated at a notched edge near a cold-worked fastener hole, and propagated towards the hole. Fractographic analysis confirmed that the crack initiated at the edge and grew towards the hole. Since the maximum measured stress in the notch was not sufficiently high to explain crack-initiation during the test, it was suspected that the tensile residual stresses at the edge contributed to the cracking. An experimental study was initiated in order to measure the tensile residual stresses induced by cold working at various edges located near cold-worked holes. Tensile residual stresses as high as 35 ksi were measured at an edge near a cold-worked hole. Elastic-Plastic finite-element analysis results (ABAQUS and StressCheck) showed good agreement with the experimental results. Fatigue analysis has shown that when these residual stresses are combined with high cyclic notch stresses that arise from external loading, the fatigue life at the edge can be drastically reduced.

INTRODUCTION

Cold-working was introduced to the aircraft industry about 35 years ago as a method to enhance fatigue lives of fastener holes. The method features a mandrel that is pulled through a fastener hole with approximately 4% interference, which causes yielding around the hole. When the mandrel is removed, compressive hoop stresses remain in a wide band around the hole as is shown in Figure 1. The peak compressive stress approaches the compressive yield strength of the material. This compressive stress field greatly inhibits the initiation and growth of fatigue cracks [1].

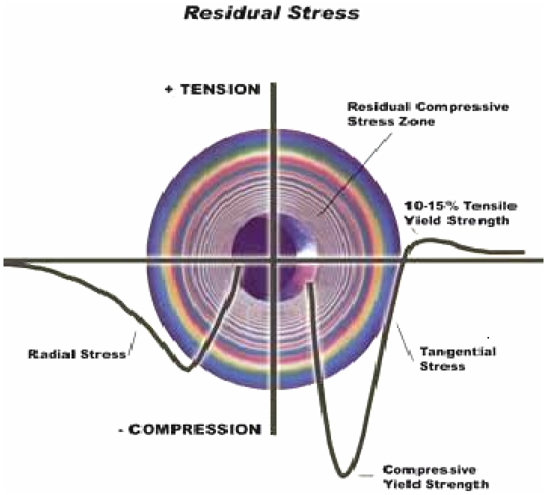


Figure 1: Photoelastic Measurements of the Stress Field at a Cold-Worked Hole
(provided by Fatigue Technology Inc. [1])

This compressive hoop stress field must be supported by a very wide tensile hoop stress field around the compressive field. Photoelastic measurements and finite-element studies have shown that, *in an infinite plate*, this tensile residual stress typically peaks at about one-third of the maximum compressive stress, and then reduces gradually to about 10 ksi, at a distance of 2.5 hole diameters from the hole center. Since stress-concentrations are usually not present in the proximity of the cold-worked hole, this tensile residual stress is generally not considered to be detrimental.

COMPONENT TESTING

During a spectrum component fatigue test performed at IAI, a crack initiated at a notched edge near a cold-worked fastener hole and propagated towards the hole, as is shown in Figure 2. The component was manufactured from 7475-T7351 alloy. The original contour of the edge, including the 10mm notch, is as shown by the sketch added to Figure 2. This is the configuration that was tested. The notched edge was located 2.47 diameters from the hole center. Strain-gages, mounted at the 10mm notch, indicated a peak spectrum stress of about 50 - 60 ksi at the notch. After the cracking was discovered, the detail was cut-away from the component and the notch was reworked, as is shown in the photo. Fractographic analysis confirmed that the crack initiated at the edge (on the non-countersunk side) and grew towards the hole. Since the maximum measured stress in the notch was not sufficiently high to explain crack-initiation during the test, it was suspected that the tensile residual stresses at the edge contributed to the cracking.

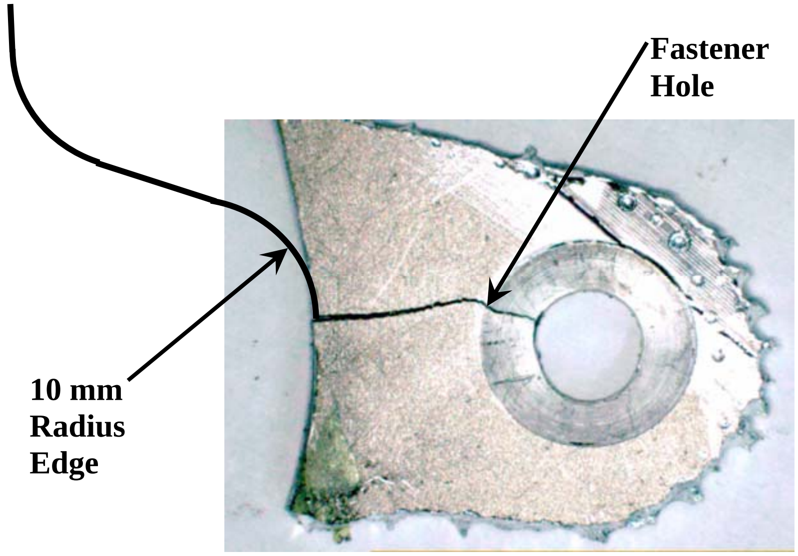


Figure 2: Crack Growth from a Notched Edge towards a Cold-Worked Fastener Hole
(detail was cut-away from a component test specimen)

EXPERIMENTAL STUDY TO MEASURE RESIDUAL STRESSES

An experimental study was initiated in order to measure the tensile residual stresses induced by cold working at various edges located near cold-worked holes. Figure 3 shows an array of strain-gages bonded, in two rows in the thickness direction, to a notched edge near a fastener hole. All the specimens were manufactured from 7475-T7351 aluminum alloy and the fastener holes were reamed and countersunk after cold-working. The notched edge was produced in two configurations, a 10mm notch (as in the component test) and a 30mm notch. Stresses at the edges were measured after cold-working and then after final reaming and countersinking of the fastener holes.

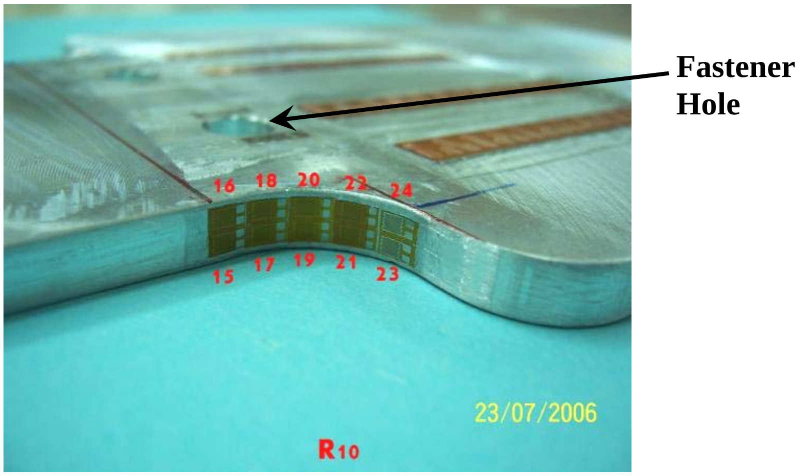


Figure 3: Test Specimen Used to Measure Residual Stresses Induced by Cold-Working (10mm notch radius)

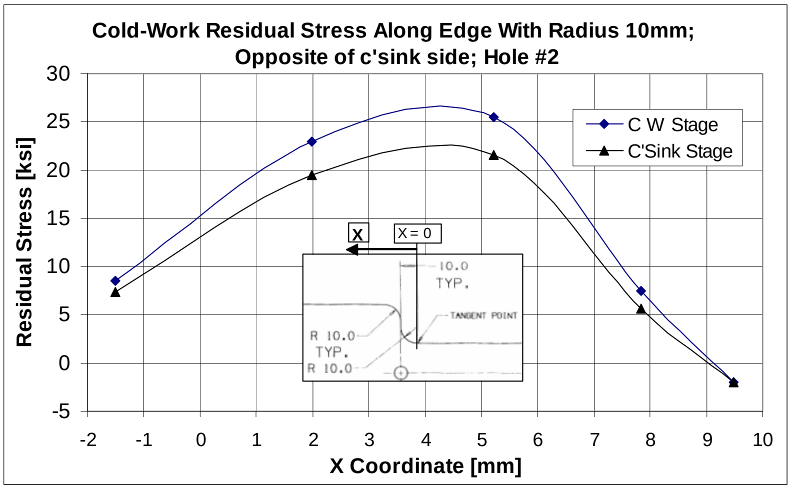


Figure 4a: **Stress Distributions along Edge of 10mm Notch Radius (opposite countersink)**

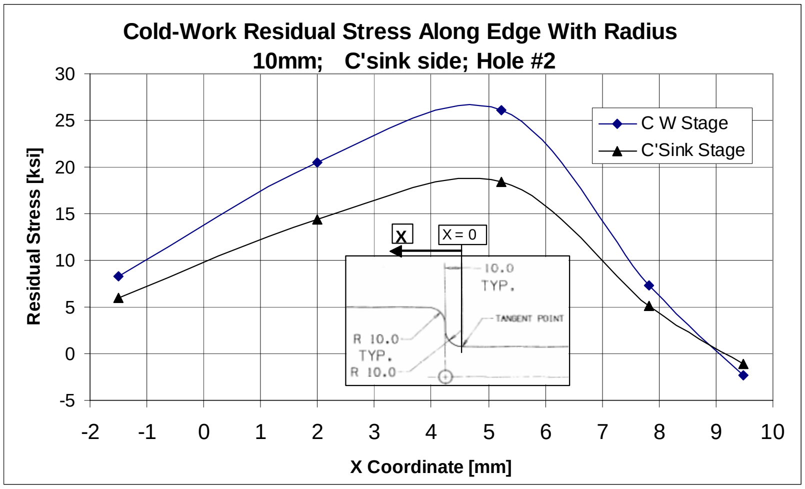


Figure 4b: Stress Distribution along Edge of 10mm Notch Radius (countersink side)

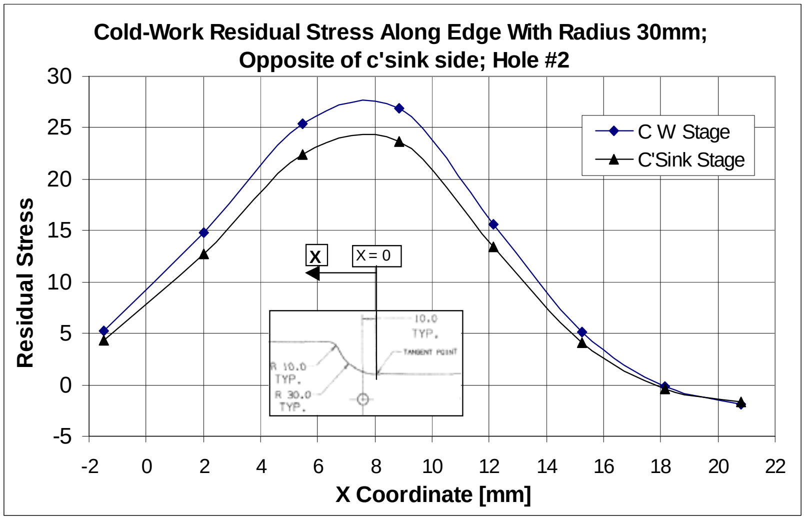
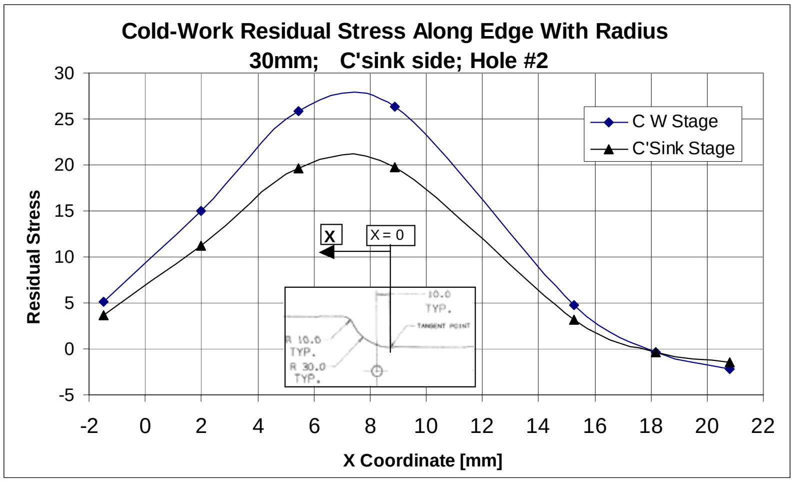


Figure 5a: Stress Distribution along Edge of 30mm Notch Radius (opposite countersink)



Figures 5b: Stress Distribution along Edge of 30mm Notch Radius (countersink side)

Figures 4a and 4b show the distribution of the notched edge residual stresses due to cold-working the nearby hole, for the 10mm notch radius configuration having an edge-distance ratio (e/D) of 2.40. The residual stresses were measured before and after reaming and countersinking, on the side opposite the countersink and on the side of the countersink. Figures 5a and 5b show similar results for the 30mm notch radius configuration having an edge-distance ratio (e / D) of 2.29. Clearly, final reaming and countersinking relieved a portion of the tensile residual stress, especially on the side where the countersinking was performed.

Stresses were also measured for a straight-edge configuration (no notch) for edge-distance ratios (e/D) of 1.95, 2.23 and 2.51. All the results are summarized in Table 1 and in Figure 15.

Table 1 summarizes the test results for all these tests. The range of the maximum edge stresses are shown, for each configuration, after cold-working and after final reaming and countersinking. It should be noted that the specimens with a notch were cold-worked with a mandrel interference of 3.1% while those with the straight-edge were cold-worked with a mandrel interference of 4.3%. As a result, the results cannot be directly compared. These results were first summarized in [2].

An additional series of tests were also performed for the straight-edge specimens. After cold-working, countersinking and reaming, a 5/16 inch fastener was installed into the 0.3095 inch hole (approximately a 1% interference) for e/D ranging from 1.95 to 2.51. The effect of this operation was to *increase* the tensile residual stresses at the edge, typically by 15% to 23%.

Table 1: Measured Results of Residual Stresses at the Edge

Configuration	Edge Distance Ratio *	Mandrel Interference	Range of Edge Stresses Induced by Cold-Working (Ksi)	Range of Edge Stresses After Final Reaming and Countersinking (Ksi)
10mm notch radius	2.40	3.1%	22 – 26	15 – 19
30mm notch radius	2.29	3.1%	26 – 27	19 – 20
Straight-edge	1.95	4.3%	26 – 35	15 – 22
Straight-edge	2.23	4.3%	15 – 23	8 – 13
Straight-edge	2.51	4.3%	11 – 17	6 – 11

*- Distance from edge to hole center / starting hole diameter

FINITE-ELEMENT ANALYSIS OF THE RESIDUAL STRESSES

Finite-element analysis (FEA) was performed by Fatigue Technology, Inc., Seattle, WA, developers of the split-sleeve cold-work process and manufacturers of the cold-work tooling. ABAQUS software, using *quadratic reduced integration*, was used to build the elastic-plastic model. The mandrel interference was simulated by applying a uniform radial displacement boundary condition at the hole inner diameter. The boundary condition was then removed, and the structure was allowed to relax back to equilibrium. This FEA was performed in order to validate the experimental results of cold-working near a straight edge [3].

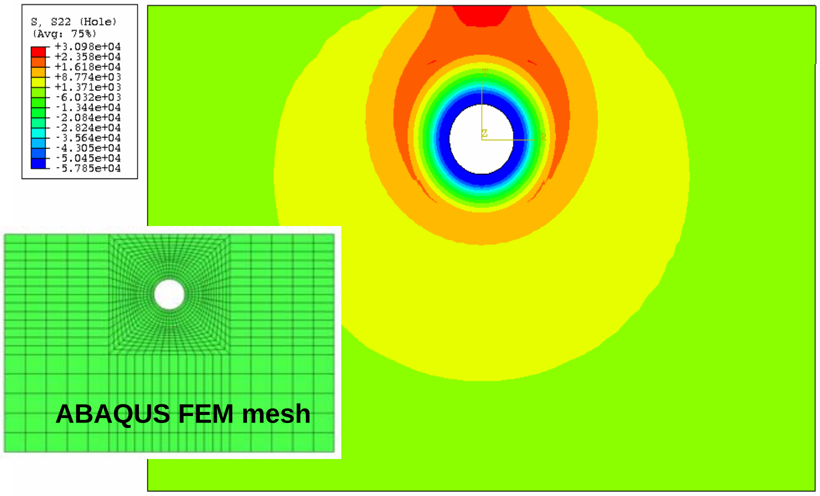


Figure 6: Stress Field around a Cold-Worked Hole near an Edge
(courtesy of Fatigue Technology Inc., Seattle, WA [3])

Figure 6 shows the stress field around the cold-worked fastener hole with an edge-distance ratio of 1.95 and a mandrel interference of 4.3% [3]. The results show a maximum compressive stress of about -58 ksi at the bore of the hole and a maximum tensile stress of about 31 ksi at the edge. It should be noted that in the direction opposite the edge, and at the same distance, the residual stress is only about 11 ksi.

FATIGUE TESTING OF COLD-WORKED SPECIMENS

A series of fatigue tests were performed for specimens containing either a 30mm notch radius or a 10mm notch radius near a cold-worked hole that was later reamed and countersunk. Each specimen contained four holes and notches, as is shown in Figure 7. The 30mm specimen had an edge-distance (edge to center of hole) of 2.66 times the starting hole diameter, while the 10mm specimen had an edge-distance of 2.78 times the starting hole diameter. (The starting hole diameter was 0.283 inches, which was later reamed to a 0.310 inch diameter.)

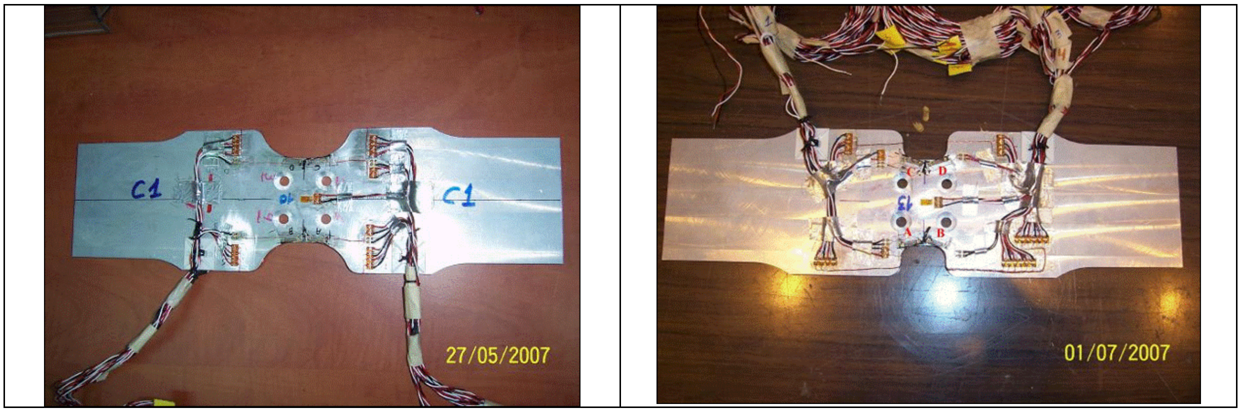


Figure 7: Fatigue Specimens having a 30mm Notch Radius (left) and a 10mm Notch Radius (right)

Three 30mm notch radius specimens were tested under constant amplitude, at a maximum stress of 20 ksi (R = 0.05). The three specimens contained a total of 12 holes. All the failures originated from the outer diameter of the countersunk holes, with a mean life of 186,000 cycles (from 154,700 cycles to 213,700 cycles). Figure 8 shows a typical failure.

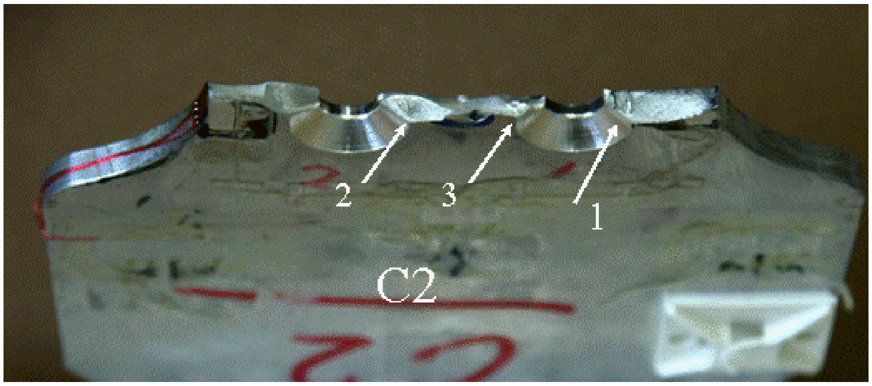


Figure 8: Typical Failure of the 30mm Notch Radius Specimen with the Failures Originating from the Outer Diameter of the Countersunk Holes

At present, only one 10mm notch radius specimen, containing four holes, has been tested. The test was performed again under constant amplitude, at a maximum stress of 20 ksi (R = 0.05). This time, the failure originated from the 10mm radius edge, adjacent to the countersunk hole, at a life of 57,000 cycles. Figure 9 shows the failure of the specimen originating from the edge. Although additional specimens will be tested, already it is clear that substituting a 30mm notch for the 10mm notch has increased the life to failure by a factor of approximately 3, and moved the failure location from the notch to the outer diameter of the countersink of the cold-worked hole.

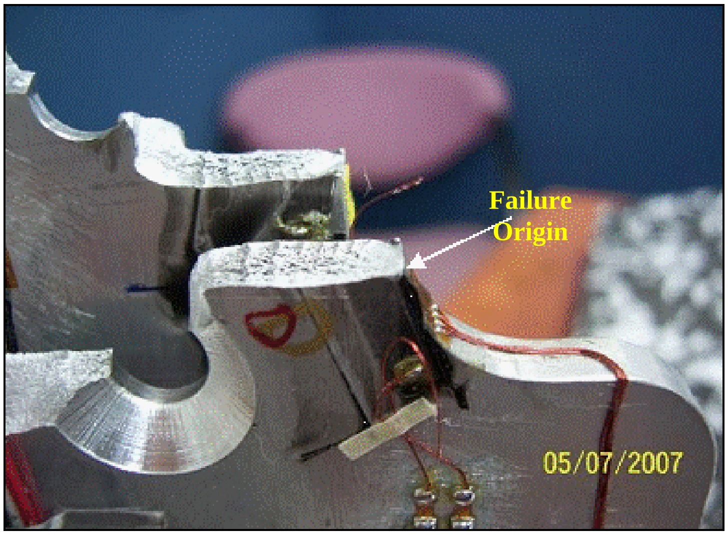


Figure 9: Failure of the Specimen with the Failure Originating from the 10mm Notch Radius

Table 2 compares the stress levels measured for the two specimen types. All the holes were cold-worked by a mandrel interference of 3.89%. It should be noted that, although the holes are separated by a distance of more than 4 diameters, the cold-working of each subsequent hole reduced the residual stresses at the edges of the previously cold-worked holes. (The total residual stress reduction, due to the interaction between the holes, was about 10%.) In addition, differences of about 5% to 8% were noted between the entry and exit sides of the mandrel used for the cold-working operation. The data in Table 2 reflects the range of stresses corresponding to *all holes cold-worked.*

Table 2: Measured Results of Residual Stresses at the Edge of the Fatigue Specimens

Configuration	Edge Distance Ratio *	Range of Edge Stresses Induced by Cold-Working (Ksi)	Range of Edge Stresses After Final Reaming and Countersinking (Ksi)	Range of Edge Stresses Under a 20 ksi External Stress after cold-working ** (Ksi)
10mm notch radius	2.78	15 – 17	13 – 15	56 – 58
30mm notch radius	2.66	13 – 16	11 – 15	48 – 49

*- Distance from edge to hole center / starting hole diameter
** - Includes the residual stresses induced by cold-working

FINITE-ELEMENT ANALYSIS OF THE FATIGUE SPECIMENS

Finite-element analysis of the fatigue specimens was performed by ESRD Inc., using StressCheck (version 7.1) software, which includes elastic-plastic analysis capability. StressCheck produces p-version finite-elements, which negates the requirement of a fine mesh. The analysis was performed using 52 elements at a level of p = 8, which is equivalent to 3324 degrees-of-freedom, to produce a quarter model of the specimen, as is shown in Figure 10. In order to simulate the elastic-plastic behavior of the cold-working process, the nonlinear option was selected [4].

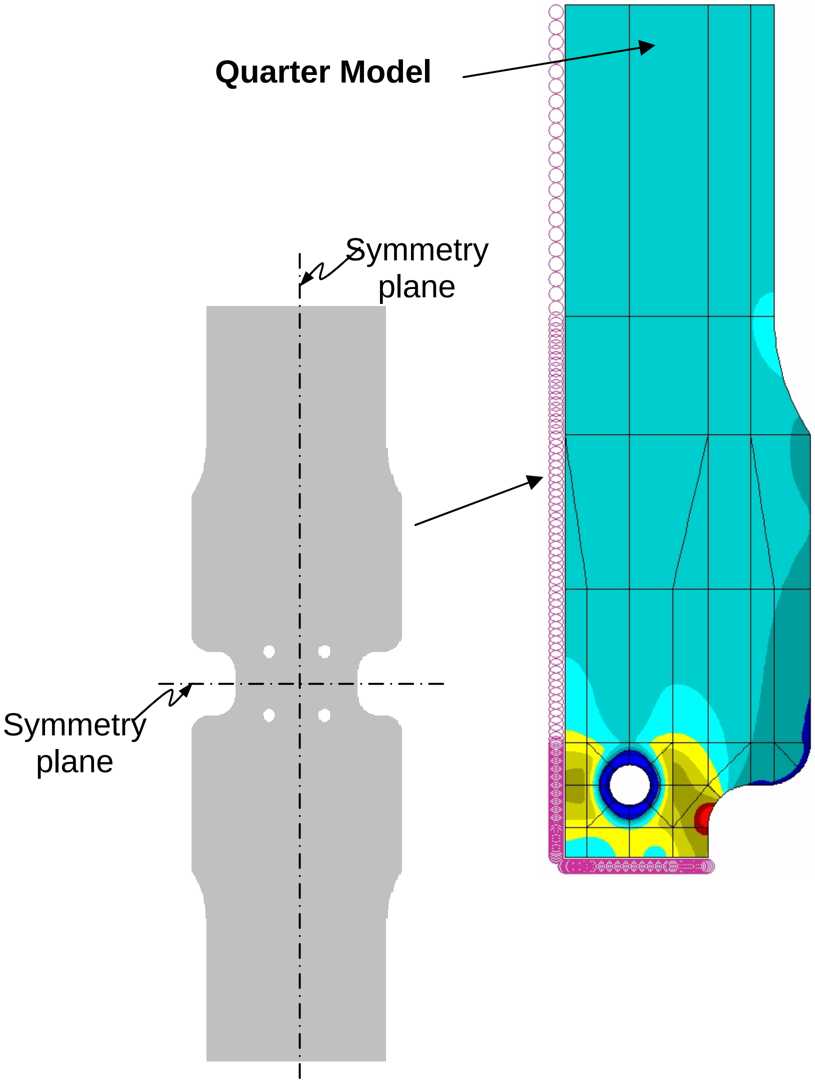


Figure 10: StressCheck FEM Used for Analysis of the Fatigue Specimens [4]

Finite-element analyses were performed, using StressCheck version 7.1, for two conditions: (A) 10mm notch radius with e/D = 2.78, mandrel interference = 3.89%, with and without external loading, corresponding to the fatigue specimen test configuration. (B) The same configuration with the hole diameter increased so that e/D = 2.10.

The stress distribution for condition (A) is shown in Figure 11, for a 20 ksi remote stress. The peak stress at the 10mm notch radius was 13.4 ksi after cold-working and 54.3 ksi after the 20 ksi remote stress was applied to the cold-worked hole. Figure 12 shows the stress distribution along the curved edge of the notch, after cold-working and under the 20 ksi remote stress. Figure 12 compares the StressCheck results to the measured stresses. The StressCheck results are compared to stresses measured after the cold-working operation and during the fatigue test calibration. The correlation was good for both cases, as is shown in Figure 12.

The stress distribution for condition (B) is shown in Figure 13, for a 20 ksi remote stress. The peak stress at the 10mm notch radius was 25.1 ksi after cold-working and 60.4 ksi after the 20 ksi remote stress was applied to the cold-worked hole. It should be noted that yielding occurred at the notch under the 20 ksi remote stress, resulting in stress redistribution.

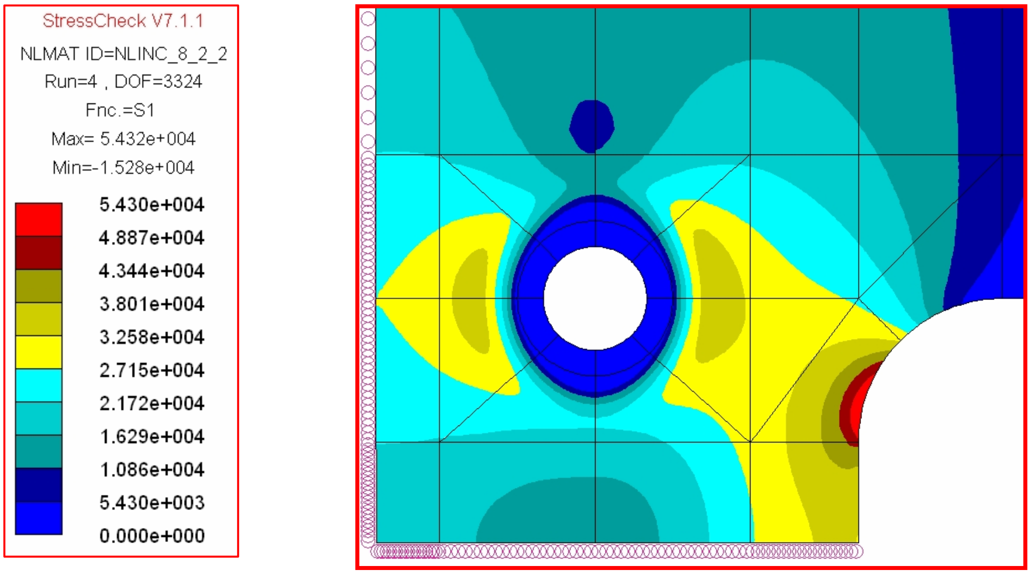


Figure 11: Residual Stress Distribution for Cold-Worked Hole (e/D = 2.78) under a 20 ksi Remote Stress [4]

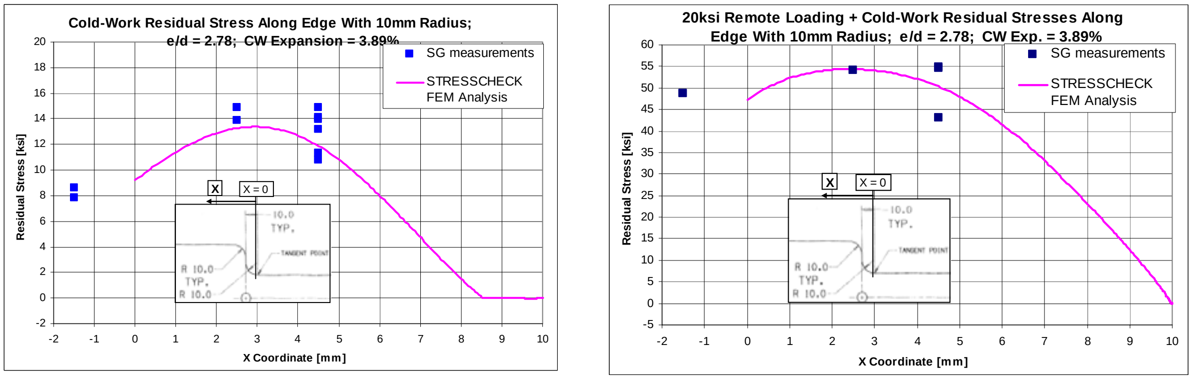


Figure 12: Comparison of Measured Stresses and Calculated Stresses at the Notch after Cold-Working and after the Application of the 20 ksi Remote Stress [4]

Photoelastic analysis of the test specimens after cold-working and under a remote stress was also performed in order to obtain a qualitative comparison to the finite-element results. A typical photoelastic result, after all holes were cold-worked, is shown in Figure 14.

All the test results and the ABAQUS and StressCheck FEM results were combined and are shown in Figure 15 which shows the tensile residual stress at the edge, induced by the cold-working process, as a function of the edge distance / starting hole diameter ratio.

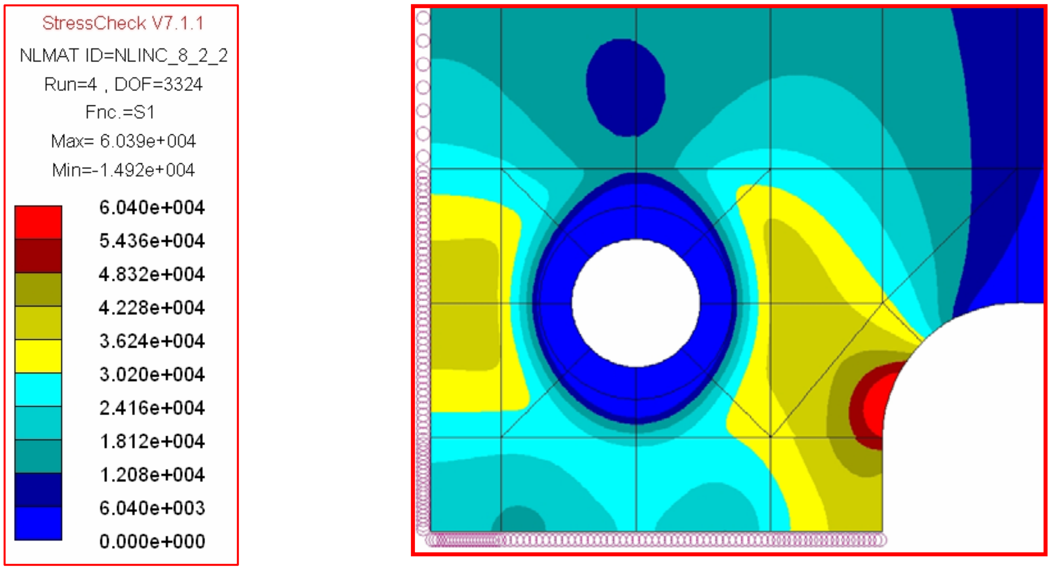


Figure 13: Residual Stress Distribution for Cold-Worked Hole (e/D = 2.10) under a 20 ksi Remote Stress [4]

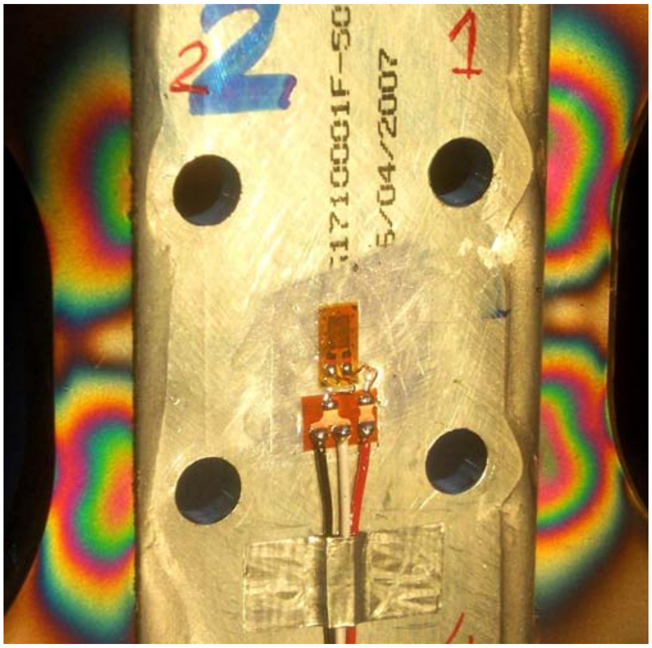


Figure 14: Photoelastic Measurements of Residual Stresses at the Edge Resulting From Cold-Working the Four Holes *(performed by Vishay Israel Ltd.)*

Figure 15 indicates that both finite-element methods (ABAQUS and StressCheck) gave very consistent results. The test results show a fair amount of scatter, both when comparing several identical holes that were cold-worked, and when comparing the test results to the finite-element analyses. The question whether the induced residual tensile stresses are a function of the notch characteristics has not been answered by the results obtained to date. Further testing and analysis are planned to treat this matter.

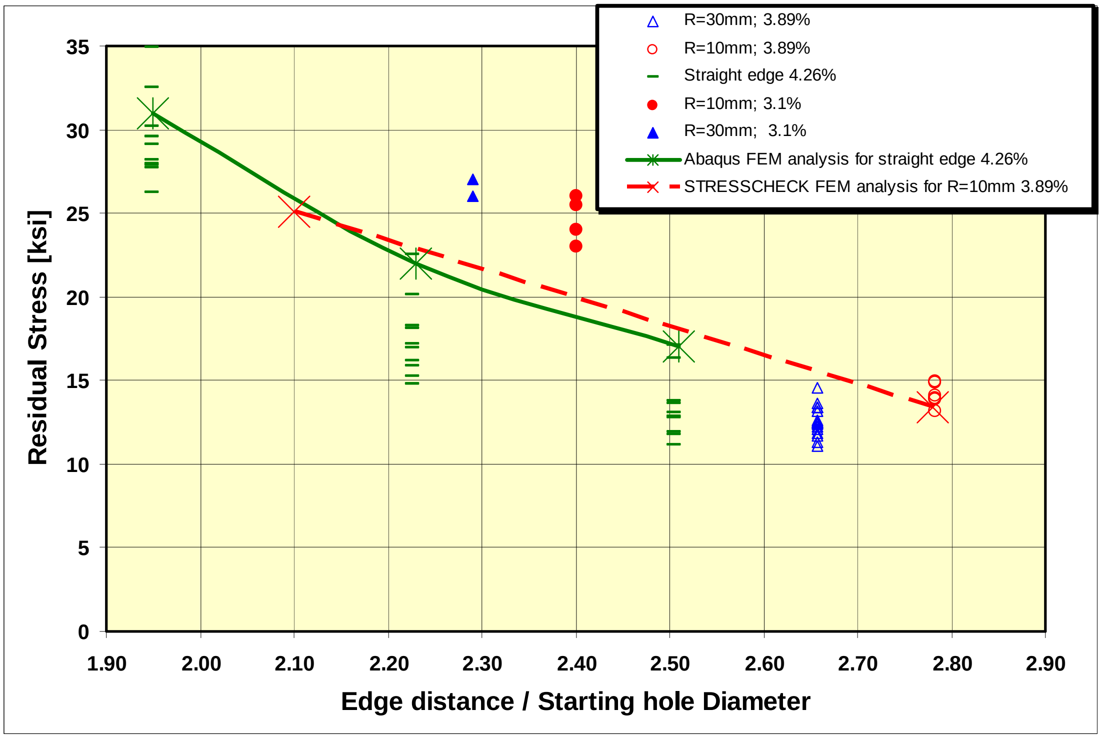


Figure 15: Measured and Calculated Residual Stresses at the Edge, Resulting From Cold-Working

FATIGUE LIFE ANALYSIS

A parametric fatigue analysis was performed in order to evaluate the effect of tensile residual stresses at a notch. 7075-T73 aluminum alloy was used for the study, since ample stress-strain and strain-life data was available for this alloy. Constant-amplitude loading with maximum *notch* stresses of 20 ksi to 50 ksi (R = 0) were taken, superimposed with residual stresses of 0 ksi to 30 ksi. The method for superimposing the notch stresses with the residual stresses is shown schematically in Figure 16. A strain-life fatigue analysis was performed using *FATLAN* software, and the results are shown in Figure 17.

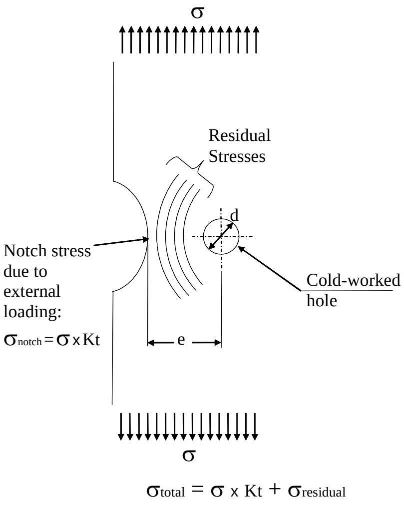


Figure 16: Method of Superimposing of Notch Stresses with the Residual Stresses

The drastic effect that the residual stress has on the mean fatigue life is shown clearly in Figure 17. For example, for a 40 ksi maximum *notch* stress, a 10 ksi tensile residual stress will reduce the mean fatigue life *from about 500,000 cycles to 145,000 cycles.* A 20 ksi residual stress will reduce the mean fatigue life *to only 28,000 cycles.*

Figure 17 summarizes the results of this study. For any combination of maximum notch stress (R = 0) and residual stress, the fatigue life can be obtained using the method shown in Figure 16.

Four specific conditions were selected in Figure 17. The first point corresponds to the fatigue tests performed on the specimens with the 30mm notch radius. A maximum notch stress of 33 ksi, combined with a 13 ksi residual stress yield a mean life at the notch of 625,000 cycles. Since all three fatigue specimens failed at a cold-worked hole (at a mean life of 186,000 cycles), and not at the notch, no specific conclusions can be drawn.

The second point corresponds to the fatigue test performed on the specimen with the 10mm notch radius. A maximum notch stress of 41 ksi, combined with a 13 ksi residual stress yield a mean life at the notch of 72,000 cycles. This compares very favorably with the failure of the specimen at the notch at 57,000 cycles.

The third point corresponds to an e/D of 2.10 with a notch radius of 10mm which was analyzed by StressCheck. From the StressCheck results, a maximum notch stress of 35 ksi, combined with a 25 ksi residual stress yields a mean life at the notch of 42,000 cycles. (It should be noted that this results accounts for the reduction of the combined notch stress to 60 ksi (as noted in the StressCheck results) due to local yielding at the notch and a redistribution of the stresses.)

The fourth point also corresponds to an e/D of 2.1, adjacent to a straight edge (no notch). A maximum edge stress of 20 ksi, combined with a 25 ksi residual stress yields a mean life at the edge of about 10 million cycles. This result demonstrates that the residual stress at the edge ceases to be a problem if there is no notch adjacent to the cold-worked hole.

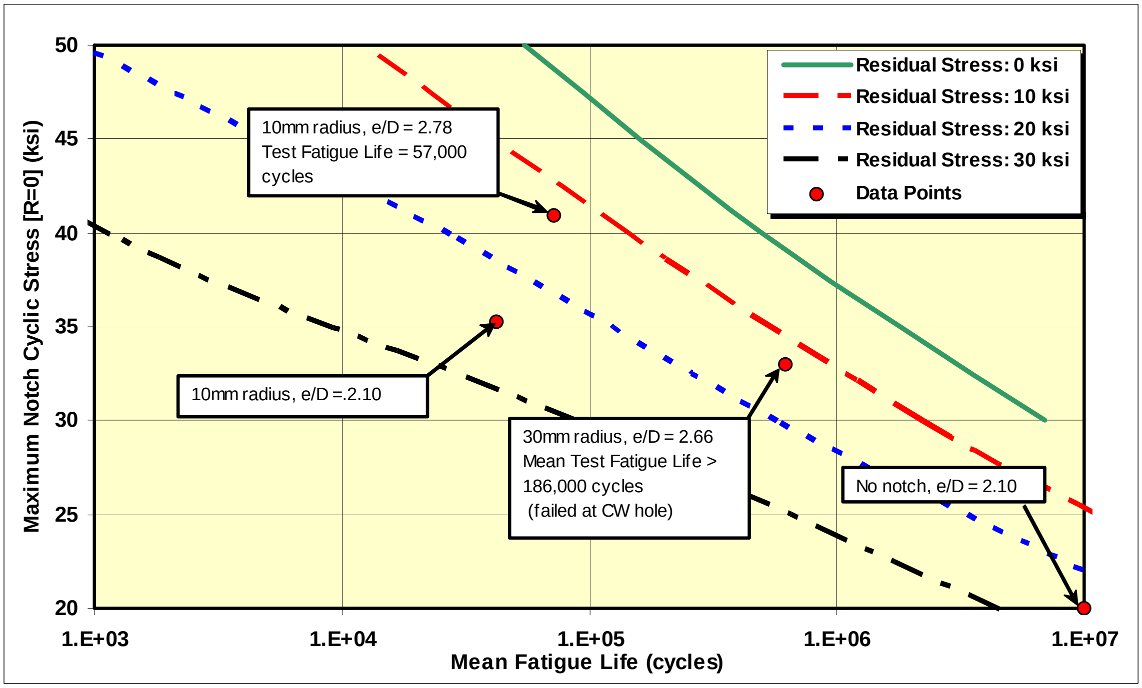


Figure 17: Fatigue Life Analysis for 7075-T73 Aluminum (R = 0) in the Presence of a Tensile Residual Stress

SUMMARY AND CONCLUSIONS

1. Testing and analysis confirm that high tensile residual stresses can exist at an edge near a cold-worked hole.

2. These induced residual stresses are a function of:

    a. edge-distance to hole diameter ratio
    b. level of mandrel interference
    c. whether the fastener hole was final reamed and countersunk
    d. fit of the fastener that is installed in the hole

3. When these residual stresses are combined with high cyclic notch stresses that arise from external loading, the fatigue life at the edge can be drastically reduced. This should be accounted for in the design of details near a cold-worked hole.

4. Additional analysis and testing is needed to further quantify these effects.

ACKNOWLEDGEMENTS

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The authors would also like to thank *Dr. Ricardo Actis* and *Dr. Sebastian Nervi* of ESRD Inc., for performing the elastic-plastic (StressCheck ver 7.1) finite-element analyses.

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