EVALUATION OF THE EFFECT OF SURFACE FINISH ON HIGH-CYCLE FATIGUE OF SLM-IN718

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ABSTRACT

The surface finish of parts produced by additive manufacturing processes is much rougher than the surface finish generated by machining processes, and a rougher surface can reduce the fatigue strength of a part. This paper discusses an effort to quantify that reduction of strength in high-cycle fatigue for selective laser melt (SLM) coupons.

A high-cycle fatigue (HCF) knockdown factor was estimated for Inconel 718, manufactured with the SLM process. This factor is the percentage reduction from the maximum stress in fatigue for low-stress ground (LSG) specimens to the maximum stress of those left with the original surface condition at the same fatigue life. Specimens were provided by a number of vendors, free to use their "best practice"; only one heat treat condition was considered; and several test temperatures were characterized, including room temperature, 800F, 1000F, and 1200F. The 1000F data had a large variance, and was omitted from consideration in this document.

A first method used linear approximations extracted from the graphs, and only where data was available for both. A recommended knockdown factor of the as-built surface condition (average roughness of approximately 245 micro-inches/inch) versus low-stress ground condition (roughness no more than 4 micro-inches/inch) was established at approximately 1/3 or 33%. This is to say that for the as-built surface condition, a maximum stress of 2/3 of the stress for LSG can be expected to produce a similar life in the as-built surface condition. In this first evaluation, the knockdown factor did not appear to be a function of temperature.

A second approach, the "KP method", incorporated the surface finish measure into a new parameter termed the pseudo-stress intensity factor, K_p, which was formulated to be similar to the fracture mechanics stress intensity factor. Using K_p, the variance seemed to be reduced across all sources, and knockdown factors were estimated using K_p over the range where data occurred. A plot of the results suggests that the knockdown factor is a function of temperature, and that for low lives the knockdown might be lower than the knockdown observed above about one million cycles, where it tended to stabilize. This was not universal for all temperatures tested. The higher temperature tests are thought to be influenced by the test temperature, which perhaps continued the aging process. Further evaluation of the method is suggested.

INTRODUCTION

An important question for using additive manufactured (AM) parts is what the effect of surface finish on fatigue strength is. AM components have surface conditions characteristic of the build processes. Typically, the "as-built" (AB) surfaces are much rougher than machined surfaces, and that surface roughness can affect the fatigue life of a part. Generally speaking, a rougher part will have a shorter fatigue life for the same loading conditions. Stated differently, the loading that will produce a given fatigue life will be reduced for rougher surface conditions. This can be conveniently quantified by a knockdown factor, which represents the percentage reduction of the fatigue strength between two different surface conditions, and provides the potential for evaluating HCF in designs where surfaces cannot be machined.

Figure 1 was included from [1], and it quantifies a surface factor that relates endurance limit of a steel part to tensile strength and surface finish. An example evaluation of surface factor appears below the graph, and a knockdown factor, or percentage reduction of fatigue strength, is then estimated by comparing the surface factors of two different surface finishes.

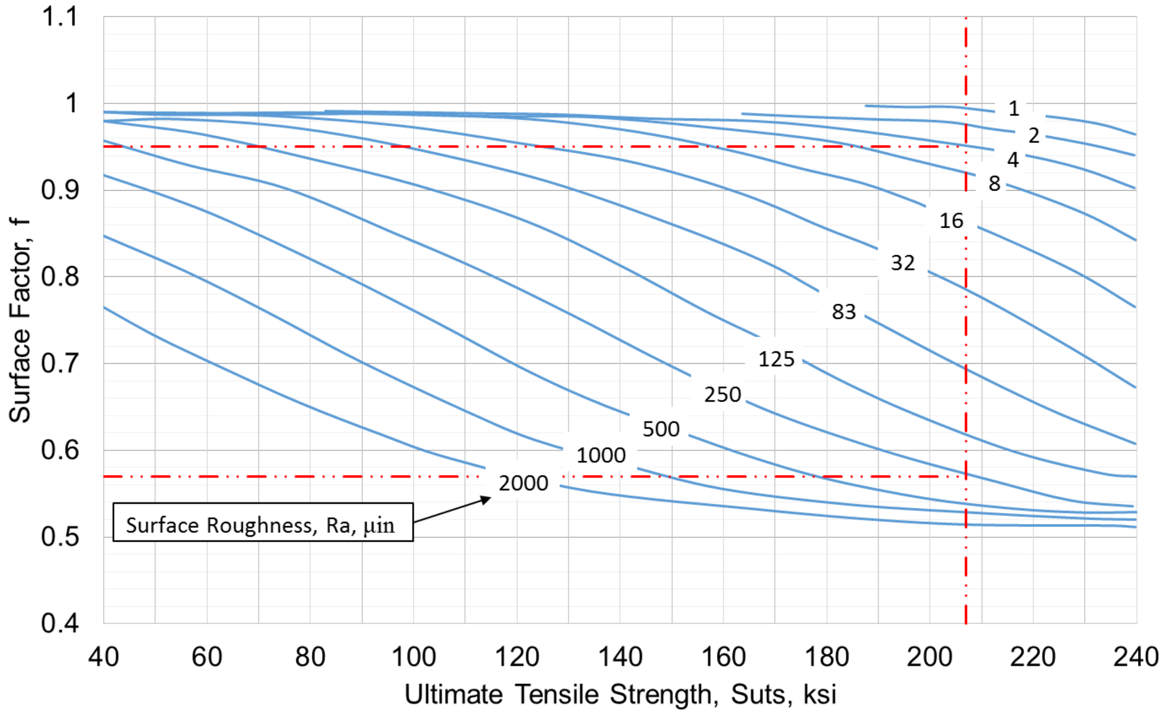

Figure 1: Fatigue surface factor for steel parts, plotted against material tensile strength and arithmetic average surface finish [1].

Given a material strength, e.g., 207 kilopounds-per-square-inch (ksi), two different surface finishes would produce different surface factors, as illustrated with red dashed lines in figure 1:

250 micro-inches (µin) surface roughness yields a surface factor of 0.57, and

4 µin surface roughness yields a surface factor of 0.95.

$$relative\ surface\ factor \approx \frac{0.57}{0.95} = 0.60 \quad (1)$$

The endurance limit for a 250 µin surface roughness can be estimated as about 60-percent of the 4 µin finish endurance limit. This can be stated as a knockdown factor as

$$knockdown \equiv 1 - relative\ surface\ factor = 1 - 0.60 = 0.40 \quad (2)$$

The concept should also be expandable to finite fatigue life, and in a dissertation by Abdulrahim [2] that characterized the value of incorporating surface finish measures into fatigue life prediction, the idea was developed further. Abdulrahim related the depth of surface features and the sharpness of the root of the features to the fatigue strength and showed that the product of the two relates to the fatigue life as a roughness parameter. Fatigue life can be related to the cyclic stress range:

$$N = A(S_r)^B \quad (3)$$

Here, *N* is the number of cycles sustained at fatigue crack initiation or alternately final rupture[1], S_r is the cyclic stress range. *A* and *B* are empirical constants related to fatigue crack final fracture.

[1] For high-cycle fatigue, the initiation life in most cases represents the majority of the life to final fracture.

The two empirical constants identified in equation (3) were evaluated in [2] as polynomial functions of the roughness. This roughness was expressed as the product of the depth of surface features and the radius of curvature of the root of the surface features:

$$A = P_1(v_D^* * \sigma_3^*) \tag{4}$$

$$B = P_2(v_D^* * \sigma_3^*) \tag{5}$$

Here, v_D^* and σ_3^* are the greatest surface feature depth and the root curvature of that feature, respectively. The conclusion of [2] was that fatigue life can be related to the product of depth times root curvature for a given surface condition.

This produces an approach to evaluate similar behavior from AM fatigue specimens, and it may suggest a simple way to incorporate as-built surface conditions into design.

BACKGROUND

High-cycle fatigue specimens were produced by four different vendors. The process was selective laser melting (SLM), which is a powder-bed fusion (PBF) process that uses laser to selectively consolidate metallic powder. The material was Inconel 718 nickel-base super alloy, and the build processes were governed by what the vendor thought to be appropriate to produce a good part.

After the build process, the specimens were stress-relieved on the build plate, and the specimens were then excised, hot-isostatic pressed (HIP), homogenized, and then solution-treated and aged per AMS 5663M [3] specifications. For the as-built surface condition (AB), the specimens were manufactured per figure 2. For the low-stress ground (LSG) specimens, additional stock was added to allow machining to the final dimensions, in order to meet the surface finish requirements of a maximum of 4 μin.

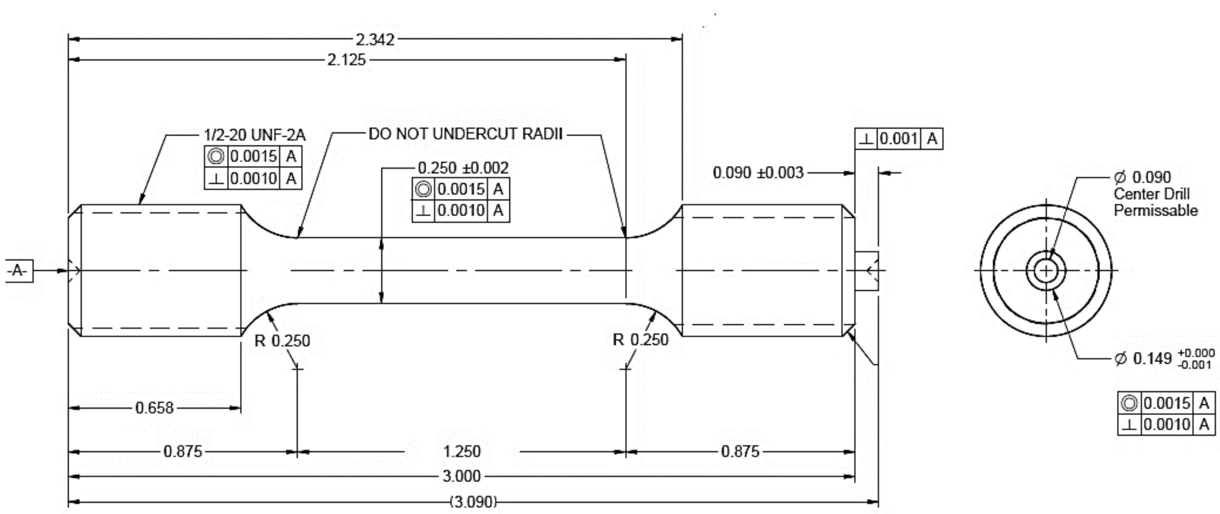

Figure 2: High-cycle fatigue specimen used in this investigation.

The specimen axis was oriented in build layer direction or z-direction, which is perpendicular to the build plane. All testing was conducted per ASTM Standard E647-13A [4] at a stress ratio, R = 0.1[2]. This along with the maximum stress in the sinusoidal load input spectrum and frequency fully define the loading. The frequency used was 40 Hertz for all tests.

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[2] Cyclic stress ratio, R is defined as R ≡ minimum stress/maximum stress.

Surface finish was measured using a two-dimensional contact-type stylus, and also a non-contact laser confocal microscope. Both provided similar results. For the LSG condition, the roughness was only recorded as "better than 4 µin. The AB average surface roughnesses for the AB surface condition for each test group can be found in table I, below.

Table I: Average Surface Finishes, As-Built, µin, RMS				
	Room	**800F**	**1000F**	**1200F**
Mean	247	267	243	245
Standard Deviation	39	43	42	67

ESTIMATION OF KNOCKDOWN FROM STRESS-LIFE (SN) CURVES—LINEAR APPROXIMATION

High-cycle fatigue (HCF) test results for Inconel alloy 718 (IN718) at room temperature, 800F, and 1200F in air appear in figures 3 – 5. The maximum stress was normalized using the mean yield strength at each temperature, with yield strength coming from a similar investigation of the same vendors where tensile properties were evaluated. The linear approximation method used groups of data from similar lives. The number of cycles to failure were averaged in the groups. The groups are enveloped in red ellipses in the figures. The lives selected are indicated by vertical dashed red lines.

$$S_{max,norm} \equiv {S_{max}}/{S_{ys}} \qquad (6)$$

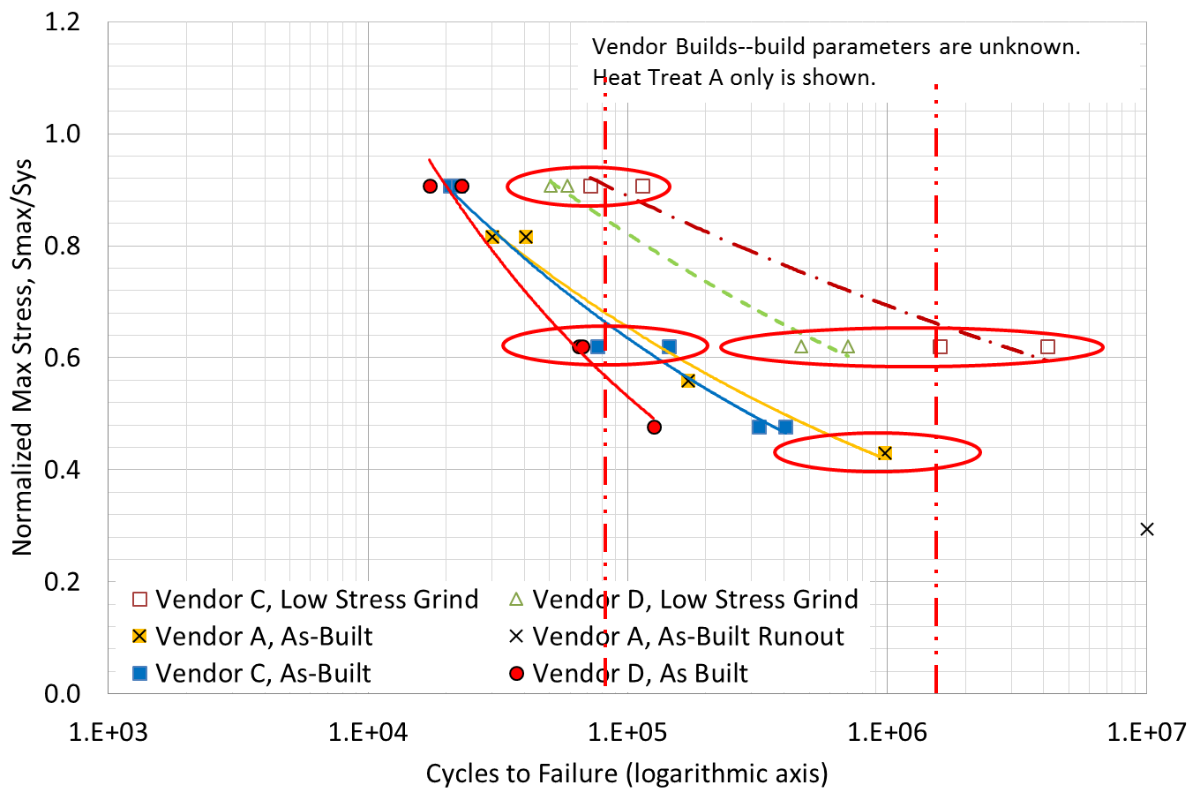

Figure 3: Fatigue results comparing low-stress ground (LSG) and as-built surface (AB) conditions tested at room temperature.

The following analysis was performed using specific fatigue lives, N, from each temperature where data appeared for both LSG and AB conditions. The data for all vendors with identical conditions was combined, and this provided essentially identical results to the same analysis done vendor by vendor. Table II provides an analysis of the knockdowns associated with the selected fatigue lives at the test temperatures. The life estimates used were computed as linear averages of all of the relevant data. Relative fatigue strength is calculated as the ratio of AB divided by LSG fatigue strengths at each life, giving a relative surface factor similar to equation 1:

$$relative\ surface\ factor \approx \frac{S_{max,norm,AB}}{S_{max,norm,LSG}} \tag{7}$$

The knockdown factors are then calculated using equation 2.

For the results shown in table II, it appears that a knockdown factor of around one-third of the LSG fatigue strength is required to get the same fatigue life for AB surface conditions. The example used in the introduction section to demonstrate the use of historic information from figure 1 used the same roughnesses and tensile strength as the test data in this document. The example result was around 40%, and although the material in the example was steel and not nickel, the results are similar, as expected. The analysis reported in table II is hampered by large variances of the surface finish in conjunction with the typically large variance of the fatigue life expectancy normally seen for a given loading condition. As such, a second analysis was performed to incorporate the surface roughness into the loading, in an effort to include that variance.

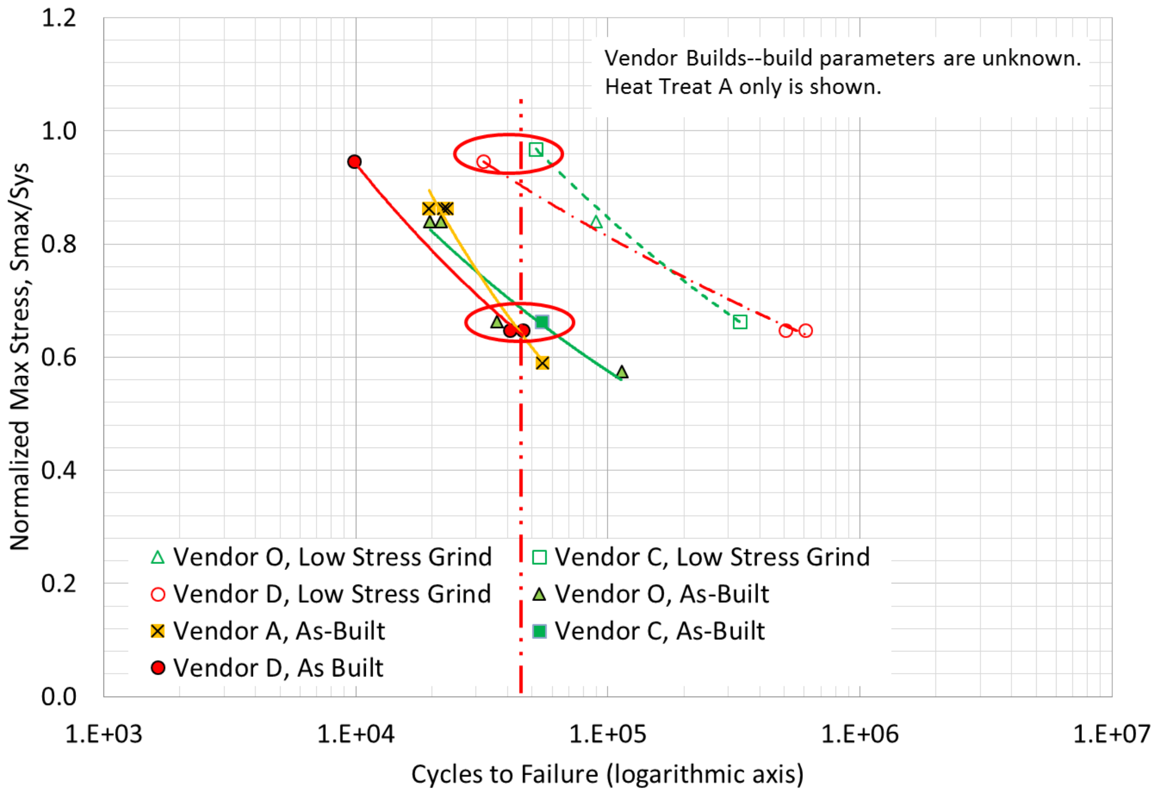

Figure 4: Fatigue results comparing LSG and AB surface conditions tested at 800F.

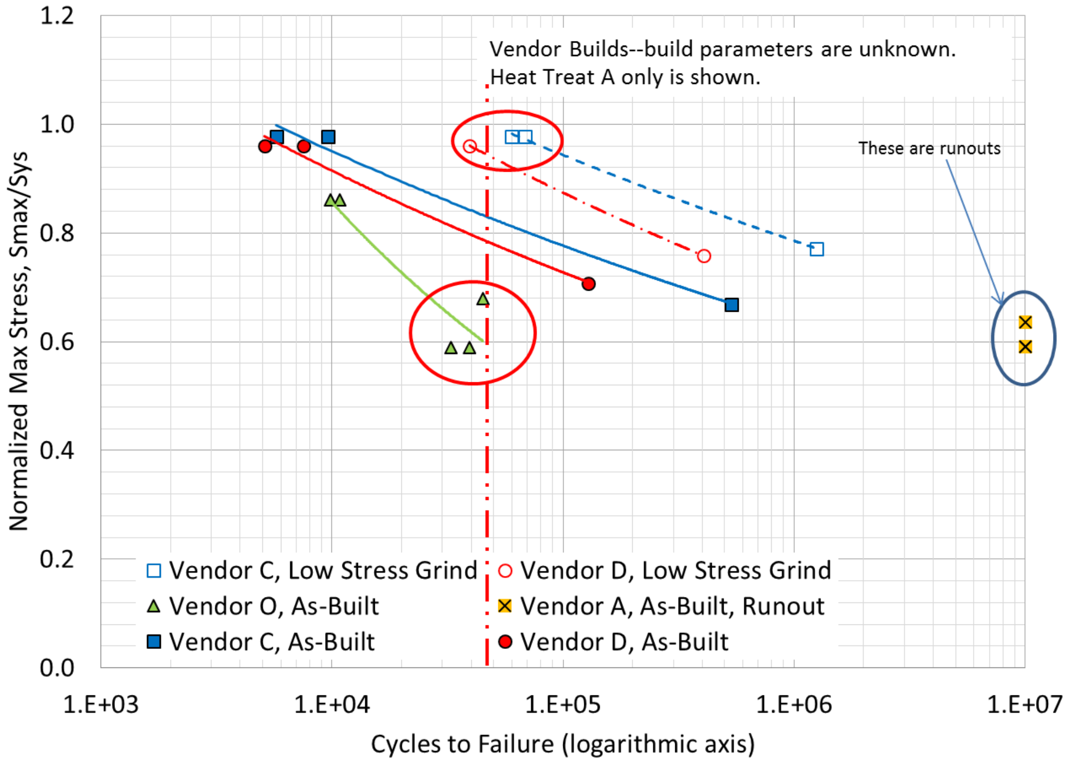

Figure 5: Fatigue results comparing low-stress ground and as-built surface conditions tested at 1200F.

Table II: Knockdown Factors for As-Built versus Low-Stress Grinding			
Room Temperature			
N (cycles)	Smax,norm(as built)	Smax, norm(LSG)	Knockdown = 1 - Smax,norm(as built)/Smax,norm(LSG)
80,863	0.62	0.91	32%
1,574,926	0.43	0.62	31%
800F			
N (cycles)	Smax,norm(as built)	Smax, norm(LSG)	Knockdown = 1 - Smax,norm(as built)/Smax,norm(LSG)
43,551	0.66	0.96	32%
1200F			
N (cycles)	Smax,norm(as built)	Smax, norm(LSG)	Knockdown = 1 - Smax,norm(as built)/Smax,norm(LSG)
47,505	0.62	0.97	36%

KNOCKDOWN FACTOR—NORMALIZED ANALYSIS, THE "KP" METHOD

In order to incorporate surface finish into the maximum cyclic stress, a parameter was devised, identified as the pseudo-stress intensity factor, K_p. The thought comes loosely from fracture mechanics wherein sub-critical crack growth correlates to the stress-intensity factor range, ΔK, which is evaluated as a product of the stress range times the square root of the flaw size times a geometry factor. As discussed above, [2] indicated that the depth of surface features times the root curvature correlated with the life for a given maximum stress in fatigue, and since the surface roughness represents a flaw in the perfect surface, then K_p is offered as a candidate similitude parameter. With a constant cyclic stress ratio, the maximum stress is equivalent to the stress range.

According to [2], root radius curvature data was helpful for correcting for surface finish, however, no curvature data was available, and so it was assumed to be constant, thus K_p was written as

$$K_p \equiv S_{max,norm} * \sqrt{f} \quad (8)$$

In equation (8), K_p is the pseudo-stress intensity factor, $S_{max,norm}$ is the normalized maximum cyclic stress, and f is the RMS[3] surface roughness in μin for each data point. This information was available for the as-built surface condition specimens tested, and for the LSG specimens, the surface finish was only shown as better than 4 μin RMS roughness.

Continuing the development, $S_{fraction}$ is the equivalent of the relative scale factor calculated in the previous section, but using K_p:

$$S_{fraction} \equiv \frac{K_p(AB)}{K_p(LSG)} * \sqrt{\frac{f_{avg}(LSG)}{f_{avg}(AB)}} \quad (9)$$

In this equation, the resulting K_p ratio is multiplied by the square root of the ratio of the averaged surface roughness measurements of the LSG and AB surface conditions in order to return to stress space. For the LSG condition, 4 μin RMS roughness was adopted for both the individual and the average surface roughness values, and thus the AB surface roughness augmented the AB maximum cyclic stresses only. The average surface roughnesses for the AB surface condition for each test group can be found in table I, above.

<u>RESULTS OF KP METHOD</u>

Figures 6 – 8 show log-log plots of K_p versus fatigue life, N. Power-law fits were provided in the charts, and the corresponding fit functions are shown on the graphs, as well. The fit functions were used to evaluate K_p, $S_{fraction}$, and the knockdown factor for each fatigue life. Convenient fatigue lives were used, indicated by blue dashed lines, and values were used only where data was available for both surface conditions. The results appear numerically in tables III – V, below each figure.

[3] RMS is “root mean square”, which is a manner of combining the surface finish data into a single number.

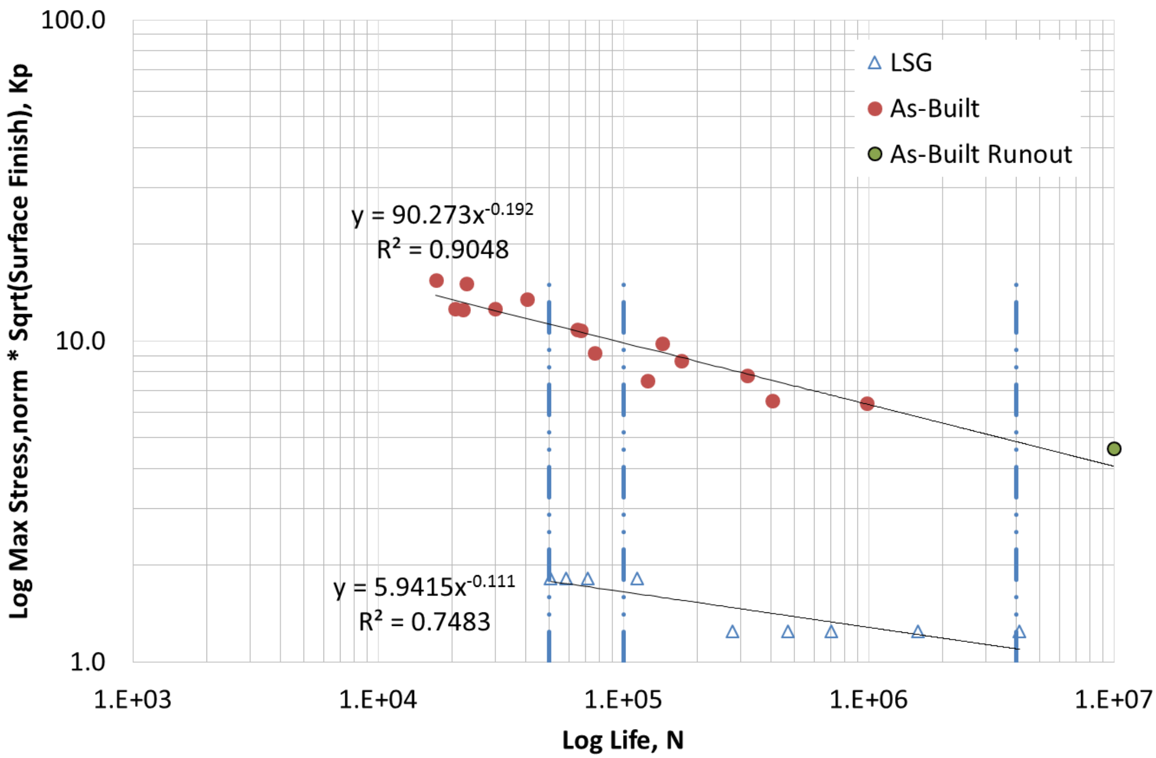

Figure 6: Log of K_p versus log of fatigue life—room temperature. Blue lines indicate lives selected for characterization.

Table III: Knockdown for HT A at RT				
N	**Kp(LSG)**	**Kp(AB)**	**Sfraction**	**Knockdown = 1 - Sfraction**
50,000	1.8	11.4	0.81	19%
100,000	1.7	9.9	0.76	24%
1,000,000	1.3	6.4	0.63	37%
4,000,000	1.1	4.9	0.57	43%

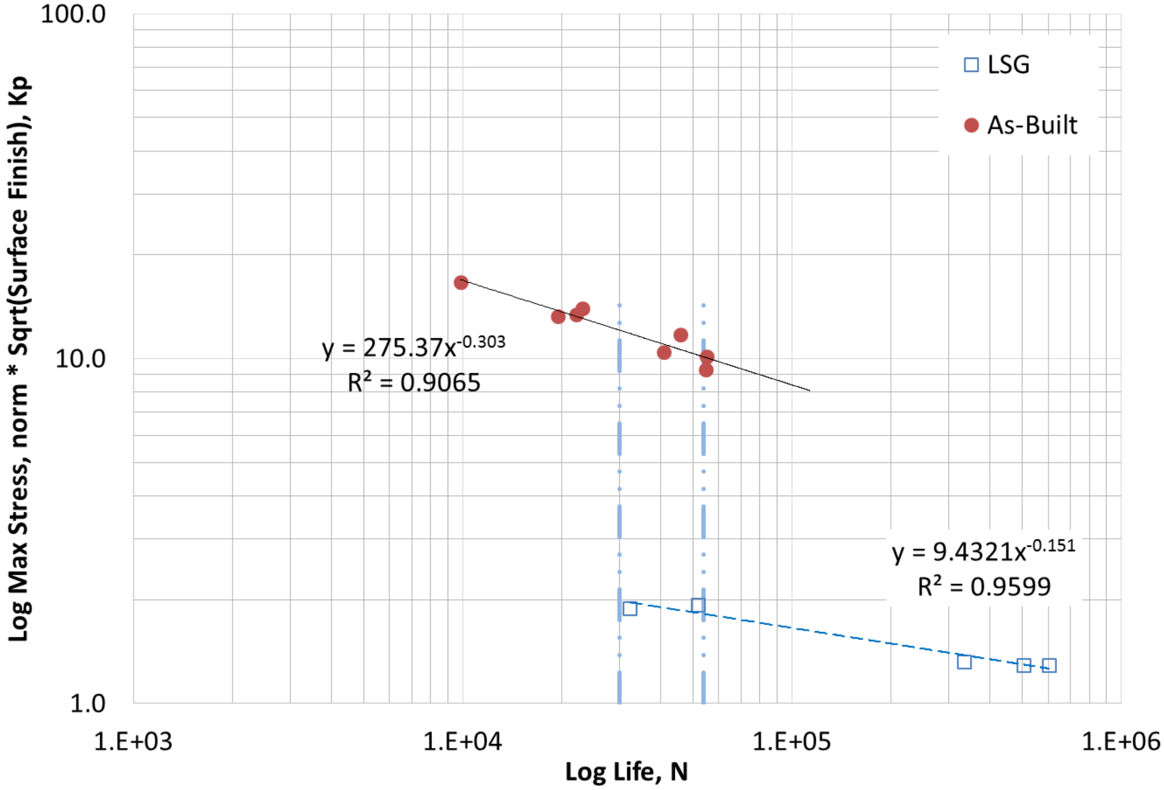

Figure 7: Log of K_p versus log of fatigue life—800F. Blue lines indicate lives selected for characterization.

Table IV: Knockdown for HT A at 800F				
N	**Kp(LSG)**	**Kp(AB)**	**Sfraction**	**Knockdown = 1 - Sfraction**
32,000	2.0	12	0.74	26%
54,000	1.8	10	0.68	32%

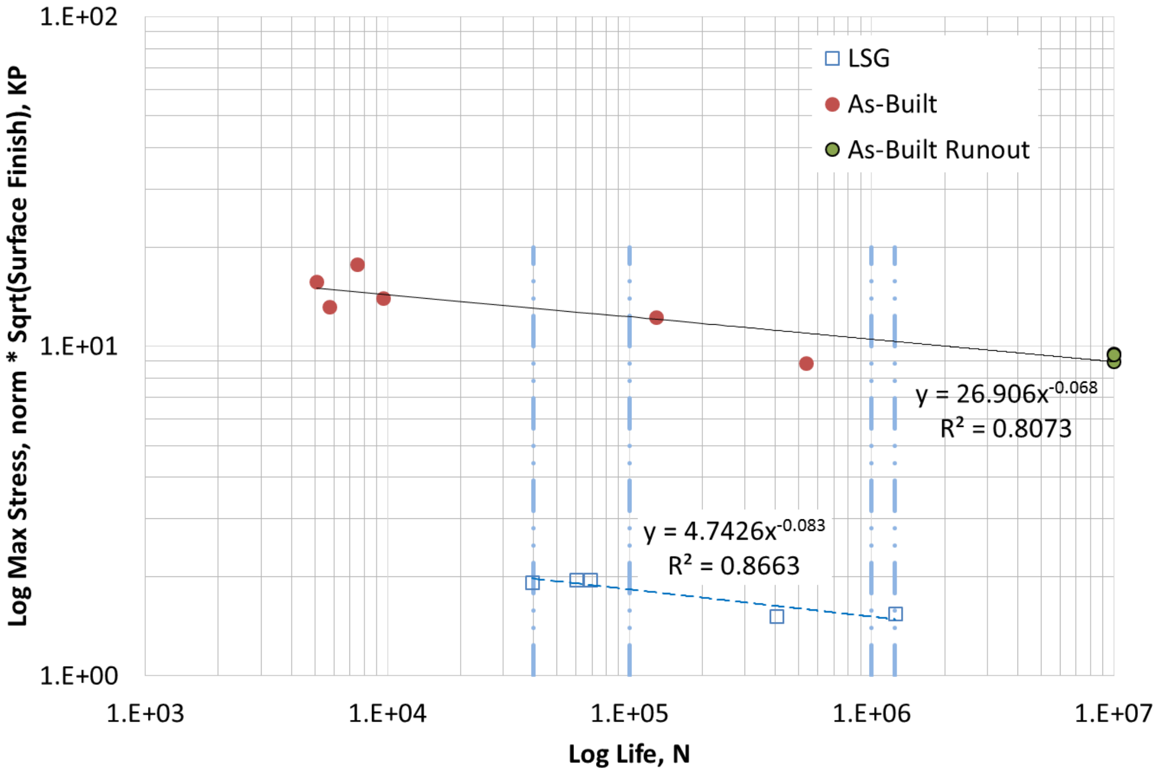

Figure 8: Log of K_p versus log of fatigue life—1200F. Blue lines indicate lives selected for characterization.

Table V: Knockdown at 1200F

N	Kp(LSG)	Kp(AB)	Sfraction	Knockdown = 1 - Sfraction
40,000	2.0	13	0.85	15%
100,000	1.8	12	0.86	14%
1,000,000	1.5	11	0.89	11%
1,250,000	1.5	10	0.89	11%

The results shown in tables III – V were graphed as a log-log plot in figure 9. Trend lines have been provided in the figure, again using a power law fit. Note that the data points shown arise from the trend line equations, and so they not indicative of spread, but only trend. Room temperature and 800F increase as fatigue life increases, while 1200F decreases with an increase of the fatigue life. The results at 1200F might arise from several different reasons: at higher temperatures, the yield strength is lower, and this may be manifested in the high-cycle fatigue results, but 1200F is above the aging temperature and aging may have continued during the fatigue test. This is consistent with figure 9.

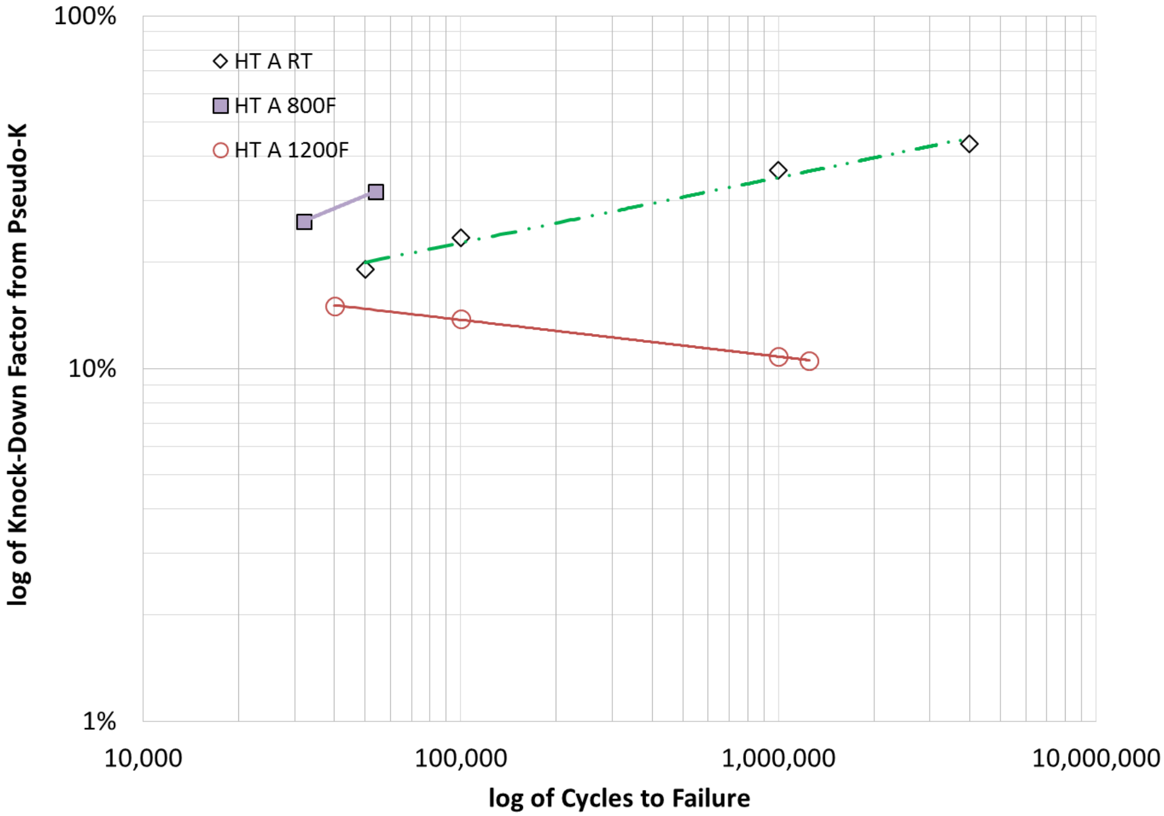

Figure 9: Log-log plot of knockdown factor versus fatigue life for all test temperatures.

Figure 10 shows the trend of the knockdown factor versus life with linear axes. As a generalization, the knockdown factor appears to be leveling off for the room temperature data, but it has not stopped increasing entirely. In addition, the 800F points are substantially above the others. The various results are discussed below.

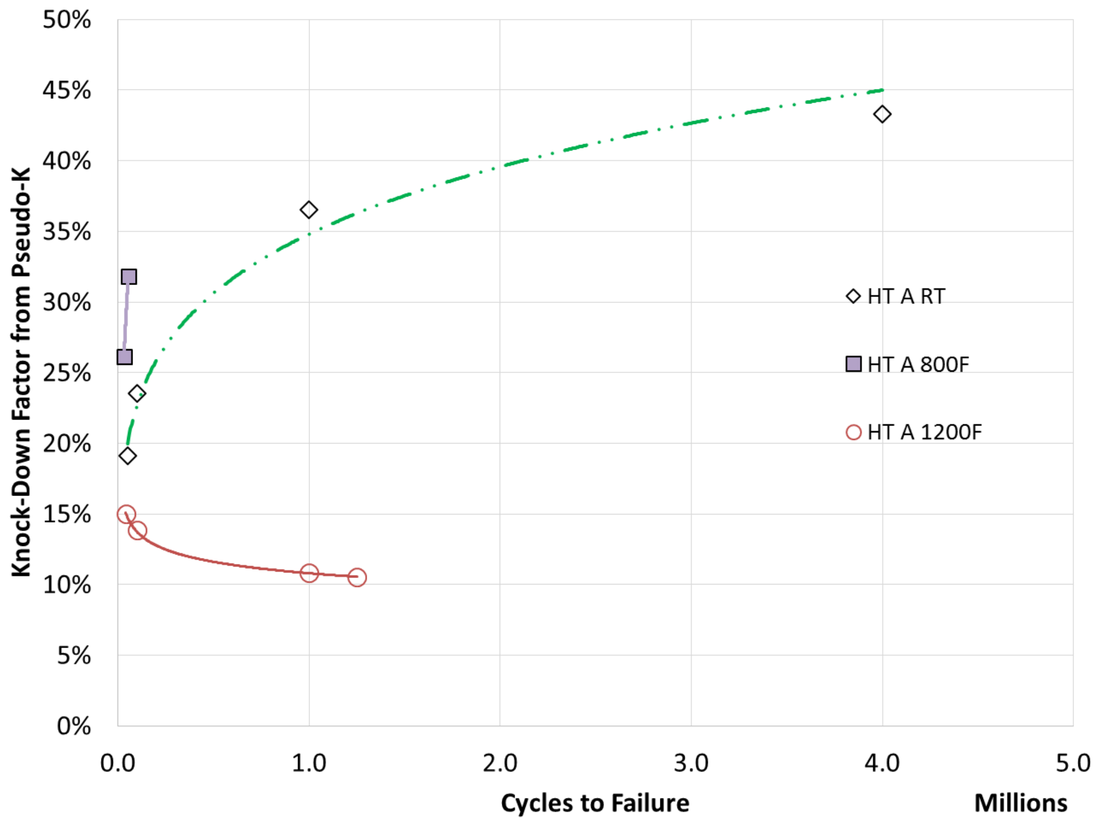

Figure 10: Linear axis plot of knockdown factor versus fatigue life for all test temperatures.

DISCUSSION

Two different analyses were conducted to evaluate a knockdown factor from the fatigue strength of the low-stress ground (LSG) surface condition to the as-built (AB) surface condition. The first analysis, a linear approximation using specimen groups with similar lives, was derived from the stress-versus-life curves at convenient fatigue lives, and it suggested that a reduction by one-third of LSG fatigue strengths would be appropriate to estimate fatigue strength for as-built surfaces of about 250 µin surface roughness. For this analysis, the estimates were coarse, and few fatigue lives were available, but the results were consistent across all data used.

A second analysis was conducted, the KP method, creating a new parameter that combined the maximum cyclic stress with the surface roughness. This resulted in a mixed correlation: knockdown factors increased at the lower temperatures and decreased at the highest one, relative to increasing fatigue life. Because the 1200F tests were at temperatures above the aging temperature, overaging or perhaps a reduction of the yield strength is thought to have had some influence.

The KP method suggested that for short life, i.e., less than one million cycles, a <u>conservative</u> knockdown factor would be about one-third, but at higher lives, the knockdown factor increases.

This KP method shows some promise. The data used in this investigation were generated to evaluate state-of-the-art in the additive manufacturing industry, and they were not ideal for the analysis suggested by [2]. To improve this, the root radius associated with the surface roughness might be incorporated into the analysis. This might improve the correlation further, based on the findings of [2]. A second improvement would be to construct a test series where manufacturing variabilities are reduced to leave only the variance of the surface finish. Ultimately, the results of the KP method are inconclusive, although the method seems to show promise.

The KP method should be better than the linear approximation, whereas it removes the variability and subjectivity that is inherent with the first process.

CONCLUSIONS AND RECOMMENDATIONS

- For the linear approximation, the knockdown factor was estimated at about one-third, and this was consistent across all temperatures and all fatigue lives. The value of the result is weakened due to the lack of usable data above 1.5 million cycles.
- For the KP method, the correlation of the data seems reasonable, and this suggests a knockdown factor of about one-third at lives below about one-million cycles. The knockdown increases with increasing life, and the results should probably not be used beyond one-million cycles.
- The pseudo-stress intensity factor, K_p method shows promise for improving correlation of roughness with a fatigue strength knockdown factor. Recommendations for future work include:
    - Reference [2] demonstrates the value of a more expansive set of data that encompasses a larger portion of the relevant processes and operational parameter space.
    - The knockdown factors associated with surface finish should be re-evaluated with surface finish characterized by surface roughness including the root radius.
    - The method to characterize surface finish should be evaluated, e.g., measurement of the surface roughness root radius, and analysis techniques.
    - Variability should be reduced by establishing more control over the SLM, heat treating, and other processes.
    - Other surface treatment processes beyond LSG should be considered, e.g., shot peening, electro-polishing, and tumbling.
- The HCF results at 1200F were unlike those for the room temperature and 800F tests, and the cause is unknown.
- The data set should be expanded to include
    - Different, dissimilar materials, e.g., Inconel alloy 625, and
    - Different cyclic stress intensity ratios.
- The different trend versus fatigue life observed for the 1200F data set should be investigated, with temperatures that are just below and just above the aging temperature to confirm the theorized influence of overaging.

ACKNOWLEDGEMENTS

A very large group contributed to this publication, and their contributions are appreciated. These included the Materials and Processes Lab, the Propulsion Lab, the Office of Strategic Analysis and Communication, and the Advanced Development Office at MSFC. This belies the true size of the group, though, who include the Nonmetallic Materials Engineering Branch wherein the Additive Manufacturing Facility resides, the Mechanical Materials Test Facility, the Metallic Materials Engineering Branch, and the Liquid Engines Office. I would especially like to thank Mr. Arthur Brown of the Metallic Materials Engineering Branch, who posed the question that led to this paper.

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