Chapter 12 – SURFACE TOPOGRAPHY INFLUENCES ON STRUCTURAL LIFE PREDICTION

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12.1 WHAT IS SURFACE TOPOGRAPHY? AN INTRODUCTION

Topography describes the complex form of a surface--the undulations which make up its character. Topography comes in all shapes and forms; what is true for the surface of our planet is also true for the surfaces of engineered structures. If you have ever driven across the Flint Hills in south-eastern Kansas, you probably recognize that the only indicator you have that you are climbing a hill is that the engine rpm goes up ever so slightly. These hills have little in common with the hills of south-eastern Kentucky, yet on an ordinary road atlas, they are labeled "hills" just the same. It is not until you look at these regions on a topographic map that the differences become clear. In an engineered structure, sometimes topography is important, and other times it is not. When we produce, for example, a residual strength analysis, the assumption of a pristine surface is the norm. For many types of analyses and under many criteria, this is acceptable. However, surface integrity is often critical to proper function of a structure. Ignoring the form of a surface, or the deviation of a surface from its intended form, either from improper machining, accidental damage, wear, or corrosion, can have profound structural implications.

A cursory scan of basic fatigue design textbooks will reveal fatigue life "knock-down factors" that are a function of machined surface roughness. Sometimes you will even find "knock-down factors" for corrosion. What these two factors (machined surface roughness and corrosion) have in common is surface topography that casts aside any assumption of a perfectly flat surface.

To focus on corrosion, the impacts it can have on structural integrity are clear. Corrosion can greatly accelerate the time to fatigue crack nucleation; it can accelerate the propagation rates of fatigue cracks both chemically and mechanically; it can alter intended load paths. The place where the topography of a surface affected by corrosion is most important is in the nucleation phase of fatigue cracks (or EAC) and in the propagation of these cracks, particularly at smaller sizes (dimensions to come!). That is where the discussions for this section will be focused. This chapter will also address many questions, such as:

- Why is topography important to consider?
- How do we measure it?
- How do we use the information?
- What is the influence of topography on fatigue life calculations?

12.2 THE IMPORTANCE OF TOPOGRAPHY

High-fidelity fatigue analyses must take surface condition into account. To be able to model the physical processes of failure, and to become more holistic, we must understand complex interactions between surfaces and applied stress, both external and residual. The effects of corrosion morphology on fatigue have long been recognized. Studies of the geometric "stress riser" influence of corrosion on fatigue response started long ago, dating back to the 1920s for aluminum alloys [1],[2] and back to the mid-1800s on steels used in the railroad industry. These works continued in earnest through the 1960s [3],[4],[5], 1970s [6], 1980s [7],[8], 1990s [9],[10],[11],[12],[13] and into the 2000s [14],[15],[16],[17],[18],[19],[20]. The stress

risers related to corrosion damage are directly related to topography. If “uniform corrosion” was indeed uniform, there would be no topography, only constant removal of material that, from a fatigue analysis perspective, could conveniently be handled by assuming a uniform, wholesale increase in applied stress with no complex stress concentrations. But, as experience shows, even “general attack” of a surface in an aluminum alloy is characterized by roughness and waviness. Consider the profile below, which is a trace of an aluminum surface subject to general attack (Figure 12-1).

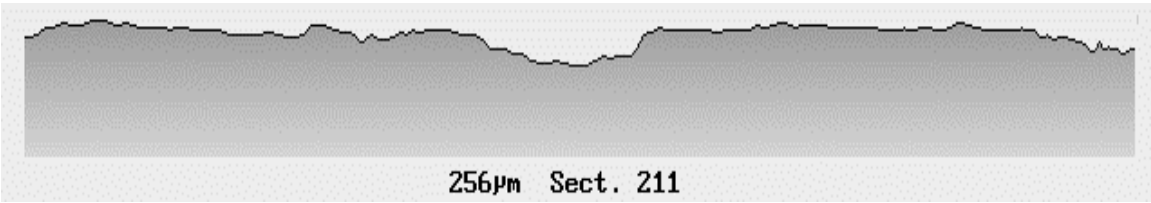


Figure 12-1: Line Profile of Aluminum Surface that has Suffered from General Attack.

The general attack profile has quite different characteristics than a surface subjected to pitting (see Figure 12-2). However, the structural implications can be similar, especially relative to a machined surface.

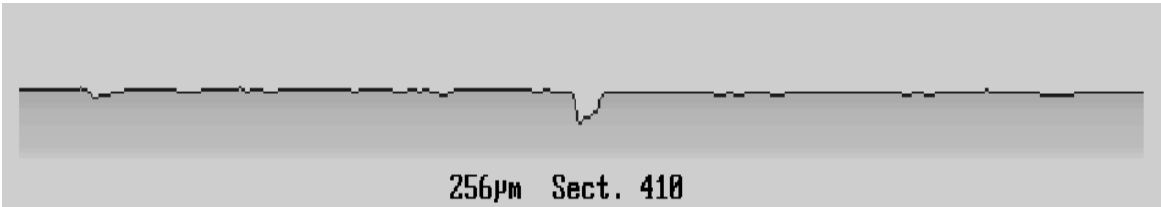


Figure 12-2: Line Profile of Aluminum Surface that has Suffered from Pitting Attack.

Even exfoliation, long considered a uniform material loss with no associated stress concentration, shows topographies that look very similar to general attack; in places, the exfoliation damage may also contain pitting. Regardless of the topography that is present, it is safe to say that in many cases, assuming a loss of material sans stress concentration (i.e., beyond that of net section stress increase) is inadequate, especially in fatigue assessments (see Chapters 6, 10 and 15) for detailed discussion regarding exfoliation).

12.3 MEASURING SURFACE TOPOGRAPHY

As with many technologies, one of the biggest hurdles one must overcome is the difference between being able to measure something in the laboratory versus measuring that same parameter in the field. For measuring surface topography in the laboratory, we might have laser confocal microscopes, or laser profilometers, or stylus profilometers. We might cross-section a sample and use some sort of image analysis software to define the surface profile. Clearly, we have many tools available to us to generate high fidelity surface profile information, in 2D and in 3D. Translating that capability into the field is much more difficult, however.

Using aircraft structure as an example, much of the corrosion in which we are interested is hidden, such as within lap joints or down the bore of fastener holes. In 2000, the USAF launched Phase II of the of Corrosion Fatigue Structural Demonstration program, and a portion of that program sought to understand the relationship between the outputs of conventional NDT methods, such as X-ray, ultrasound, and eddy current, and the surface topography information required to feed structural effects models. DSTO Australia went down a similar path in the same time frame when developing their ‘Process Zone Model’

for modeling exfoliation/fatigue interactions [21],[23]. The conclusion at that time was that although the 'Process Zone' was very successful at modeling the influence of exfoliation on fatigue response, the level of detail required for the corrosion damage morphology was well beyond what could be delivered by available NDT methods.

Figure 12-3 shows an example of data extracted from a field-supportable eddy-current scan of a lap joint compared with a scan down the same line using laser profilometry. The eddy-current scan has a 500-micron resolution, and the laser scan has a resolution of 25 microns. Although the eddy-current data is suitable for estimating basic thickness loss, it does not provide the spatial resolution necessary for high fidelity fatigue analyses (determined in this study to be 25 microns). The eddy-current data in this example would miss finer details associated with pitting, or instance. Keep in mind that not every analysis would require high-fidelity topography information.

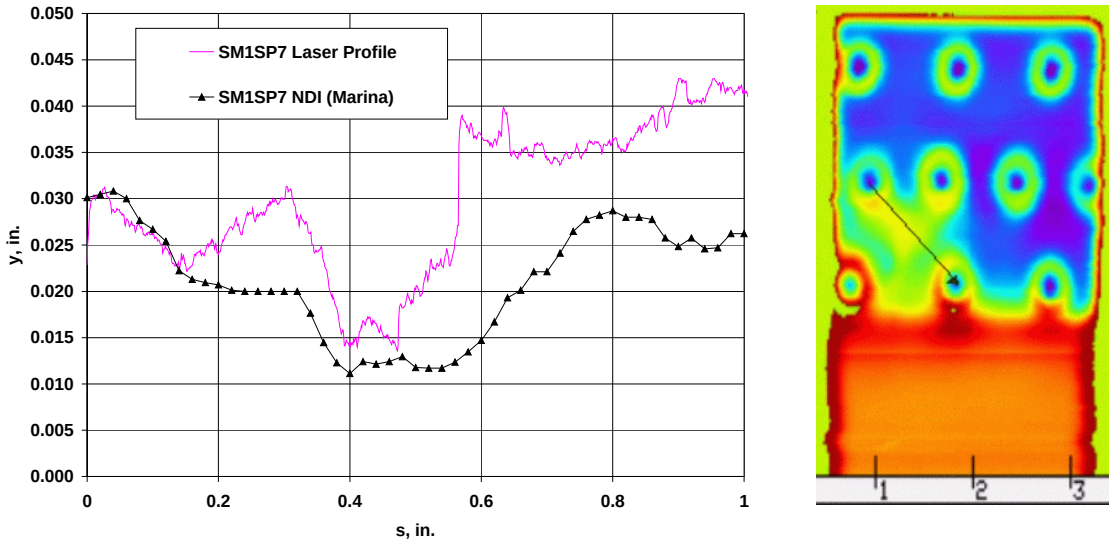


Figure 12-3: Eddy-Current Line Scan Compared with Laser Profile for Same Location.

To try and bridge the gap between NDT capability and structural analysis requirements for corrosion, studies have been undertaken to see if the parameters necessary for surface topography determination can be inferred from the global thickness loss determined by eddy-current. One example is shown in Figure 12-4, where the roughness of corroded samples does indeed correlate to global thickness loss. Note the roughness/ thickness loss relationship also varies by product thickness, as one might expect.

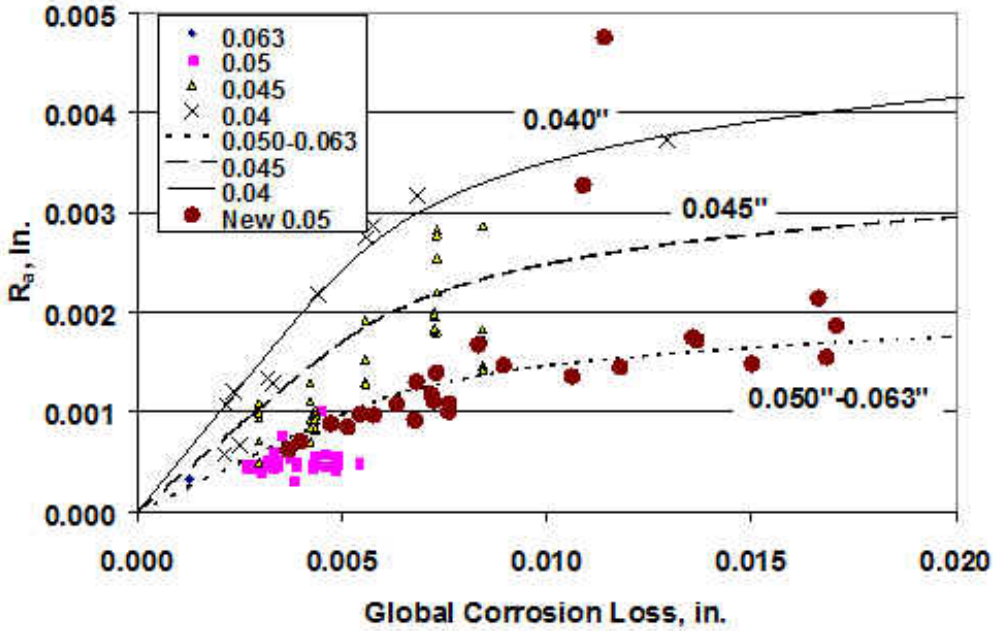


Figure 12-4: Surface Roughness Related to Corrosion Thickness Loss (the solid, dashed and dotted lines represent approximate power law curve fits for each initial product thickness, 0.040", 0.045" or 0.050 – 0.063").

As mentioned in the chapter on exfoliation/fatigue modeling, there is benefit to be gained from pursuing these types of relationships for common engineering materials. The 'Process Zone Model' fell victim to this lack of information. Time would be well spent trying to understand limit states of surface roughness and damage morphologies for various alloys in a variety of product forms and grain orientations.

12.4 TOPOGRAPHY AND FATIGUE ANALYSIS

As this section and countless case studies from field failures show, local topography of a surface can be critical to a structure's fatigue resistance. At the same time, not every structure is fatigue critical or even corrosion fatigue critical. The ability to consider topography in fatigue analysis is another tool we can use to determine the susceptibility of structure to certain types of damage, either in the design stage or in the sustainment phase of a structure's life.

In aircraft, many classification criteria exist for determining what is a primary structural element, a structurally significant item, a fracture critical component, etc. We can combine this knowledge with an understanding of stress levels, local details, and material properties to gain an understanding of which structure might be vulnerable to damage (typically cracking) and which will require inspection during use to ensure safety. This template clearly exists for fatigue, and the methods now exist to expand this capability to include corrosion (although the philosophy in the industry still seems to lag technical capability).

The first step – well before we figure out how much detailed corrosion topography we *can* gather – is to determine what we *need* to gather. This is a function of the structure's susceptibility to corrosion/fatigue (surface topography is much more important to fatigue analysis than it is to residual strength analysis). Structural requirements should define the NDT requirements. At the design stage, if the NDT cannot provide what we need, or if the inspection requirement proves to be too burdensome, then a redesign would likely be in order. In the sustainment stage, a gap between NDT requirement and NDT capability

might force us into determining some sort of gap-filling algorithm that transforms NDT capability into the type of information we need with reasonable confidence (as shown earlier in Figure 12-4).

Determining what we need to gather (and the locations for which we need to gather the corrosion information) is part of corrosion criticality analyses and corrosion tolerance assessments. And as we stated above, the capability exists today to do this type of activity with far more fidelity than it is currently being practiced.

The methods put into practice at APES are centered on determining surface topography correction factors that are used in conjunction with conventional fatigue analyses. These essentially take the form of 'beta corrections' to the stress intensity solution for a crack growing from a flat surface. If the crack is emanating from a deep pit, for instance, the presence of that pit will amplify the stress intensity the crack sees. From an analytical standpoint, this increase in K translates into an increase in crack growth rate, which further translates into a decrease in fatigue life from that crack size to failure compared to the 'uncorroded' baseline condition.

As with traditional beta solutions, finite element technology allows us to build families of beta correction curves for various 'typical' surface topography conditions from varying degrees of general attack to increasing depths and shapes of pitting. In addition, it is possible to develop these beta solutions for any structural detail if that level of fidelity is warranted. Figure 12-5 shows a simplified example of beta corrections for the two surface profiles shown earlier in this section (refer back to Figure 12-1 and Figure 12-2).

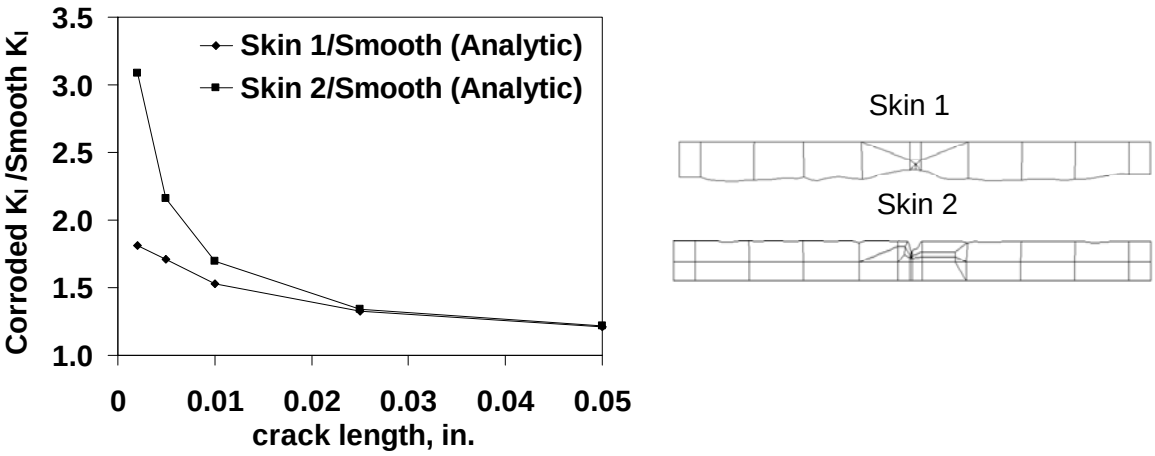


Figure 12-5: Sample Correction Factors for Corroded Surfaces as a Function of Crack Length.

The graph plots normalized stress intensity for the two profiles, the normalized value being the stress intensity of a crack emanating from a corroded surface divided by the stress intensity of the same crack emanating from a flat surface. Two things stand out from the figure – neither of which should be all that surprising. First of all, when the crack is small, the influence of the corrosion is quite large. This effect dissipates quite rapidly as the crack extends away from the surface, but the effect never really goes away (normalized value does not reach unity). Second, the 'pitted' surface (Skin 2) has a much more severe initial correction factor associated with it than does the general attack surface (Skin 1).

One can also examine these beta corrections from a probabilistic sense, wherein a family of corrections (Figure 12-6) for corrosion can be determined by placing cracks of varying sizes at different locations (x-coordinate along surface 'S1_2' in Figure 12-6) along a corroded surface.

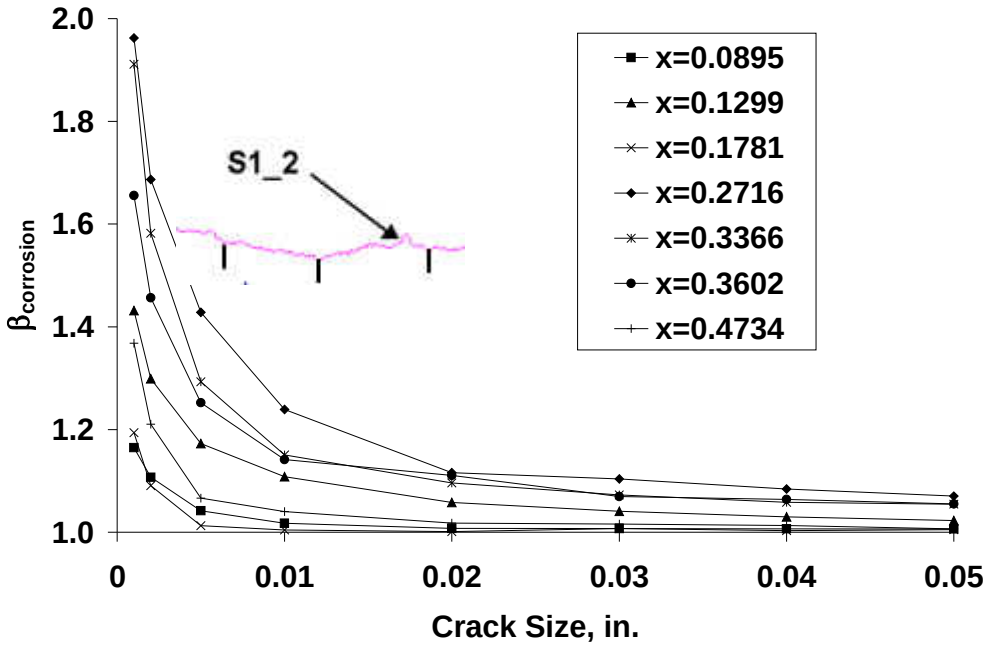
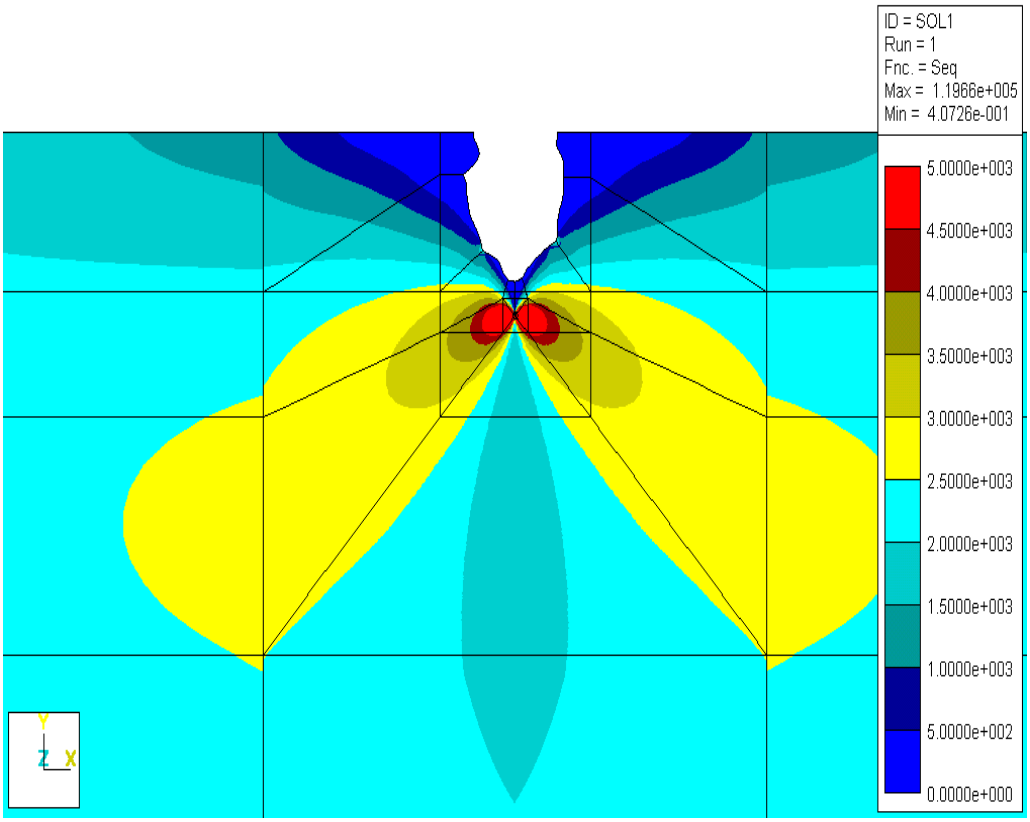


Figure 12-6: Family of Beta Corrections for Corrosion for Various Cracks Along a Line of Surface Topography.

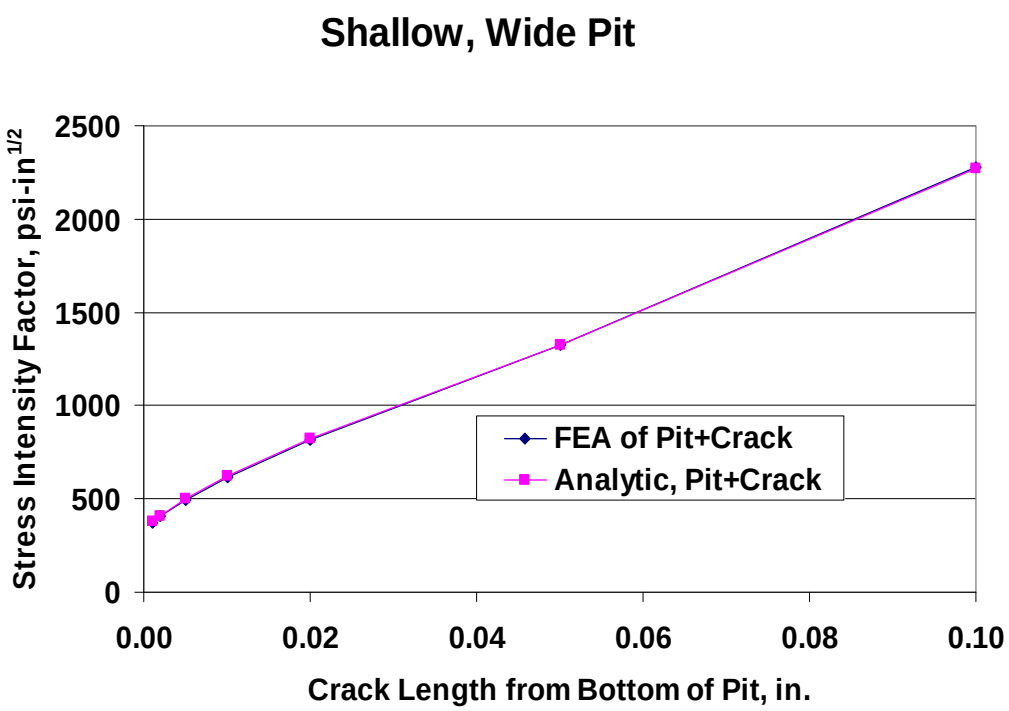
More severe topography gives rise to higher beta correction factors, to the point in fact that very sharp pits (such as those which might attack the short-transverse grain direction of a structural aluminum alloy, for instance), can effectively be modeled as cracks of equivalent depth. This tends to be a slightly aggressive treatment of pitting effects on fatigue, but for certain pit morphologies, this assumption appears to work reasonably well.

The original pitting model developed by APES, Inc. was based on a small study driven by DSTO/AMRL of Australia [23]. The work involved pitting/fatigue in 7050-T7451 aluminum alloy, a material common in their F/A-18 aircraft. In this limited study, planform views of two pits were lifted from fractographs, and these shapes were recreated using two-dimensional finite element analysis (2D-FEA). These analyses confirmed that sharp, deep pits could be modeled as cracks of equivalent depth.

As can be seen from Figure 12-7 and Figure 12-8, these planforms were of quite different shape, but they produced very similar stress states and stress intensity factors, which was a result of similar pit radii at the very tip (bottom) of the pit.

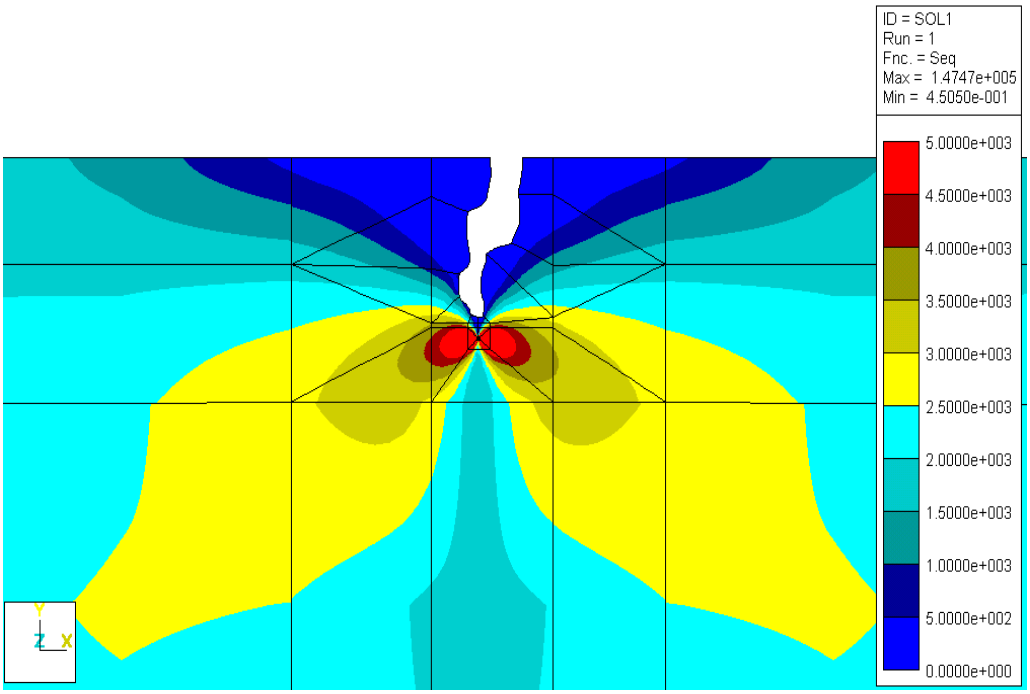


(a)

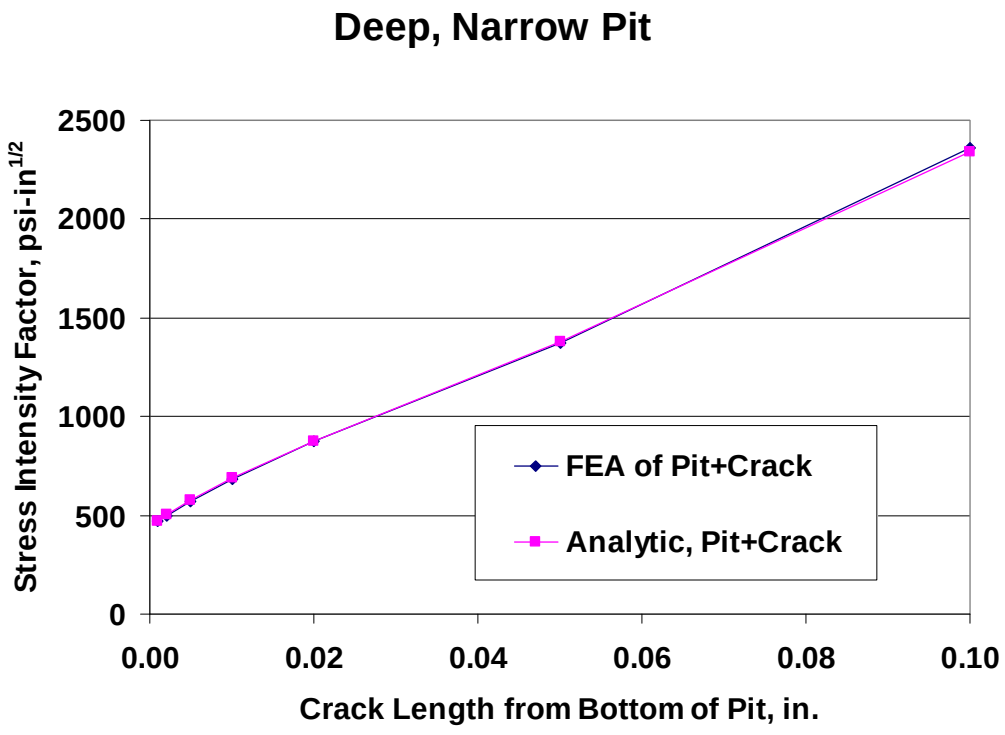


(b)

Figure 12-7: (a) Shows the Von Mises Stress Contours for the Wide Pit with a 0.001 Inch Pit at the Base; and (b) Shows How the SIFs Compare Between FEA and the Analytic 2D-PC Model.



(a)



(b)

Figure 12-8: (a) Shows the Von Mises Stress Contours for the Narrow Pit with a 0.001 Inch Pit at the Base; and (b) Shows How the SIFs Compare Between FEA and the Analytic 2D-PC Model.

In Figure 12-7, the Von Mises stress contours are shown for a wider 'shallow' 0.004 inch (100 micron) pit with a 0.001 inch (25 micron) crack at the base. Similar models were built which varied crack depth from

this same pit geometry, with crack lengths approaching 0.1 inch (250 microns). The stress intensity factors at the crack tip (which would be influenced by the pit) were compared with a simple model that treated the pit as a crack of equivalent depth to which the real crack was added. Figure 12-7 shows the comparison between the FEA model of the real pit + crack (labeled as FEA) and the assumption that the pit is simply an extension of a 2D crack (labeled as Analytic). The Stress Intensity Factors (SIFs) at all combinations of pit depth and crack length are within 1% of each other.

This exercise was repeated with a narrower and deeper pit (0.007 inch, 175 microns). Figure 12-8 shows similar plots for this other pit geometry. Again, the differences between FEA and simplified model were negligible, and so the original APES pitting model, which we now call the 2D Pit/Crack (2D-PC) model was born.

Later work with the US Air Force [24],[25] saw the pitting models expand and benefit from 3D Finite Element Analysis (3D-FEA), which generated beta correction factors for cracks next to hemispherical corrosion pits. In essence, the use of 3D-FEA created a less severe option to the pit-as-crack model developed using the 2D-FEA (see Figure 12-9).

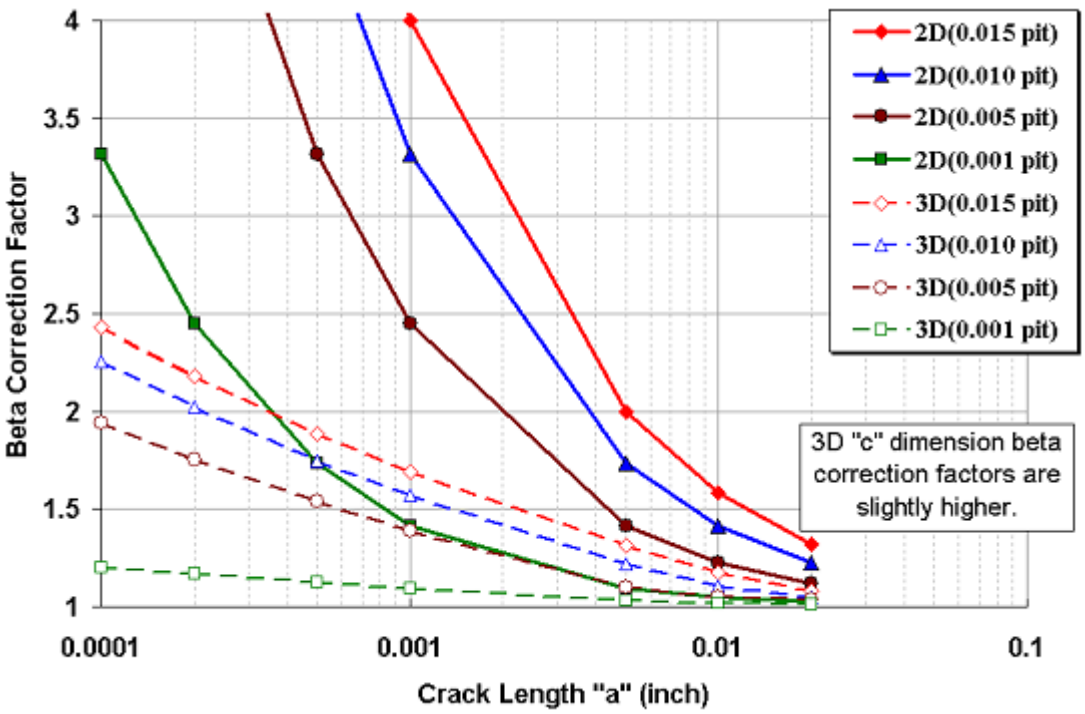


Figure 12-9: Comparison of Sample 3D and 2D Beta Correction Factors for Pitting.

12.5 TOPOGRAPHY INFLUENCES ON FATIGUE LIFE CALCULATIONS

No one clear cut answer exists for the effects of surface topography on fatigue life calculations. However, it is clear just from service failures alone that corrosion, for example, causes structures to fail much sooner than expected. Perhaps one of the most telling examples of the effects of surface topography on fatigue life calculations comes from the modeling of exfoliation corrosion. In the chapter on exfoliation fatigue modeling (see Chapter 15), the observation was made that exfoliation is typically just considered a material loss issue, wherein it can be modeled as a simple reduction in component thickness. This approach is reasonable for strength and stability calculations. And while the impact that this thinning has on fatigue life

computations is real and noticeable, the reduction in life arrived at by this modeling approach misses a very key physical interaction, namely: the surface is far from pristine. It is in fact quite tortuous with many pit-like discontinuities (referenced earlier). These pit-like discontinuities are what drive the often-dramatic life reductions seen in cases of exfoliation/fatigue interactions. It is worth presenting Figure 12-10 as part of this discussion, although it is repeated in Chapter 15. In this chart, experimental exfoliation fatigue data is plotted alongside three different modeling approaches:

1) Thickness loss only;
2) Thickness loss in conjunction with beta corrections from 2D-FEA; and
3) Thickness loss in conjunction with beta corrections from 3D-FEA.

The most important thing to recognize in this example is that when one considers thickness loss as the only influencing factor, then life capability is over-predicted by a factor of four, consistently, at all thickness loss levels examined. Only by including the effects of surface topography do the computed fatigue lives approach those of the experiment.

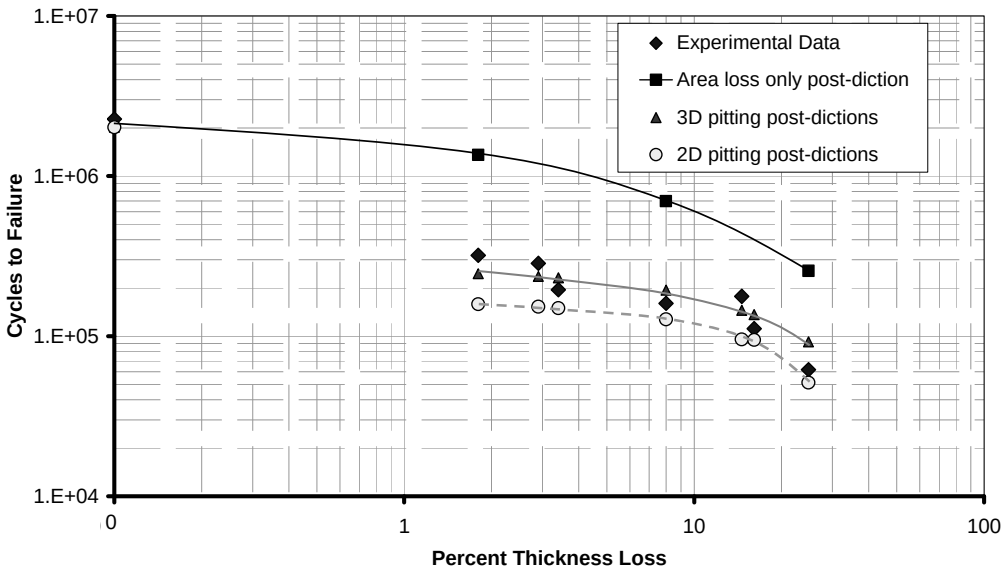


Figure 12-10: Cycles to Failure vs. % Thickness Loss for Exfoliated Coupons (Note that only by incorporating pitting into the model do the post-dicted fatigue lives approximate those of the coupons. Assuming area loss only is extremely unconservative (factor of *four*)).

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