NRC Workshop on Structural Materials: Research for Beyond 80 Years @ October 2, 2024

Fatigue Evaluation for AM (Additive Manufacturing) Materials

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- Master S-N Curve Method of Sec.VIII, Div.2
- EAF Evaluation in LWR Environments
- Draft Proposal of Fatigue Evaluation Method for AM materials
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Introduction

- For long-term operation of light water reactors, some components or parts will be replaced.
- Some material suppliers have withdrawn, and some suppliers have been merged. Hence, supply chain is very important, and one option is Additive/Advanced Manufacturing. AM can reduce lead time of material, and this may prevent the extension of plant outage.
- In the ASME B&PV Code Committee, Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment are developing codes of AM manufacturing, and BPV III Working Group on Advanced Manufacturing are developing the codes for nuclear component use.
- Based on recent studies, tensile properties of AM materials will be able to satisfy the requirements of equivalent material of the ASME Sec. II.

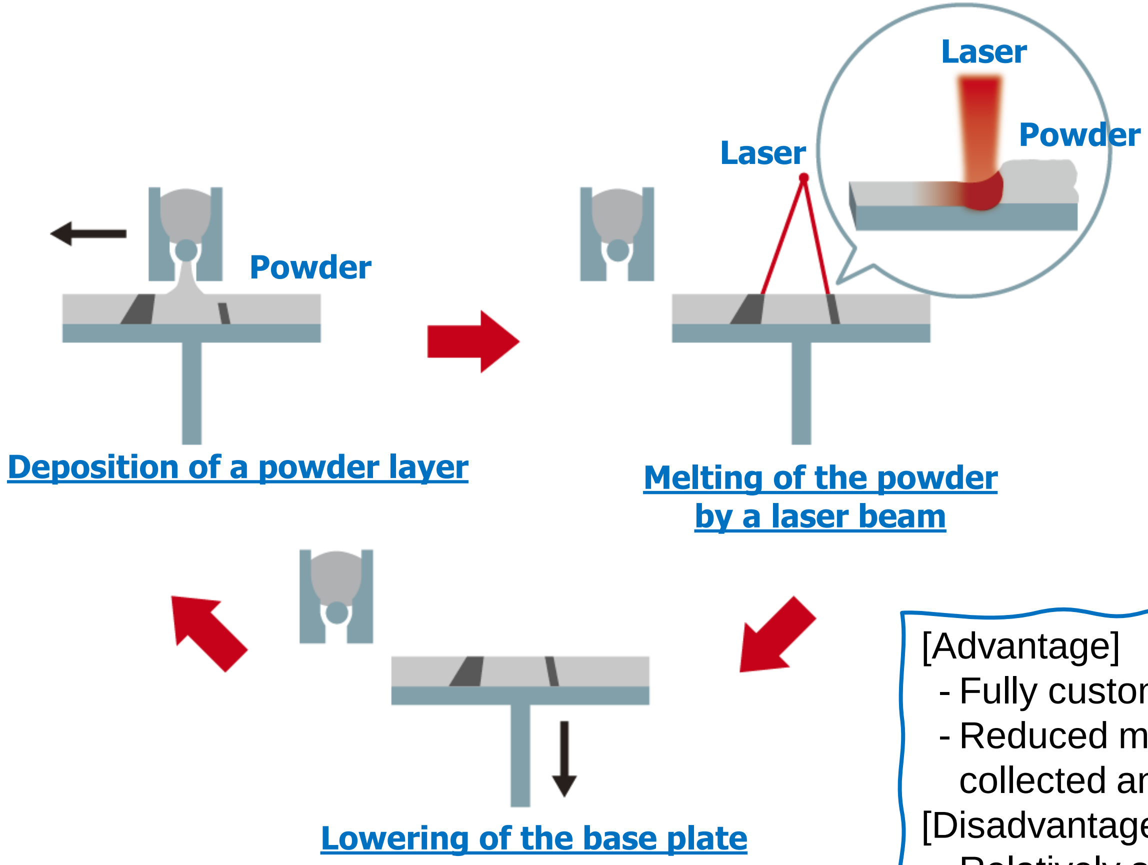
Introduction

- However, fatigue evaluation for AM materials needs to be discussed.
- SC on UAM is considering of applying the Master Curve Method of the ASME Sec. VIII, Div.2, which is a fatigue evaluation method for welded components based on load-controlled fatigue tests using welded specimens.
- On the other hand, Class 1 components of nuclear power plants are required Environmental Assisted Fatigue (EAF) evaluation.
- The F_{en} evaluation method for EAF was developed based on strain-controlled fatigue tests using smooth small specimens.
- The fatigue evaluation of AM materials for nuclear components are discussed.

Additive Manufacturing (AM)

- There are a lot of AM technologies, but typical ones are Powder Bed Fusion (PBF) and Direct Energy Deposition (DED).

Laser Powder Bed Fusion (L-PBF)



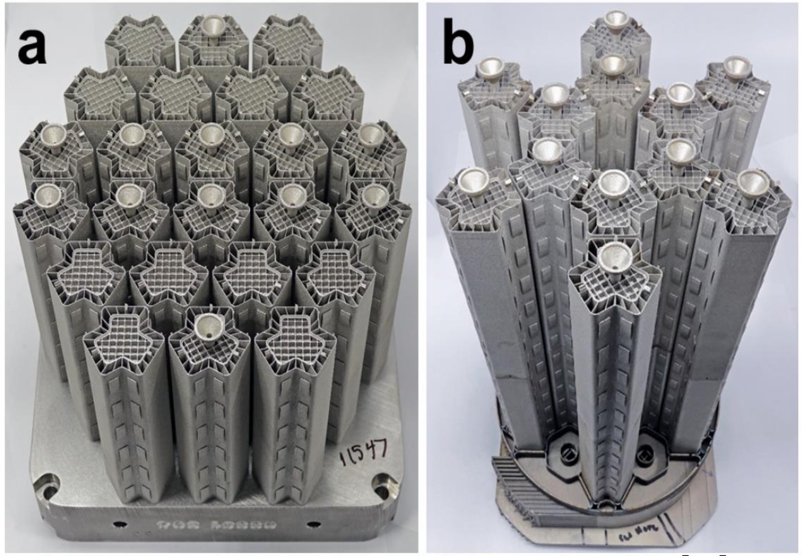


Figure 12: 24 LPBF fuel cans; a) As-built, b) Stacked and assembled on a LPBF base manifold. [*1]

[Advantage]
- Fully customized parts on a batch by batch basis, flexible designs
- Reduced material waste; After the part is complete, any excess powder can be collected and recycled.

[Disadvantage]
- Relatively slow and long working time

[*1] Lonnie J. Love, et al., “Application of Laser Powder Bed Fusion for Transformational Challenge Reactor Core”, ORNL/TM-2019/1323, 2019.

Additive Manufacturing (AM)

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- There are a lot of AM technologies, but typical ones are Powder Bed Fusion (PBF) and Direct Energy Deposition (DED).

Direct Energy Deposition (DED)

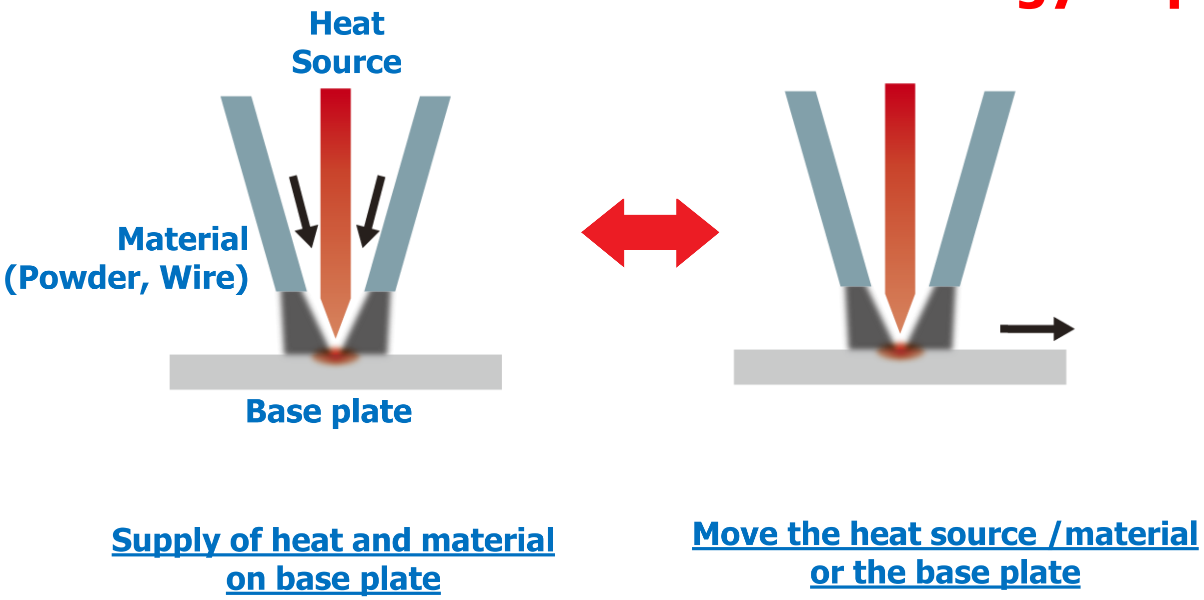


Figure 2. Valve cage in 316L stainless steel in process using GMA-DED, and cage and valve body after final machining
Used with permission from Best Engineering in Energy Solutions [*2]

[Advantage]
- Speed of deposition
- Ability to manufacture very large structures

[Disadvantage]
- Lower dimensional resolution; Machining after printed may be necessary.

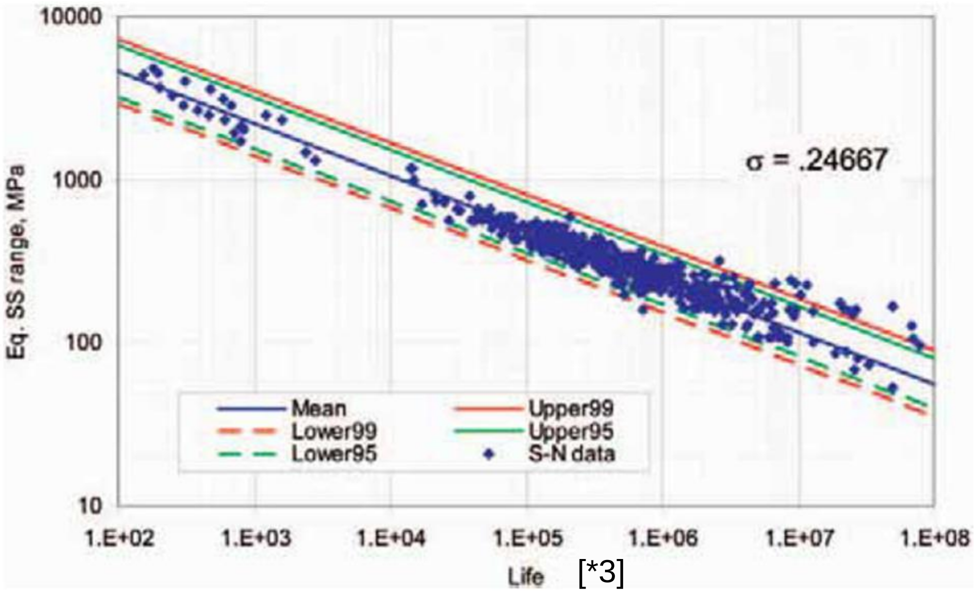
[*2] EPRI, "Quick Insight Brief: Directed Energy Deposition-Additive Manufacturing", 3002019764, 2020.

Additive Manufacturing (AM)

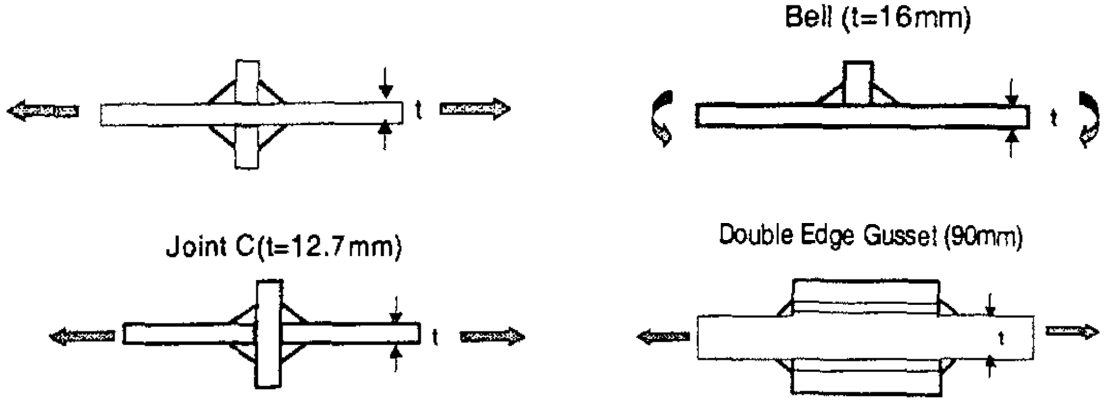
- Tensile properties of AM materials depend on the manufacturing process.
- ASME PTB-13-2021 “Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing” addresses the construction of pressure retaining component using the AM Powder Bed Fusion process using both Laser and Electron Beam energy sources.
- Also, code cases of DED materials for Class 1, 2 and 3 pressure-retaining items is under preparation.
- Those codes requires the tensile properties to satisfy the ASME Sec.II Part D. So, the design stress intensity values (S_m) and the maximum allowable stress values (S) can be applied to AM materials manufactured by the qualified AM process
- However, fatigue evaluation of AM materials is another story.
- SC on UAM is considering of applying the Master Curve Method of the ASME Sec. VIII, Div.2.
- Can the Master Curve Method be applied to Class 1 nuclear components?

Master S-N Curve Method of Sec.VIII, Div.2

- The design fatigue curve of the Master S-N Curve Method was developed based on basically load-controlled fatigue tests in air using welded joint test specimens, and the fatigue lives are defined as the failure of the test specimens.
- The applicability of the Master S-N Curve Method to AM materials is being studied, but the test condition is in air, not LWR environments.[*5]



[*3]



Typical welded joint test specimens [*4]

[*3] Dong, P., et al, "The Design Master S-N Curve in ASME Div 2 Rewrite and its Validations," Welding in the World, Vol. 51, Issue 5-6, 2007.
[*4] Dong, P., et al., "Master S-N Curve Method for Fatigue Evaluation of Welded Components," WRC Bulletin 474, 2002.
[*5] Krents, T., et al., "Characterization Of Fatigue Behaviors Of Notched 316L DED AM Specimens", PVP2024-123384, 2024.

EAF Evaluation in LWR Environments: Design Fatigue Curve

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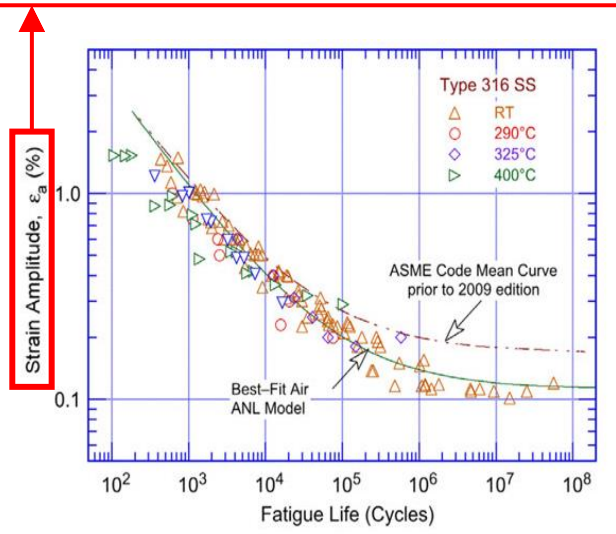
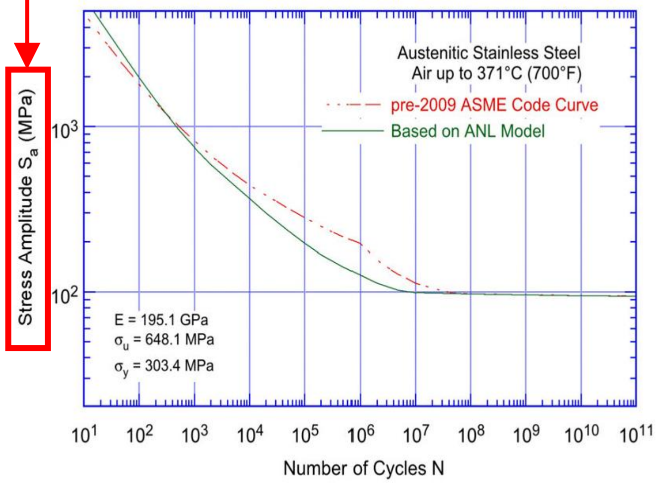
- The design fatigue curves of Sec.III come from Strain – Number curves, and the stress is pseudo stress set by multiplying the strain by a Young's modulus. The Strain – Number curves were developed using strain-controlled fatigue tests in air using small specimens.

ε_a (Strain Amp.)×Young's modulus → S_a (Stress Amp.)

[*6]

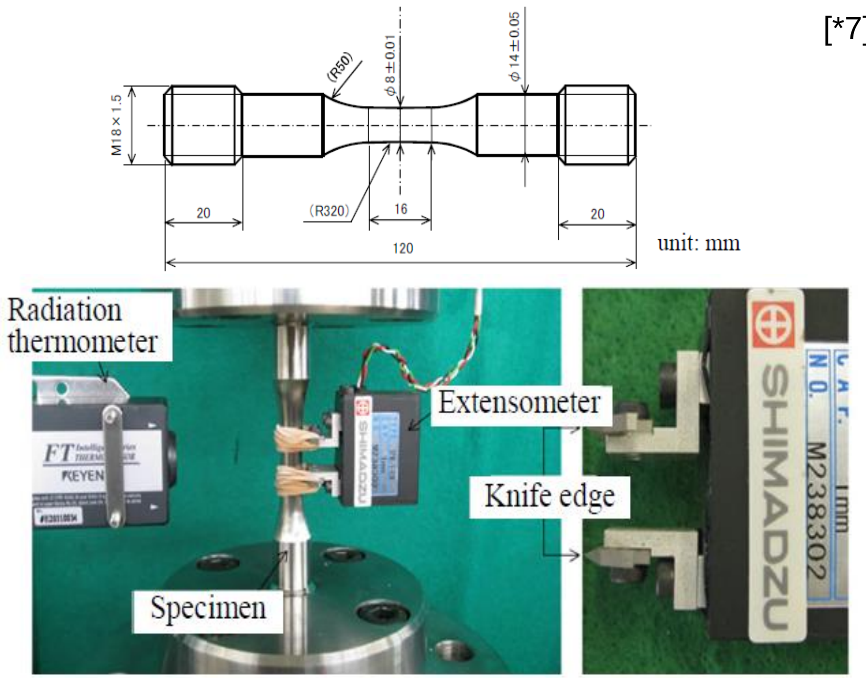


Strain-Controlled Fatigue Tests



Design Fatigue Curve

[*7]



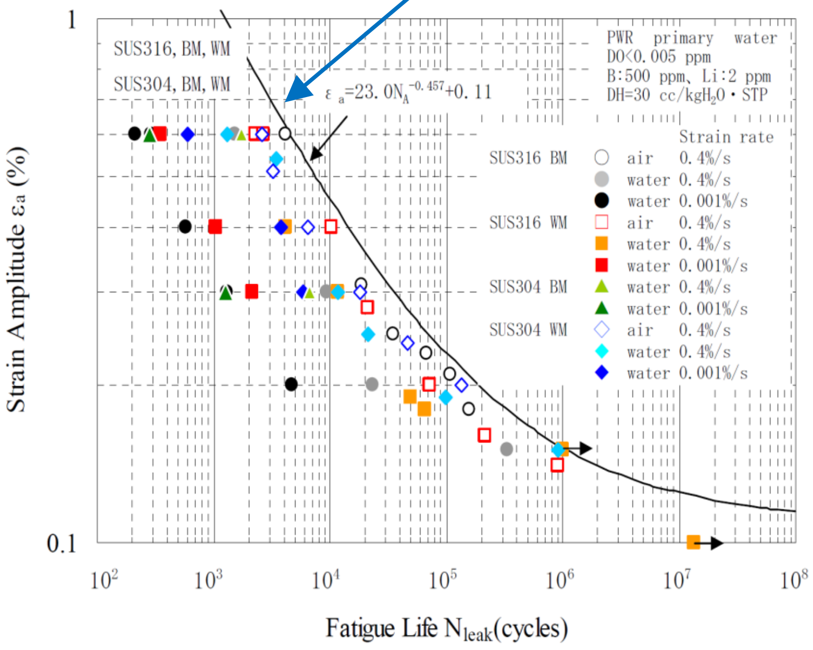
Typical Strain-Controlled Fatigue Test

[*6] Chhopra, O., Stevens G., "Effect of LWR Water Environments on the Fatigue Life of Reactor Materials", NUREG/CR-6909, Rev.1, 2018.
[*7] Wang, Y., et al., "Development of New Design Fatigue Curves in Japan -Discussion of Best-Fit Curves Based on Fatigue Test Data with Small-Scale Test Specimen," PVP2018-84052, ASME, 2018.

EAF Evaluation in LWR Environments

- It is known that fatigue lives in LWR environments are shorter than those in air. Generally, the fatigue lives are reduced due to slower strain rate and higher temperature.
- The environmental correction factor (F_{en}) is defined as the ratio of fatigue life in LWR environment (N_W) and that in air (N_A), and the fatigue usage in environment (U_{en}) is obtained by multiplying F_{en} and the fatigue usage in air (U_f).
- Those fatigue data including environments were obtained using strain-controlled fatigue tests using small specimens.
- No one knows the F_{en} method is applicable to the Master S-N Curve Method, because the fatigue testing methods are completely different.

Best-Fit ε-N Curve in air (Stainless Steels)



[*8]

$$F_{en} = N_A / N_w$$

$$U_{en} = U_f \times F_{en} = \sum_{i=1}^{n} U_i \times F_{en,i}$$

[*8] JNES, Final Report of EFT Project, 07KIZAIHO-0002, 2007

Draft Proposal of Fatigue Evaluation Method for AM materials

- The base best-fit curve of austenitic stainless steel is assumed to evaluate an AM material. Record 19-2068 is proposing new design fatigue curves using tensile strength (σ_u) as a variable, and its best-fit curve of austenitic stainless steels is given as below.

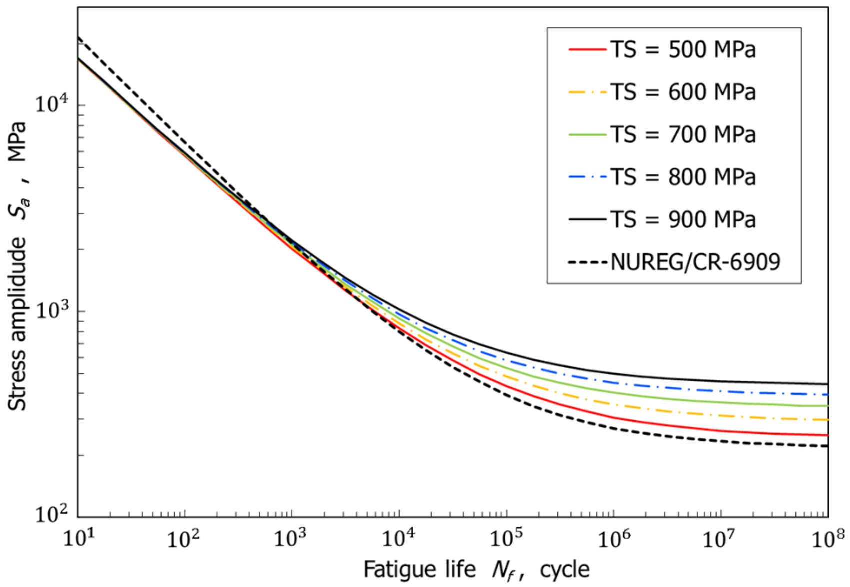
$$S_a = (5.09 \times 10^4) N_f^{-0.485} + 0.488\sigma_u \quad \text{[MPa]}$$

$$\varepsilon_a = 0.261 N_f^{-0.485} + 0.488(\sigma_u / E_0) \quad \text{[mm/mm]} \ (E_0 = 195000 \text{ MPa})$$

- The above best-fit curve can give an accurate S-N curve by applying the tensile strength as a variable. The tensile strength can be obtained from the tensile test of the AM material.
- The best-fit curve of NUREG/CR-6909 is located at lower side. If the best-fit curve of NUREG/CR-6909 is used for evaluation of AM materials, it will be unconservative side because it does not consider the dependence of tensile strength.
- The base best-fit curve is determined for each AM material using its tensile strength.

The best-fit curve of austenitic stainless steels

[*9]



[*9] Kanasaki, H., et al, “Proposal of Fatigue Life Equations for Carbon & Low-alloy Steels and Austenitic Stainless Steels as a Function of Tensile Strength,” PVP2013-97770, ASME, 2013.

Step 1: Procedure of Evaluation for Fatigue Tests of AM Materials

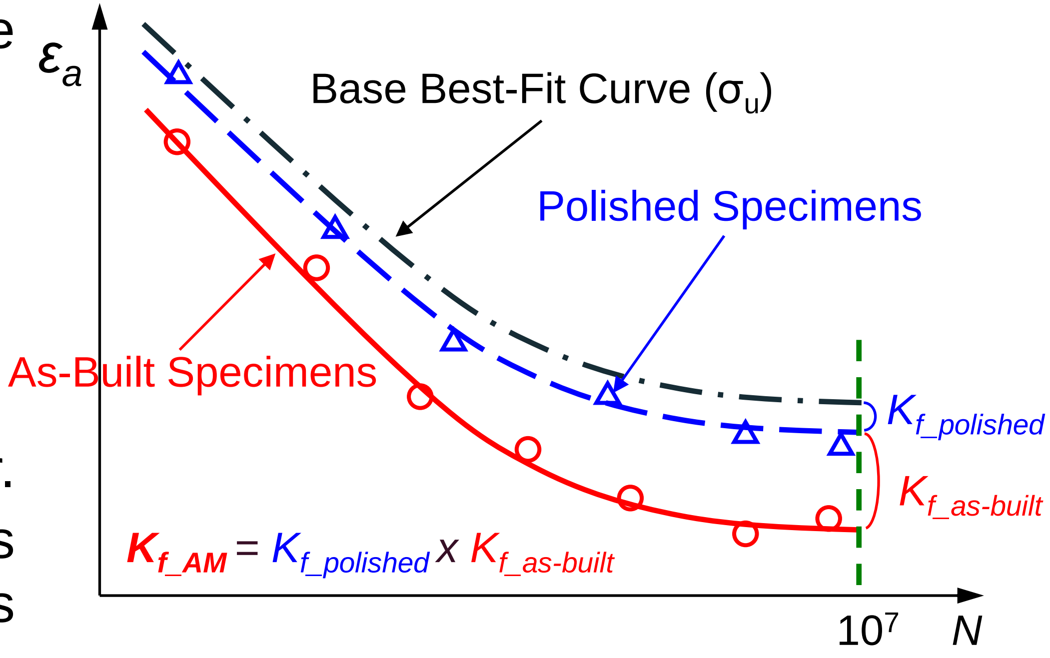
1. Two kinds of fatigue test specimens of a AM material are manufactured. One is for polished round bar specimens, and the other is for as-built round bar specimens. Also, tensile tests for the AM material are performed to obtain tensile properties.
2. Strain-controlled fatigue tests are performed for the polished specimens and the as-built specimens.
3. The base best-fit curve is determined using its tensile strength obtained by the tensile test.
4. Each regression curve is analyzed for the polished specimens and the as-built specimens, and the following ratios are calculated

$$K_{f\_polished} = \frac{\varepsilon_a(Best\!-\!Fit\ Curve(\sigma_u))}{\varepsilon_a(Polished\ Specimens)}$$

$$K_{f\_as-built} = \frac{\varepsilon_a(Polished\ Specimens)}{\varepsilon_a(As\!-\!Built\ Specimens)}$$

$$\boldsymbol{K_{f\_AM}} = K_{f\_polished} \times K_{f\_as-built}$$

5. $\boldsymbol{K_{f\_AM}}$ is the total fatigue strength reduction factor. Here, the above ratios are determined at 10^7 cycles as a reasonable number of cycles as the same as factor for the effect of surface finish ($\boldsymbol{K_{sf}}$) in 19-2068.



Step 2: Application of $\sqrt{area}$ Approach to AM Materials

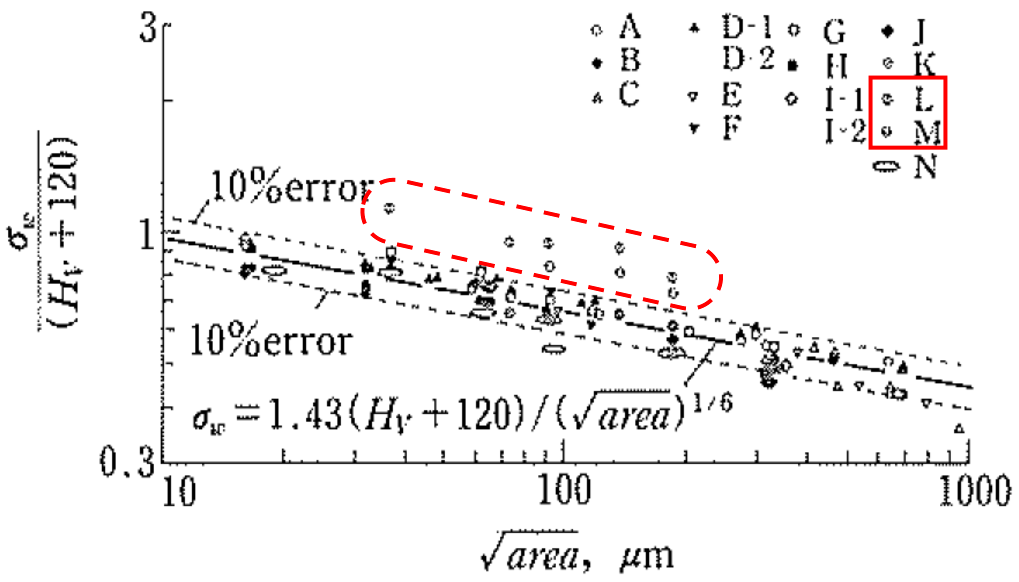
- To estimate fatigue endurance limit (σ_w, MPa), the following equation that estimates σ_w using hardness (HV, kgf/mm^2) and square root of the projected area in the direction of the maximum tensile stress ($\sqrt{area}$, μm^2) was proposed by Prof. Murakami [*10].

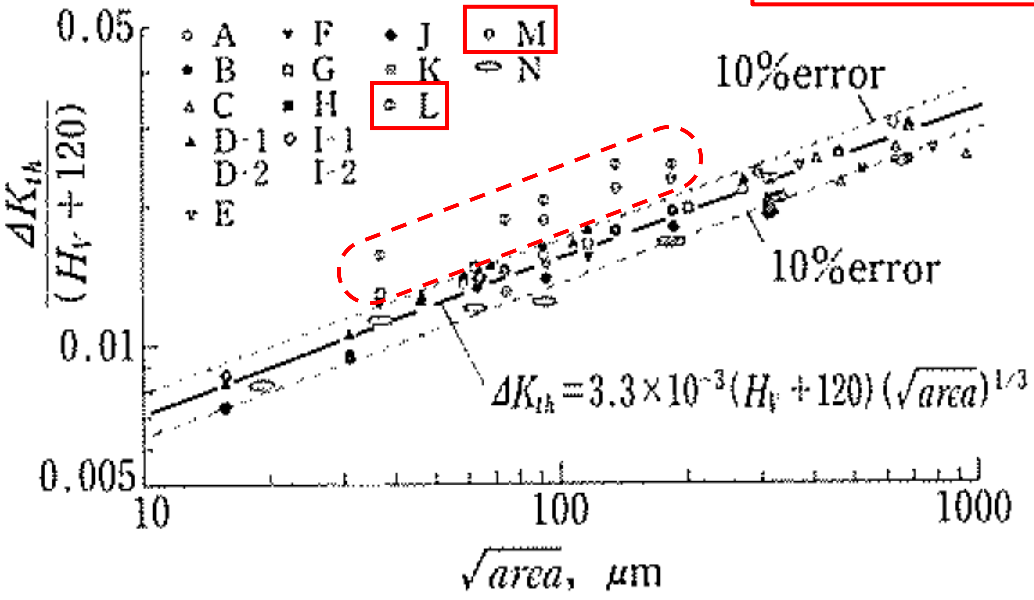
$$\sigma_w = 1.43\frac{HV+120}{(\sqrt{area})^{1/6}}$$

- Also, the following equation to estimate ΔK_{th} (MPa√m) was proposed [*10].

$$\Delta K_{th} = 3.3\times10^{-3}(HV+120)(\sqrt{area})^{1/6}$$

Stainless Steels
L: SUS630
M: YUS170
Most of the others are carbon steels.





[*10] Murakami, Y., “Effect of Small Defects and Inclusions”, Yokendo, 1993. (in Japanese)

Step 2: Application of $\sqrt{area}$ Approach to AM Materials

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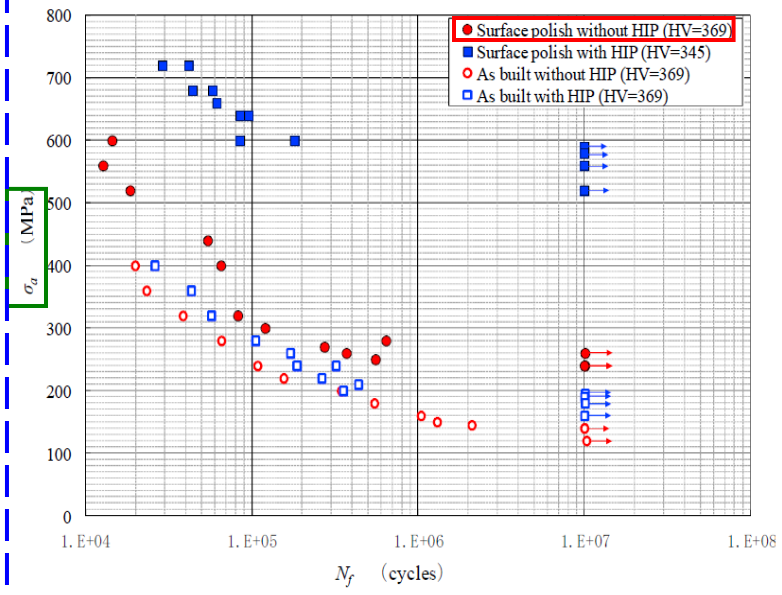
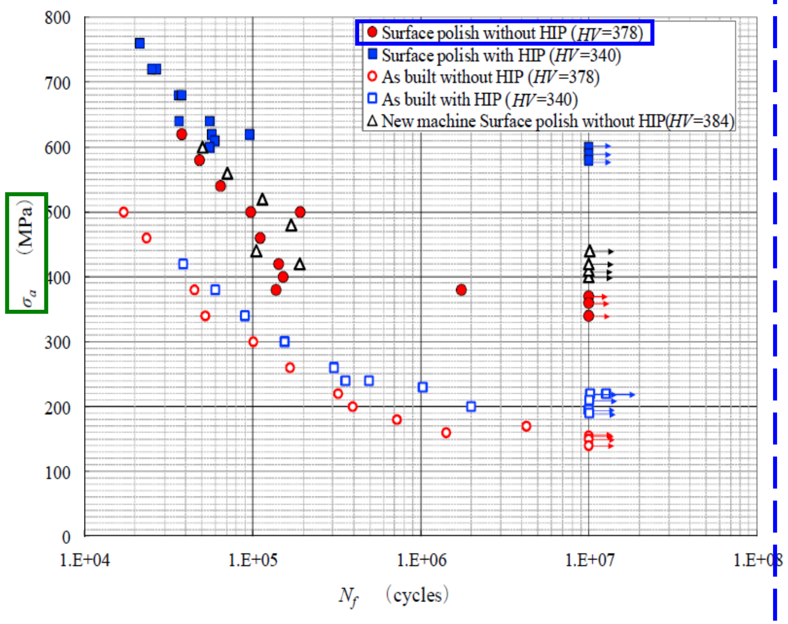
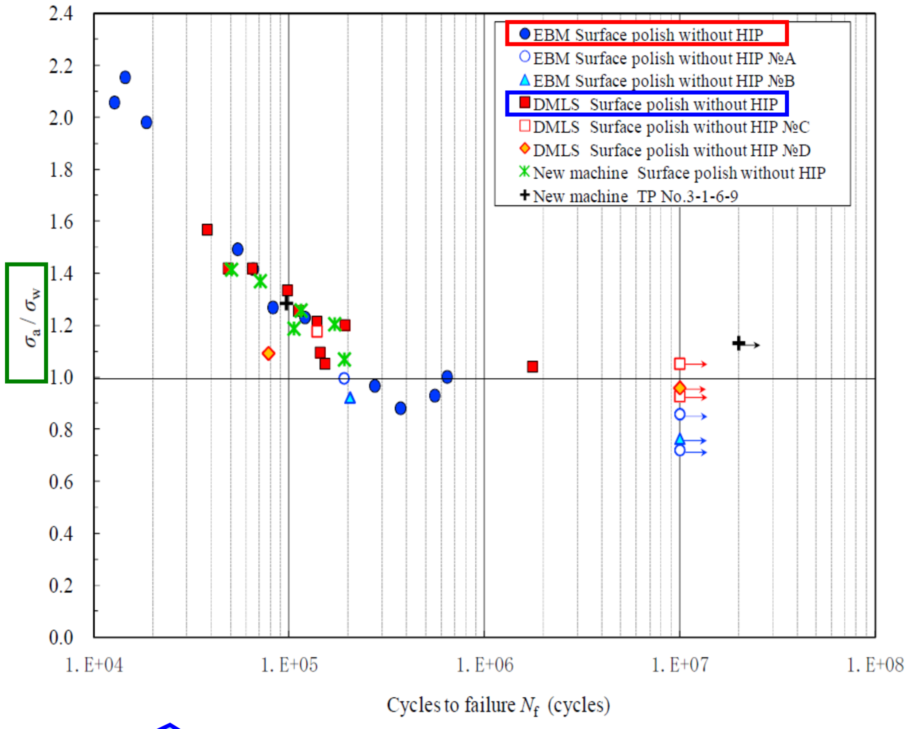
- Prof. Murkami applied the $\sqrt{area}$ approach to an AM material of Ti-6Al-4V [*11].
- When stress amplitude σ_a is normalized by the estimated fatigue strength σ_w of the $\sqrt{area}$ approach, σ_a/σ_w shows almost 1.0 in the high cycle regime. This suggests that the $\sqrt{area}$ approach can treat the different AM manufacturing method by σ_a/σ_w.



(a) EBM (Electron Beam Melting)



(b) DMLS (Direct Metal Laser Sintering)



[*11] Murakami, Y., et al., “Defect Analysis for Additively Manufactured Materials in Fatigue from the Viewpoint of Quality Control and Statistics of Extremes”, Procedia, Structural Integrity, 2019.

Step 2: Application of $\sqrt{area}$ Approach to AM Materials

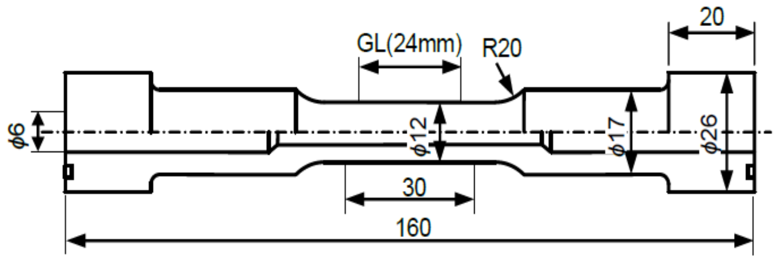
- 13th International Fatigue Congress (Fatigue 2022[+1]) was held at Hiroshima in November 6-10, 2023. Some presenters showed the applicability of the $\sqrt{area}$ approach to AM materials. But this congress are presentation only conference…
- Some parameters may need to be adjusted, but if the applicability of the $\sqrt{area}$ approach using the fatigue endurance limit $\sigma_{w\sqrt{area}}$ is confirmed to AM materials, K_{f_AM} can be expressed as follows. Here, the difference between strain-control fatigue testing and load-control fatigue testing must be paid attention.

$$K_{f\_AM} \propto \frac{\varepsilon_a\left(Best\!-\!Fit\ Curve(\sigma_u)\right)}{\sigma_{w\sqrt{area}}}$$

- If the above method can be applied to AM materials, fatigue tests are not necessary at a procedure qualification test for a AM material, and only tensile tests and investigation of size of defects ($\sqrt{area}$) are required to prepare the fatigue curve of the AM material.

Step 3: Applicability of F_{en} Method to AM Materials

- The applicability of F_{en} method to AM materials is studied.
- EAF tests are needed for AM materials.
- EAF tests for round bar specimens can be performed using an autoclave.
- Hollow specimens are generally used in Japan to perform EAF tests to improve the difficulty of measurements of strains and loads and the expense for the autoclave testing [*12].
- The hollow specimen can be used for polished specimens but may not be applicable to as-built specimens.
- The EAF fatigue testing method of AM materials needs to be studied.



[*12] Asada, S. et al., "Applicability of Hollow Cylindrical Specimens to Environmental Assisted Fatigue Tests", PVP2017-65514, ASME, 2017.

Recent Data: PVP Paper of Rolls-Royce

- Rolls-Royce studied the derivation of a fatigue design curve specific to AM LPBF 316LN stainless steel with Hot Isostatic Press (HIP) process step, for use in ASME III, Subsection NB-3200 or NB-3600 fatigue crack initiation assessments on nuclear plant applications [*13].

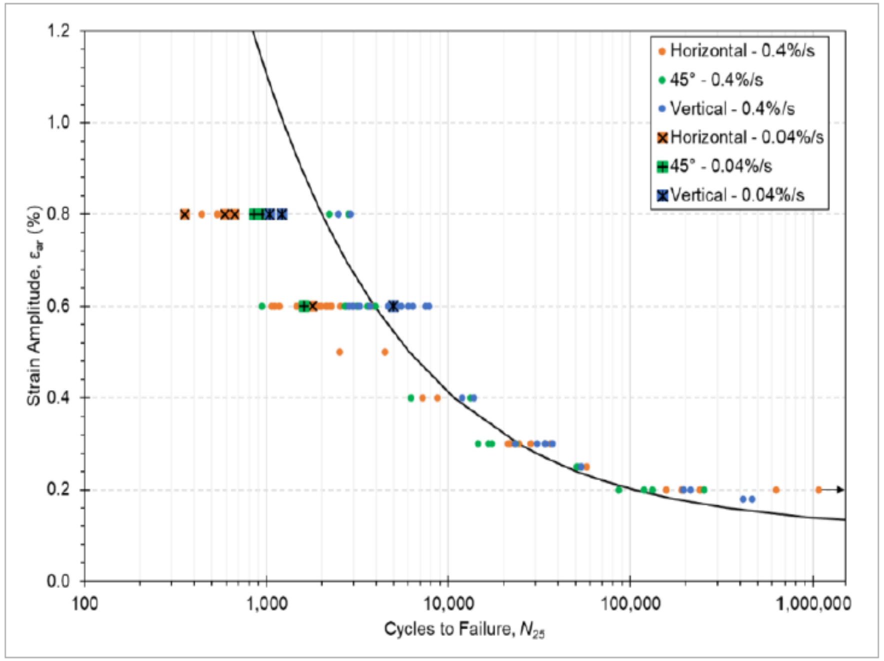


FIGURE 7: ADDITIONAL IN-AIR FATIGUE TESTS AT 0.04%/S STRAIN RATES UNDER AMBIENT CONDITIONS

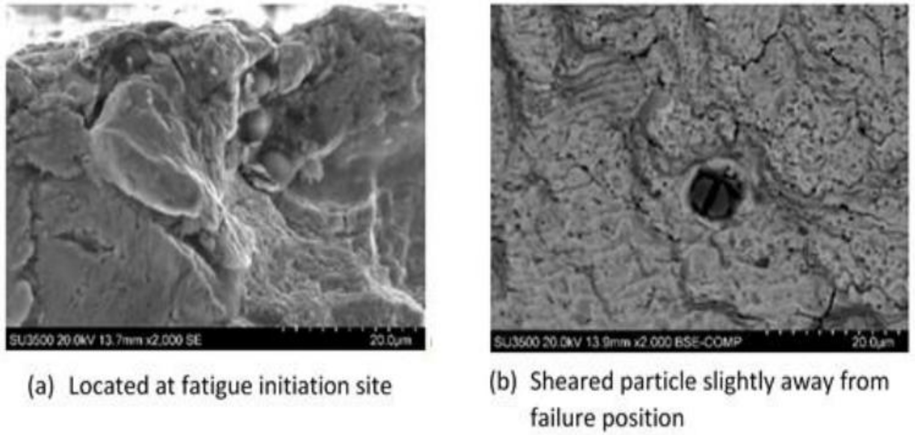


FIGURE 5: MN-RICH PARTICLES OBSERVED ON FRACTURE SURFACES

[*13] Press, B. et al., “Generation of a Fatigue Design Curve Suitable for Use on Addivitive Manufacture Nuclear Plant Components Produced from 316LN Stainless Steel Using Laser Powder Bed Fusion”, PVP2023-106379, ASME, 2023.

Summary and Future Works

- For long-term operation of light water reactors, some components or parts will be replaced. AM materials will support that.
- Tensile properties of AM materials are ensured by qualification test required by the code.
- However, the fatigue evaluation method of AM materials for nuclear component use must be studied, because EAF evaluation is needed to Class 1 components. No one knows the F_{en} method is applicable to the Master S-N Curve Method of the ASME Sec.VIII, Div.2, and both fatigue testing methods are completely different.
- Strain-controlled fatigue test data of AM materials for nuclear component use are limited. Further fatigue tests and investigation of the AM materials are desired.
- When appropriate data are available, Step 1 (procedure of evaluation for fatigue tests), Step 2 (applicability of the $\sqrt{area}$ approach) and Step 3 (Applicability of F_{en} Method to AM Materials) will be studied.

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