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CORRECTING FOR RESIDUAL STRESS EFFECTS ON FATIGUE CRACK GROWTH RATES OF ADDITIVELY MANUFACTURED TYPE 304L STAINLESS STEEL

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Abstract

Additively manufactured (AM) metal builds contain residual stress that can influence measured fatigue crack growth rates (FCGRs), which may then bias the interpretation of the performance of AM materials. In the present work, the on-line crack compliance (OLCC) method was used to determine the residual stress intensity factor, K_{res}, while simultaneously collecting fatigue crack growth rate data in edge crack compact (C(T)) specimens of both AM and wrought materials. Measured near-threshold FCGR data in AM 304L C(T) specimens appear elevated in comparison with data from wrought specimens over a range of applied ΔK. By quantitatively accounting for residual stress, the results for materials processed by the different methods are brought into good agreement, demonstrating the importance of accounting for residual stress when interpreting fatigue crack growth data in AM materials.

Introduction

The two major metal additive manufacturing (AM) processes, laser directed energy deposition (DED) and laser powder bed fusion (PBF), are layer by layer manufacturing techniques that involve melting and subsequent solidification of feedstock powders. In both processes, the complex thermal history results in significant residual stress that influences mechanical behavior, such as fatigue performance. Plates cut from two vertical DED wall builds (Figure 1(a)) and two vertical D-shaped PBF cylinders (Figure 1(b)) were used in this study to compare FCGRs parallel and perpendicular to the build direction.

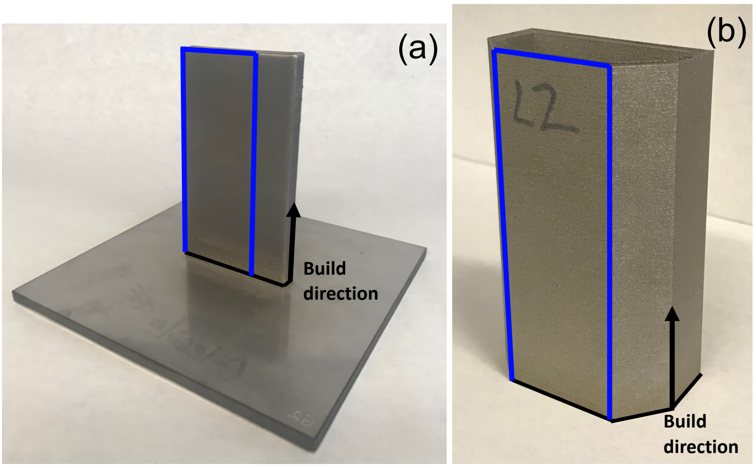

Figure 1: (a) DED build and (b) PBF build; blue rectangles indicate plates cut for specimen extraction.

While destructive measurements of secondary specimens can provide estimates of residual stress effects, an accurate means of quantifying K_{res} in individual (primary) specimens offers better insight into the fatigue behavior of AM material. The OLCC method, the methodology and validation for which are described in a companion presentation, quantifies K_{res} from data collected during a fatigue crack growth test, which can then be used to account for the influence of residual stress on measured FCGRs.

Results

Results of decreasing applied ΔK (ΔK_{app}) fatigue crack growth tests of DED and PBF materials reveal that the highest measured FCGRs were observed in the PBF material, that intermediate rates were measured in the DED material, and that the annealed wrought material had the lowest FCGRs over a range of ΔK_{app} as shown in Figure 2(a). In addition, the FCGRs in the horizontal orientation (H) are generally greater than in the vertical (V), although this difference is more pronounced in the DED material compared to the PBF material. The differences in FCGRs can be understood by considering K_{res} measured in the C(T) specimens by the slitting method when the notch is cut and the OLCC method during the fatigue crack growth tests (Figure 3). The K_{res} values are all positive and are greater in the PBF material than in the DED material. K_{res} is also greater in the horizontal orientation compared to the vertical orientation, although this difference is small in the PBF material and large in the DED material. These trends are consistent with the trends in FCGRs since tensile K_{res} increases the total stress intensity factor ratio, R_{tot}, resulting in higher FCGRs. The annealed wrought material had nominally zero residual stress (data not shown). The FCGR test data were corrected (giving a corrected stress intensity factor, ΔK_{corr}) [1] to account for residual stress effects by linear superposition of K_{app} and K_{res} [2] and by normalizing the rates to a common stress ratio of $R = 0.1$ using the Walker relationship [1, 3, 4]. Similarly, the adjusted compliance ratio [5] was included in the ΔK_{corr} calculation to account for the effects of crack closure. All FCGR data (wrought and AM for both crack growth orientations and processing methods) are shifted and fall onto a single trend (Figure 2(b)) when plotted versus ΔK_{corr}.

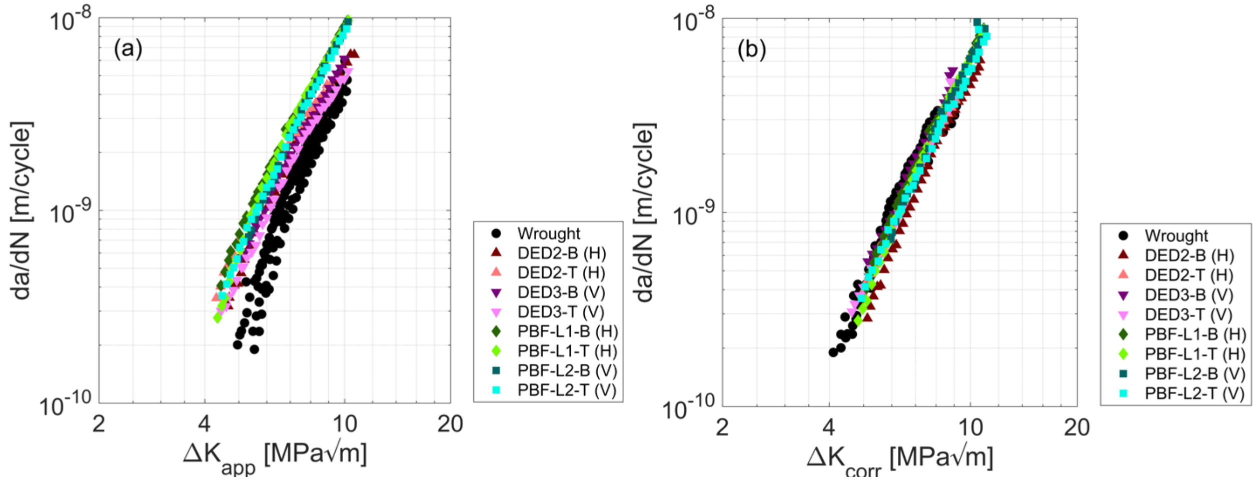

Figure 2: (a) Measured FCGRs for DED, PBF, and wrought stainless steel and (b) FCGRs corrected for crack closure (primarily observed in wrought) and K_{res} contributions to R_{tot} (primarily in AM).

Conclusions

The FCGR data for AM Type 304L stainless steel show that crack growth perpendicular to the build direction occurs faster than crack growth along the build direction at the same ΔK_{app} for the DED material due to greater tensile residual stress in the build direction. Greater contributions of tensile residual stress in PBF specimens result in higher observed FCGRs than in the DED specimens. Correcting the data for the influence of the K_{res} brings the data for both processing methods and both test orientations into agreement. The corrected results also agree with those for an annealed (stress free) wrought reference material corrected primarily for the influence of fatigue crack closure.

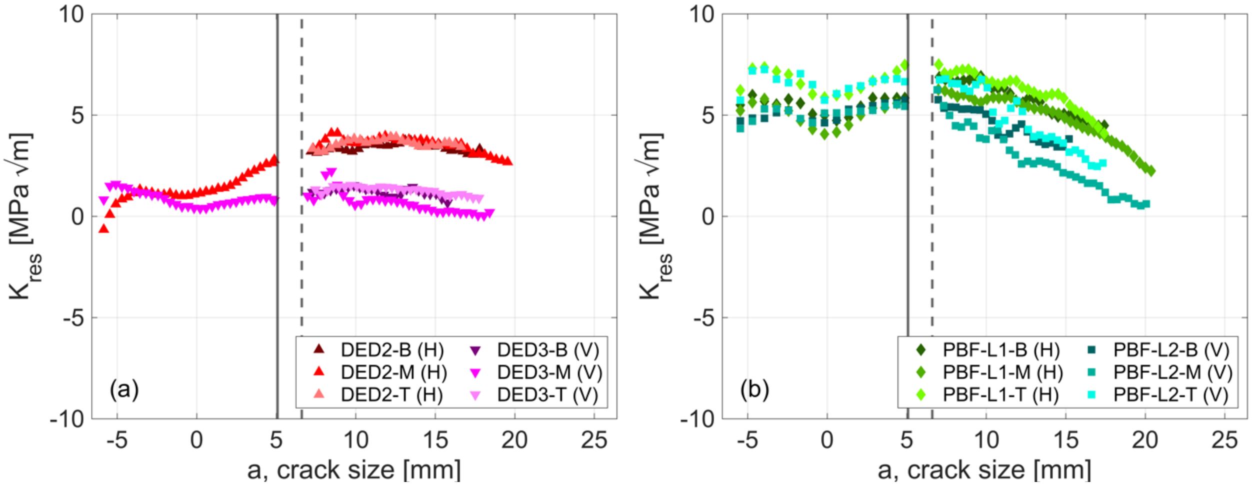

Figure 3: Residual stress intensity factor, K_{res} quantified by the OLCC for (a) DED and (b) PBF specimens. Notch slitting results are to the left of the solid vertical line and OLCC results are to the right of the dashed vertical line.

Acknowledgements

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