TOOLS AND METHODS FOR LANDING GEAR FATIGUE ANALYSIS WITH SURFACE TREATMENT EFFECTS

R. Plaskitt[1], M. Hill[1], A. Halfpenny[1], B. Griffiths[2], A. Clark[3], B. Madsen[4]

[1] Hottinger Bruel & Kjaer Ltd, United Kingdom, rob.plaskitt@hbkworld.com
[2] Select Engineering Services, USA
[3] USAF Landing Gear Systems, USA
[4] General Atomics Systems Integration, USA

Abstract: Landing gear manufacturing and overhaul/maintenance processes alter surface material properties that influence fatigue life. The effect of these processes was not accurately accounted for in legacy United States Air Force (USAF) landing gear designs. As aging aircraft in the USAF fleet continue to be pushed beyond their originally intended service life, it has become increasingly more critical to characterize the effect of specific surface processing conditions on fatigue life. Surface treatment factors (K factors) from this strain-life fatigue testing programme are used to modify baseline strain-life curves to account for material surface conditions during fatigue prediction calculations from finite element stress analyses. HBK and SES have tested and characterised >20 fatigue curve datasets to derive multiple surface treatment K factors for 3 common landing gear materials; 300M steel, 4340 steel and 7075 aluminium alloy. Surface treatment conditions include chromium, cadmium and nickel plating, anodising, shot peening and combinations and/or repetitions of these, for example, “shot peen, chrome, strip, chrome” to represent repeated landing gear overhaul/maintenance processes. SES has developed analysis tools to support fatigue test data management, K factor and strain-life curve parameter calculation, plot comparisons, and automated material property assignment for fatigue simulations. This paper will:

- Introduce the project in relation to USAF landing gear surface treatment procedures.
- Overview the material and surface treatment test and characterization process.
- Describe the surface treatment K factor database and curve fitting tools.
- Describe the tools used to integrate these surface treatment parameters with CAE-based fatigue simulation tools.

Positive outcomes and conclusions resulting from completed surface treatment research and analysis include:

1. Increased confidence in life extension for aging aircraft landing gear components.
2. The timely removal of landing gear components from service to decrease the risk of failure.
3. The potential for improvements to repetitive overhaul processes that will reduce their negative impact on fatigue life.

Keywords: fatigue modelling, landing gear, maintenance, surface treatment, K factors

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BACKGROUND

This work originates from a 2016 USA government Small Business Innovation Research (SBIR) request "Landing Gear Fatigue Model K Modification" [1] from Department of Defence Air Force to develop more precise predictive models for the fatigue characteristics of landing gear by developing the modification factors, and states:

> "Landing gear experiences numerous processing steps that expose it to environments and chemicals that influence microstructure and surface finish in a way that negatively impacts fatigue life. These effects are difficult to include in landing gear fatigue models because specific effect curves (K modification) are unavailable for specialized landing gear material/process combinations typically used by the Air Force. It is desirable that modification factors be developed for the following material/process combinations so Air Force can incorporate fatigue reductions into landing system models.
> The primary method of fatigue initiation used is strain life sequenced damage accumulation. This research addresses repeated processing of components, for example, 'shot peen, chrome, strip, chrome' to represent repeated landing gear overhaul/maintenance processes. Typical landing gears will be subject to adverse processes multiple times throughout the components' life cycle."

Griffiths et al [2] in a 2019 ASIP paper with similar authors states: "As of October 2018, the average age of aircraft across the entire USAF fleet was 28 years, with some specific aircraft averaging as much as 56 years. Many of these aircraft have been maintained well beyond their original design life." Three years later in 2022, the "Air Force Times" [3] reported "The service's aircraft now average 29 years old; about half the inventory dates back to the 1980s or earlier. … Attempts to replace geriatric fleets with new technology have been slow moving. When planes get old they inevitably need more maintenance — whether on a day-to-day basis or as part of more intensive overhauls that extend an aircraft's life span but take up more time in depots."

In [4], Clark, (the landing gear systems lead engineer at "Air Force Sustainment Center"), summarises the USAF landing gear structural integrity design process as:

- Safe Life Design:
  - design to 4 lives, test to 2 lives, fly to 1 life.
- Common Failure Modes of Landing Gear Materials
  - general corrosion, stress corrosion cracking, grinding burn (decreases hardness and causes tensile residual stress), and hydrogen embrittlement.
- Protective Coatings & Processes
  - coatings to protect against corrosion, control of processes to reduce the risk of grinding burns and hydrogen embrittlement.

These protective coatings and processes are collectively referred to as surface treatments and are applied to landing gear components to both control their dimensionality and to protect their structural integrity against these failure modes. In [5], Griffiths summarises how landing gear surface treatments affect surface material properties (microstructure, roughness, and residual stress), and how multiple coatings are applied, stripped and re-applied for an indeterminate number of overhauls. These surface treatments have known detrimental effects on fatigue life but were not considered in legacy USAF design. Many landing gear components currently in service have been overhauled or re-worked numerous times.

Select Engineering Services (SES), in a teamed effort with General Atomics Systems Integration (GA-SI) and Hottinger Bruel & Kjaer (HBK), has conducted research/testing for the USAF 417th SCMS/ GUEA Landing Gear office. The purpose is to develop efficient test and analysis methods to improve the accuracy of landing gear fatigue life predictions. This paper is a summary of the authors 2019 ASIP paper [2] and 2021 HBK Technology Days presentations [4] and [5] (reducing 60 pages and slides into 4), extends the reported fatigue tests and adds the MAPA "Material Assessment & Predictive Analysis" tools.

MATERIALS, COATINGS AND PROCESSES

A comprehensive review of landing gear materials (x23), coatings (x8) and processes (x8) are described and listed in Table 1 and Table 2 of [2]. The number of potential material / coating / process combinations is very high and is further increased and complicated if repeated overhaul cycles are considered. A full fatigue test programme for all potential combinations is not practical and would be prohibitively expensive. The material / coating / process combinations were identified and prioritised for fatigue testing based on the facilities and procedures available for maintenance and overhaul at Hill Air Force Base:

- Materials tested to date include 300M steel, 4340 steel and 7075 aluminium alloy.
- Surface treatment conditions tested to date include chromium, cadmium and nickel plating, anodising, shot peening, grinding/machining, and combinations and/or repetitions of these.

A fatigue methodology and fatigue test programme was developed to both prioritise combinations and make most efficient use of available resource budget: time, financial and material. The chosen fatigue methodology was a combination of the standard strain-life fatigue method (to determine a material baseline) combined with a strain-life surface treatment factor adjustment. This combined approach was chosen because the strain-life method provides a superior fatigue life model for landing gear, and the surface treatment factor model requires significantly fewer test samples than trying to characterise every surface treatment separately.

FATIGUE METHODOLOGY

Strain-life fatigue

The strain-life fatigue method was selected as the preferred basis for all fatigue testing and all landing gear fatigue life predictions. The strain-life fatigue method has been established for many years and is described in established fatigue literature such as Bannantine, Comer & Handrock [6], Schijve [7] and Lee, Hathaway & Pan [8]. In [4], Clark states landing gear repair and design historically used stress-life fatigue and now use strain-life based fatigue life prediction. In the ICAF 2005 and 2007 UK National Review [9] and [10], Siddall of Messier-Dowty landing gear systems, reported their transition to a strain-life approach to safe life fatigue analysis of all structural items on new aircraft programmes. Siddall reviewed the reasons for this change and noted:

(i) that where very high strain levels are seen during fatigue cycling, the stress-life method breaks down – typically for military aircraft and when assessing growth in civil aircraft weights.
(ii) that a strain-life curve normalised to stress is equivalent to a stress-life curve in the high cycle region, so the strain-life method is applicable across the whole range of high and low cycle conditions seen by various landing gear configurations.
(iii) and concluded that one fatigue method, the strain-life fatigue method suits all fatigue cycle regions for landing gear design fatigue life prediction.

The strain-life fatigue method requires strain controlled fatigue testing over a range of strain amplitudes and range of fatigue cycles to failure, followed by characterisation using statistical methods to fit parameters for the Ramberg-Osgood-Neuber cyclic plasticity model and Coffin-Manson-Basquin strain-life model. This is described in detail and mathematically in Section 4 "Material Characterization and Statistical Analysis" of [2].

A minimum of 25 fatigue tests are recommended to characterise material fatigue performance from low cycle fatigue (about 10^3 cycles) through to high cycle fatigue (about 10^7 cycles). This results in a strain-life fatigue curve with sufficient statistical reliability and confidence interval, for both the mean life (regression) curve, and a design life curve with 97.7% certainty of survival with 95% confidence. Halfpenny demonstrates this statistically in "Case Study 1 – Sample Size" in [11], showing 20 to 30 evenly distributed, equally biased, fatigue test samples are the minimum practical sample size for strain-life material characterisation from low to high cycle fatigue, from 10^3 to 10^7 cycles.

Surface treatment factors, K_{sur}

The K_{sur} method for surface treatment factors models the effect of a surface treatment and is also described in established fatigue literature [6-8]. The K_{sur} method was originally derived for stress-life fatigue curves and assumes that surface effects are mostly confined to the high cycle fatigue region. It is reasoned that under high cycle fatigue loading, the applied loads are relatively low and localised fatigue initiation sites are dependent on the surface condition. The K_{sur} method adjusts the slope of the stress-life fatigue curve in the high cycle region to account for surface treatments that reduce fatigue life (K_{sur} <1) and those that extend fatigue life (K_{sur} >1).

The classical stress-life K_{sur} method assumes that independent surface treatment factors (K_1 , K_2 , K_3) can be combined to account for sequentially applied treatments, as the example in Equation (1). However, this research demonstrates that it is not quite as straightforward as just combining treatment factors. As an example, if the factor for a specific surface roughness is applied, it results in a reduction. In the case of cadmium plating, a surface that was ground to a certain roughness, then sand blasted, and finally cadmium plated, resulted in a net zero reduction in fatigue life. If the grinding roughness treatment factor were simply combined with the cadmium plating treatment factor, this would give an inaccurate and conservatively low estimate of fatigue life.

$$K_{sur} = K_{treatment\ 1} \times K_{treatment\ 2} \times K_{roughness} \quad (1)$$

As noted by Siddall above, landing gear are subject to low and mid cycle fatigue loading with high strain levels, and these are not adequately represented by the stress-life fatigue method. The applied loads and resulting strains are higher in these fatigue regions, and these higher load and strain cycles have a more significant impact on fatigue initiation than surface effects. As a result, most landing gear design analysis now use the strain-life fatigue method because this fatigue damage model includes this low and mid cycle range, as well as the high cycle fatigue range.

Significantly the K_{sur} method requires a much smaller fatigue test sample size to achieve the required statistical accuracy and confidence. A minimum of 12 fatigue tests are required to characterise each surface condition with respect to a baseline curve compared with 25 fatigue tests for a full range equally biased low to high cycle strain-life curve. This is possible for two reasons (i) fitting only a single K_{sur} factor instead of fitting five strain-life parameters, and (ii) being able to bias the fatigue tests for more results in the mid to high cycle fatigue region.

Extending surface treatment factors, K_{sur}, to strain-life fatigue

The standard Coffin-Manson-Basquin strain-life equation is given in Equation (2):

$$\varepsilon_t = \varepsilon_e + \varepsilon_p = \frac{\sigma'_f}{E} N_r^b + \varepsilon'_f N_r^c \qquad (2)$$

Where ε_t is the total strain amplitude of the fatigue test, is ε_e is the elastic strain amplitude from the Basquin term, and ε_p is the plastic strain amplitude from the Coffin-Manson term. N_r is the number of reversals to failure, E is the cyclic elastic modulus from the Ramberg-Osgood cyclic plasticity model. The remaining Basquin parameters fatigue strength coefficient σ'_f and fatigue strength exponent b, and Coffin-Manson parameters fatigue ductility coefficient ε'_f and fatigue ductility exponent c, are derived through regression analysis.

To apply the surface treatment factor K_{sur} to a strain-life curve the Basquin fatigue strength exponent b is replaced by b', with an expression for K_{sur} given in Equation (3).

$$K_{sur} = \frac{\varepsilon_{b'}}{\varepsilon_b} = (N_e)^{b'-b} \qquad (3)$$

Where b is the Basquin fatigue strength exponent of the elastic line for baseline polished fatigue test specimens, and b' is the exponent of the elastic line for the surface treatment specimens, and N_e is the endurance limit number of reversals. The exponent b' is calculated by least squares optimisation. This is easier to visualise graphically, where K_{sur} is the ratio of treatment elastic strain $\varepsilon_{b'}$ to baseline elastic strain ε_b at the endurance limit N_e as shown in Figure 1.

This is described in more detail in Section 4 “Material Characterization and Statistical Analysis” of [2] including the calculation of exponent b' by least squares optimisation and for strain-life design curves at a specified reliability target and confidence interval.

SAMPLE RESULTS AND FATIGUE METHODOLOGY VALIDATION

Sample results for 300M steel with electrolytic nickel plating are shown in Figure 2 and Figure 3:

- Figure 2 (a) shows Ramberg-Osgood cyclic stress-strain curve for polished baseline and surface treatment. The difference in these curves suggests a change in the nominal cross-sectional stiffness.
- Figure 2 (b) shows an approximate plating depth of 0.21mm and would account for this overall reduction in effective stiffness. This has no impact on the K_{sur} results as these are derived from measured strain and not stress.
- Figure 3 (a) shows Coffin-Manson-Basquin strain-life curves for polished baseline and surface treatment. This shows the surface treatment has a very significant detrimental effect on high cycle fatigue.
- Figure 3 (b) shows an equivalent *collapsed* view of these strain-life curves.

The purpose of the *collapsed* view in Figure 3 (b) is for better visual comparison of the goodness of fit of the K_{sur} curve for validation of the K_{sur} surface treatment factor characterisation method applied to strain-life curves. In this case, rather than fitting a K_{sur} curve through the measured data points, the data points are rotationally transformed by K_{sur} to ideally overlay the polished data points. This *collapsed* view also allows a comparison of the relative design curves.

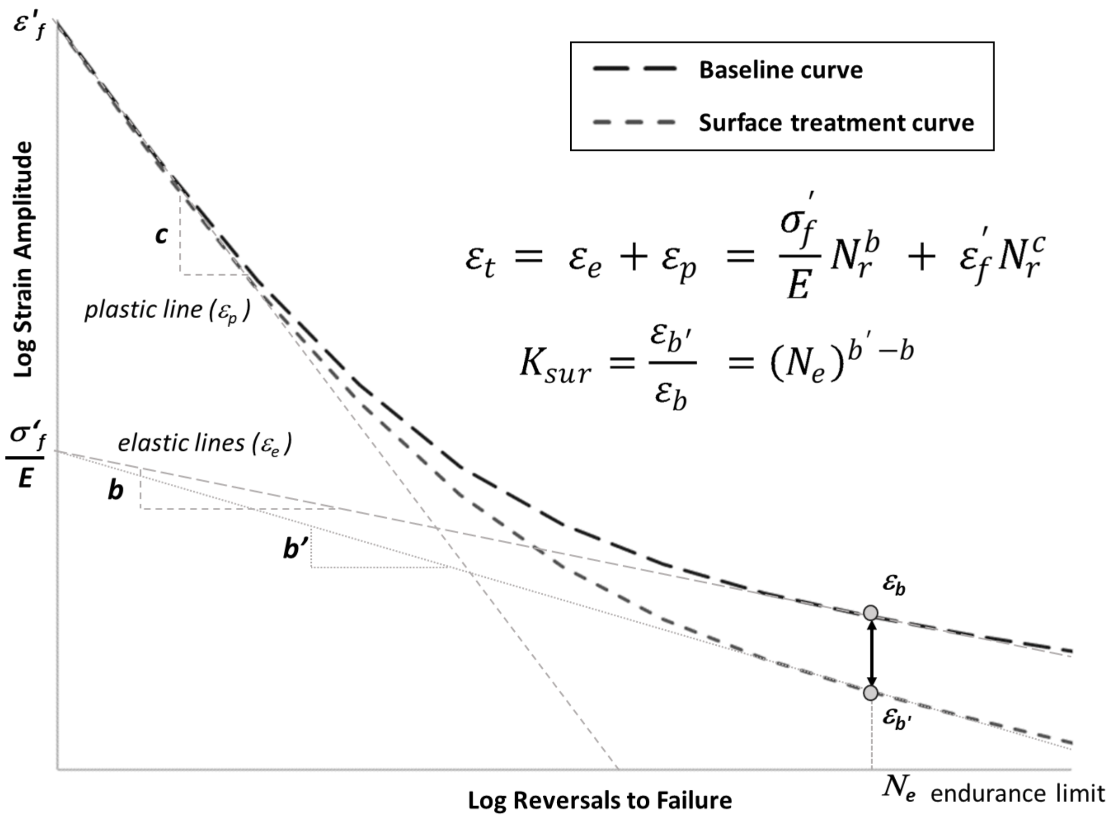
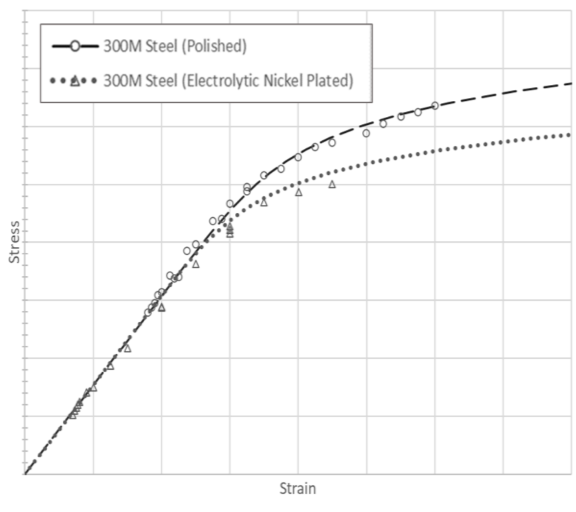


Figure 1: The Coffin-Manson-Basquin strain-life equation with surface treatment K_{sur} method.

(a) Cyclic stress-strain curves.



(b) Optical microscopy of a failure surface.

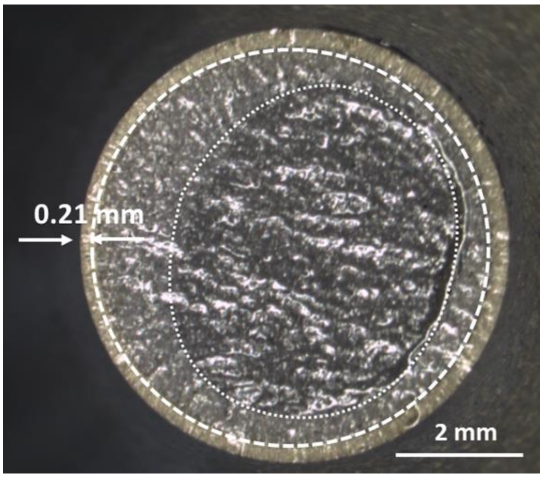


Figure 2: (a) Ramberg-Osgood cyclic stress-strain curve for polished baseline and surface treatment, and (b) Optical microscopy of a failure surface showing coating thickness and failure initiation around the entire periphery of the specimen

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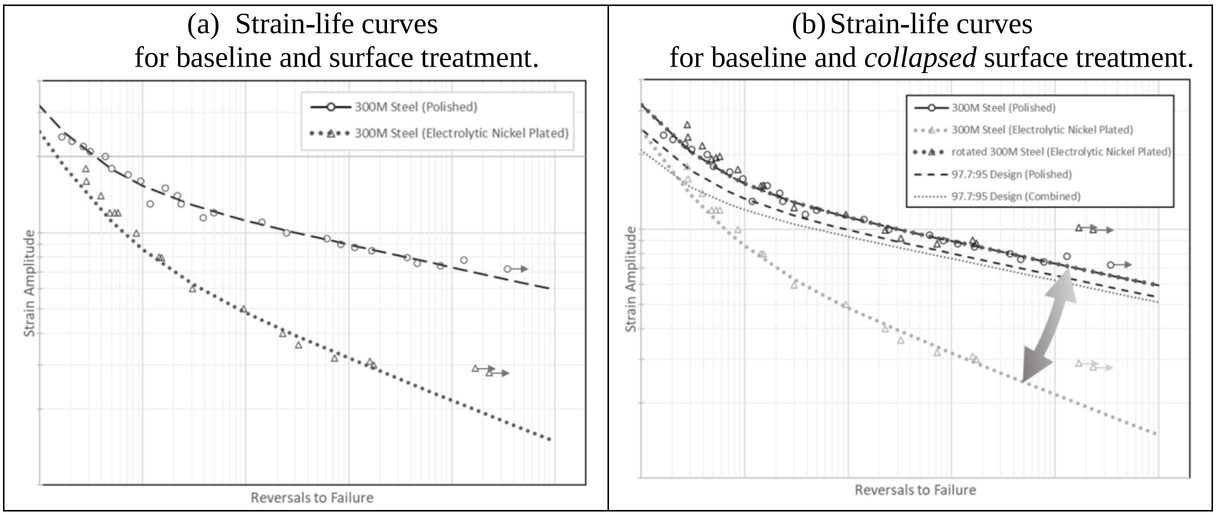

Figure 3: (a) The Coffin-Manson-Basquin strain-life curves for polished baseline and surface treatment, and (b) with an equivalent *collapsed* view of the surface treatment strain-life curve.

Multiple material and surface treatment coating and process combinations have been tested and characterised, and the K_{sur} surface treatment factor characterisation method with strain-life fatigue validated. For this paper only one sample result can be shown, and 300M steel with electrolytic nickel plating was chosen (i) to highlight the reduction of stiffness resulting from the nickel coating for the same nominal 6mm gage diameter fatigue test specimen, (ii) to highlight a large K_{sur} surface treatment factor and how the *collapsed* view enables this to be rotationally transformed to overlay with the polished curve.

Results for other materials and surface treatment coating and process combinations have shown varying levels of K_{sur} surface treatment factors, some that are detrimental to fatigue performance, some that have negligible effect, and some that are beneficial to fatigue performance. In all cases other than electrolytic nickel, the shot peening process was very effective in restoring the negative effect of the tested coatings.

USAF LANDING GEAR ANALYSIS WITH “MAPA”

In [4], Clark states contemporary USAF landing gear analysis combines ANSYS finite element stress analysis for static stress margin of safety and 1G residual stress analysis for below stress corrosion cracking thresholds, and nCode DesignLife for fatigue stress/strain analysis and strain-life fatigue life modelling with Miners’ fatigue damage accumulation.

It is useful to recall the original aims of the 2016 SBIR request [1] for “Landing Gear Fatigue Model K Modification” from Department of Defence Air Force: “to develop more precise predictive models for the fatigue characteristics of landing gear by developing the modification factors”. The extension of surface treatment factors, K_{sur}, to strain-life fatigue, and extensive strain-life fatigue testing and characterisation for materials and surface treatment coating and process combinations provide the base material fatigue data for these more precise predictive models. To deliver to USAF these landing gear fatigue life analysis benefits, SES have developed the MAPA “Material Assessment & Predictive Analysis” tools. These MAPA tools were introduced by Griffiths [5] in 2021, and this paper summarises the MAPA 2023 capability below and in Figures 4 to 6.

- MAPA Data Manager
  - To manage all raw fatigue test data, and resultant strain-life and K_{sur}, fatigue parameters.
  - To compare raw data and fitted curves.
  - Table 1 shows the material and surface treatment conditions in this database.
- MAPA Curve Fit Editor
  - To curve fit raw fatigue test data into strain-life and K_{sur}, fatigue parameters.
  - To control the curve fitting process, include/exclude data points, set design curve reliability and confidence levels, etc.
  - To generate material fatigue datasets with built-in K_{sur} for use in nCode DesignLife.
  - To synthesise new material fatigue "what if" datasets with consecutive surface treatment conditions from tested polished baseline material and tested K_{sur} factors.
- MAPA Simulation Manager
  - Generate node group files in ANSYS for input to nCode DesignLife, utilizing solid model geometry selection tools in ANSYS.
  - Automate material property assignment and bill of materials.
  - Export configuration/material assignments for use in nCode DesignLife.

Table 1: MAPA Data Manager list of materials and surface treatments.

Material	Surface Treatment
300M steel	Polished , without shot peen (***baseline***), with shot peen.
	Electrolytic nickel coating (plated to size, ground to size), with and without shot peen.
	Electroless nickel coating (plated to size), with and without shot peen.
	Cadmium coating, with and without shot peen. (*always plated to size, never ground*)
	Chrome coating (plated to size, ground to size), with and without shot peen.
	Chrome coating (plated to size, ground to size), shot peen, strip & replate six times.
4340 steel	Polished, without shot peen (***baseline***).
	Chrome coating (ground to size), with and without shot peen.
	Chrome coating (ground to size), shot peen, strip & replate six times.
7075 aluminium	Polished, without shot peen (***baseline***).
	Anodised, with and without shot peen.

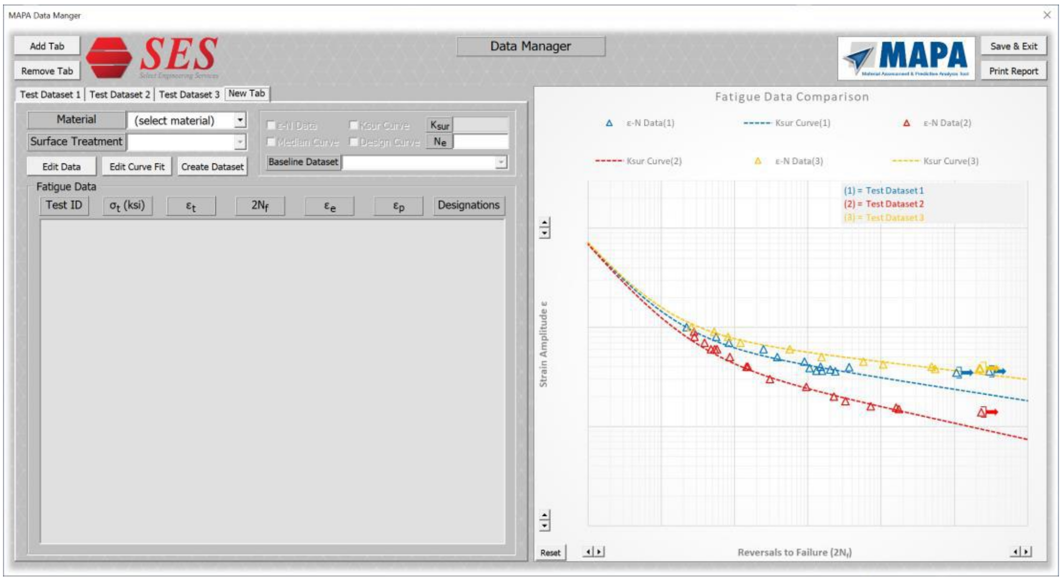

Figure 4: MAPA Data Manager

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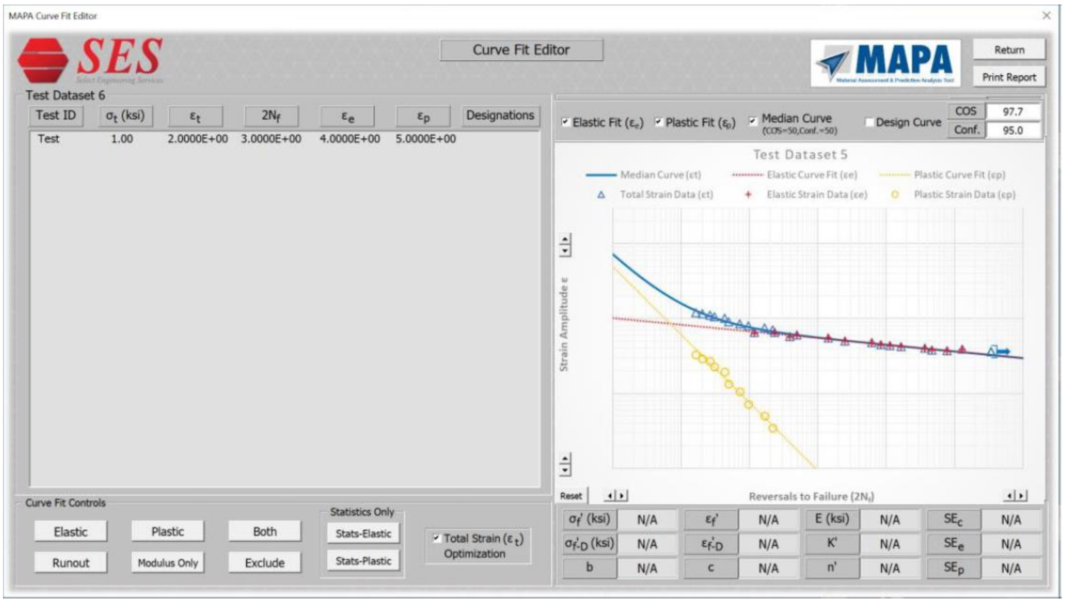

Figure 5: MAPA Curve Fit Editor

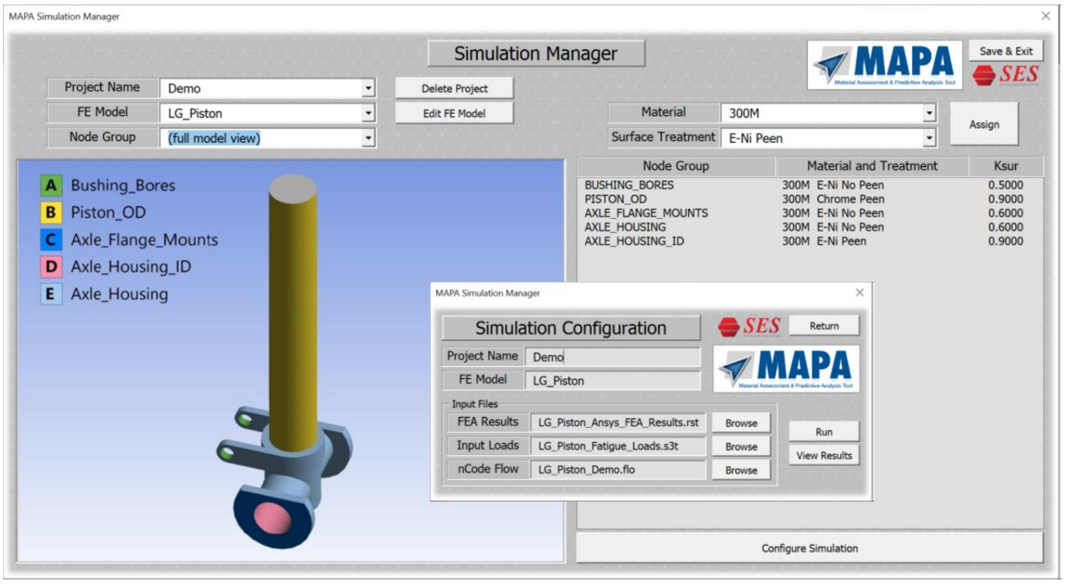

Figure 6: MAPA Simulation Manager

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CONCLUSIONS

It is previously known that different surface treatments can have a detrimental or beneficial effect on high cycle fatigue. For the material and surface treatment combinations tested and listed in Table 1, these fatigue tests and subsequent characterisation have quantified these surface treatment effects. They have shown that the surface treatment factor, K_{sur} method, can be successfully applied with the strain-life fatigue method with an acceptable fit to the measured data. This validates the decision enabling the reduction in fatigue test sample size enabling more efficient testing, i.e., more surface treatments quantified within the same budget or total number of tests. Furthermore, the surface treatment factor, K_{sur} model, can be used in statistical analyses to represent a combined material and surface treatment design curve with a specified reliability and confidence.

Fatigue test results have led to the following conclusions that are specifically relevant to selected materials and surface treatment conditions:

1. Chrome plating of steel (or anodizing of aluminium) has a significant and adverse effect on the high-cycle fatigue performance of the material. However, its effect on low-cycle fatigue performance is much less. The K_{sur} method shows good correlation with the observed results.
2. Shot peening prior to chrome plating (or anodizing) appears to negate completely the detrimental effects of the process.
3. Repetitive surface treatment applications appear to contribute to the statistical scatter, but do not adversely affect the mean fatigue behaviour.

Fatigue testing work is continuing to consider more materials, more surface treatments, coating depths, the effect of re-applications, etc. However, the results are revealing that surface treatment K_{sur} factors are often transferable between similar materials with similar surface treatments. Used correctly, the surface treatment K_{sur} factors can be combined to investigate the effects of multiple surface treatments. This allows useful design insights to be made before a specific surface treatment combination and overhaul repetition is tested.

SES continues to develop the MAPA Data Manager and Curve Fit Editor tools to contain this knowledge, including raw fatigue test results, fatigue characterisation parameters and enabling this “what if” synthesis of new surface treatment combinations.

SES continues to develop the MAPA Simulation Manager to automate the preparation and running of fatigue analyses with appropriate material fatigue properties for the surface treatment of specific landing gear systems component surfaces.

For USAF, the positive outcomes and conclusions resulting from this surface treatment research and analysis include:

1. Increased confidence in life extension for aging aircraft landing gear components.
2. The timely removal of landing gear components from service to decrease the risk of failure.
3. The potential for improvements to repetitive overhaul processes that will reduce their negative impact on fatigue life.

As USAF, other aircraft fleet managers and other industries consider extending the service life of their assets with similar surface treatment maintenance and overhaul processes, the resulting fatigue performance effects must be accounted for. SES and HBK have a roadmap, a knowledgebase and software tools to provide fatigue testing, fatigue data and fatigue prediction capability to meet these material, surface treatment, coating and process fatigue requirements.

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