Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

VERY HIGH CYCLE FATIGUE BEHAVIOR OF AlSi7Mg ALLOY: EFFECTS OF POWDER CONDITION IN LASER POWDER BED FUSION

Md Mehide Hasan Tusher, Ayhan Ince*
Department of Mechanical, Industrial & Aerospace Engineering, Concordia University,
Montreal, Quebec, Canada
*e-mail: ayhan.ince@concordia.ca

Abstract—The recyclability of metal powders in Laser Powder Bed Fusion (L-PBF) processes is crucial for both economic and environmental sustainability in additive manufacturing. This study investigates the influence of powder recycling and subsequent heat treatment of the recycled powder on the very high cycle fatigue performance and defect characteristics of L-PBF-manufactured AlSi7Mg components. CT analysis revealed comparable total defect counts between new powder and recycled powder specimens, with recycled powder showing fewer surface defects but slightly higher internal defects. Both specimens exhibited almost identical spatial distributions of defects, with new powder demonstrating marginally better sphericity. Specimens fabricated from recycled powder exhibited the highest fatigue performance across all stress levels. Those fabricated from new powder performed better than those using heated recycled powder but were still outperformed by recycled powder. Specimens fabricated with heated recycled powder demonstrated the lowest fatigue performance. The improved fatigue performance of recycled powder despite slightly lower defect sphericity suggests that beyond powder condition and defects count, other factors such as microstructural characteristics, defect position and alignment, oxidation state, particle size distribution, and loading frequency play significant roles in determining fatigue behavior. These findings provide insights into the effects of powder condition on the fatigue performance of L-PBF AlSi7Mg components, highlighting the complex interplay of various factors affecting material behavior in very high cycle fatigue conditions.

Keywords-Additive manufacturing; Very high cycle fatigue; AlSi7Mg alloy; Powder recycling; Laser powder bed fusion

I. INTRODUCTION

In recent years, additive manufacturing (AM) has become an important manufacturing technology by providing unprecedented design freedom and material efficiency [1-3]. An area of interest among various AM techniques for the production of complex metallic components is powder bed fusion (PBF) processes, especially with aluminum alloys like the AlSi7Mg alloy [4-6]. This material has been widely discussed due to its good castability, corrosion resistance, weldability, and the attractive strength to weight ratio for aerospace, automotive and other engineering applications [4, 7, 8]. Over the past few years, this alloy has become one of the most important alloys for AM applications. The reuse of powder in PBF systems may offer significant economic and environmental benefits, but it may also raise concerns about the reliability of material performance [9]. A key issue is how powder recycling affects the fatigue behavior of manufactured components considering that fatigue failure is crucial in structural applications. The sensitivity of aluminum alloys to processing conditions, along with the risk of powder degradation during recycling, requires a comprehensive understanding of its impact on long-term performance. L-PBF technology presents an opportunity for powder recycling, offering potential sustainability benefits [9]. However, these advantages must be carefully balanced against possible degradation in mechanical properties. While the static mechanical properties of AlSi7Mg have been extensively studied, there remains a significant knowledge gap regarding the impact of powder condition on fatigue behavior particularly in very high cycle fatigue (VHCF) regime [4, 5]. This limitation is especially notable for L-PBF AlSi7Mg components, where the relationship between powder properties and VHCF behavior remains poorly understood. Furthermore, post-processing treatments such as heat treatment in mitigating the negative effects of powder recycling on VHCF performance require further investigation.

This study investigates the fatigue behavior of additively manufactured AlSi7Mg specimens produced from three distinct powder conditions: new powder (NP), recycled powder (RP), and heat-treated recycled powder (RPH). Through detailed S-N curve analysis and statistical evaluation, we examine the relationships between powder condition and fatigue performance. The research employs stress-controlled fatigue tests combined with rigorous statistical analysis to quantify the variations in fatigue response across different powder conditions. Special attention is given to the scatter in fatigue data, as understanding the variability in performance is crucial for reliable component design in aluminum-based AM parts.

The preliminary findings from the AB samples provide initial insights into powder recycling effects on the VHCF performance of L-PBF AlSi7Mg alloy, though further testing is planned to establish more comprehensive conclusions. While this study currently focuses on AB condition specimens, ongoing research will examine additional samples across different powder conditions (new, recycled, and heated recycled) and heat treatment states (T5 and T6). These early results contribute to the developing understanding of sustainable AM practices, with future work aimed at providing more definitive guidance for industrial implementation. The complete investigation incorporating additional AB specimens and planned T5/T6 condition testing, will offer a more comprehensive assessment of how powder recycling affects component reliability.

II. Sample Fabrication, Testing and Analysis

Pre-alloyed plasma atomized AlSi7Mg powder was used to manufacture test samples, with chemical composition analyzed through ICP-MS and LECO testing (Table I). Two batches of samples were fabricated using recycled powder, with one batch incorporating recycled powder that was heated during the printing process. FusiA Impressions 3D Metal Inc., Québec, Canada [10] provided cylindrical samples (11 mm diameter) fabricated vertically using an EOS M290 machine. Dog bone-shaped fatigue specimens were machined from fabricated AlSi7Mg cylinders, with a control volume of 188.50 mm^3 as depicted in Fig. 1. Testing was conducted on an in-house Ultrasonic Fatigue Testing Machine at 20 kHz ± 400 Hz frequency using a load ratio of R = -1. Samples were aligned parallel to the build orientation, maintained at ambient temperature using forced air during VHCF testing, and monitored with temperature sensors. Statistical analysis was performed using Minitab statistical software. For detecting any defects in sample's gauge section, a CT scan was done using YXLON FF35CT and then the CT data were analyzed using Dragonfly software, Version 2024.1 developed by Comet Technologies Canada Inc., Montreal, Canada [11].

TABLE I. Chemical Composition of the Powder (wt.%)

Chemical Content	Powder Condition	
	NP	***RP***
Si	6.7	6.97
Mg	0.55	0.50
Fe	0.06	0.09
Cu	<0.01	<0.005
Mn	<0.01	<0.005
Zn	<0.01	<0.005
Be	<20 ppm	---
Ti	0.10	0.115
Other, each	<0.03	<0.01
Other, total	<0.10	<0.05
Al	Bal.	Bal.

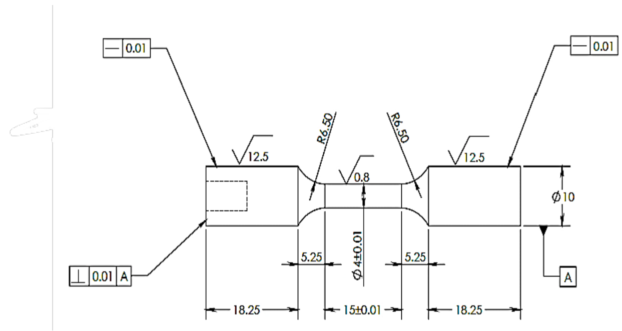

Fig. 1. Dimensions of the fatigue samples.

III. Results and Discussion

A. Stress-life results

The fatigue performance as shown in Fig. 2 among the three powder conditions shows distinct differences. Recycled powder specimens exhibit the best performance across the entire stress range by demonstrating superior fatigue performance compared to the other conditions. New powder specimens perform moderately by showing better fatigue life than the recycled heated powder but falling short of the recycled powder without heating. In contrast, the recycled heated powder specimens display the poorest fatigue performance. The stress amplitude (S_a) versus number of cycles (N_f) plot reveals that AB samples fabricated using recycled powder exhibit superior fatigue resistance, maintaining the highest stress amplitude values approximately 118.5 MPa at a cycle of 1×10^8. The AB samples manufactured using new Powder show intermediate performance with stress amplitudes around 113 MPa at a cycle of 1×10^8, while the samples fabricated using heated recycled powder consistently display the lowest fatigue resistance, with value of approximately 111 MPa at a cycle of 1×10^8.

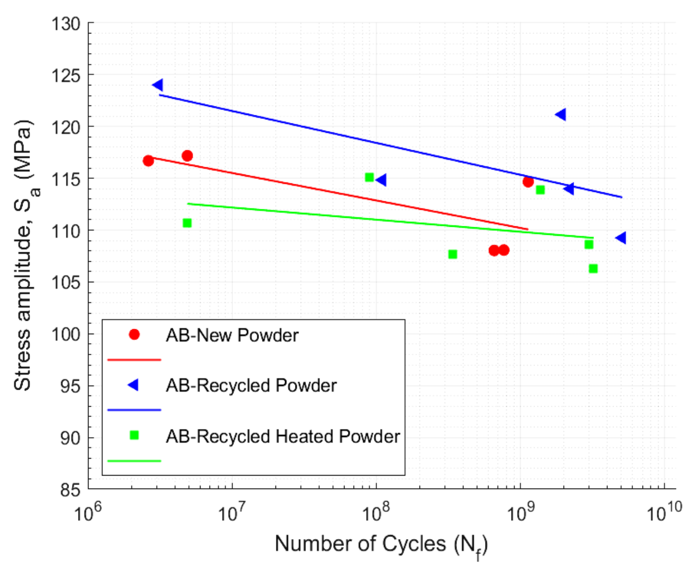

Fig. 2. Stress-life curves with best fit line.

All materials demonstrate a characteristic downward trend in stress amplitudes as the number of cycles increases, with the recycled powder maintaining its superior performance advantage throughout the entire fatigue life. This suggests that recycling process without heat treatment may enhance the material's fatigue properties compared to both new powder and heat-treated recycled powder alternatives. In order to fit the fatigue data using linear regression, equation (1) is implemented where the logarithm of the data on both axes is used. In equation (1), S_f' is fatigue strength coefficient and b is fatigue strength exponent.

$$S_a = S_f'.N_f^b \qquad (1)$$

B. Statistical analysis

The fatigue behavior of different powder conditions was analyzed through linear regression of S-N curves. The analysis revealed distinct characteristics for each powder type as tabulated in Table II. The new powder exhibited a moderate fatigue strength degradation rate with a slope of -2.65 and an intercept of 134.1 MPa, showing a reasonable correlation (R^2 = 0.5761) between stress amplitude and number of cycles. The recycled powder demonstrated a steeper slope (-3.08) with a higher intercept (143.01 MPa), indicating faster strength degradation despite potentially higher initial strength, though with increased data scatter (R^2 = 0.4762). Notably, the heated recycled powder showed significantly different behavior, characterized by a much shallower slope (-1.21) and lower intercept (120.7 MPa), but with very poor correlation (R^2 = 0.1378) suggesting high variability in fatigue response. These findings indicate that powder condition significantly influences fatigue behavior, with new powder showing the most predictable response while recycling and heat treatment of the recycled powder introduce additional variability in fatigue performance. It is important to note that this statistical analysis was performed on limited data sets. However, the relatively low R^2 values across all conditions suggest the presence of other influencing factors and highlight the need for conservative design approaches when using these materials in fatigue-critical applications. These findings suggest that while there may be subtle differences in fatigue behavior among the samples fabricated using new, recycled, and heat-treated recycled powders, these variations are not substantial enough to conclude that powder condition alone is the dominant factor influencing VHCF performance of L-PBF AlSi7Mg components.

TABLE II. REGRESSION VALUES OF THE S-N DATA

Regression Variables	Powder Condition		
	New powder	*Recycled powder*	*Heated recycled powder*
b, fatigue strength exponent	-2.65	-3.08	-1.21
S_f', fatigue strength coefficient	134.1	143.01	120.7
R^2	0.5761	0.4762	0.1378

Other factors such as microstructural characteristics (grain size, characteristics of Si boundary), defect characteristics (defect count, defect type, position, alignment of the defects to the loading), oxidation state of the powder, particle size distribution, loading frequency likely play crucial roles in determining fatigue behavior.

C. Pore analysis

To understand the underlying reasons for varying fatigue performance, CT data were analyzed for two untested samples: one for NP and the other for RP. In the future, additional samples will be examined for all conditions, specifically NP, RP, and RPH, to thoroughly analyze and identify the correlation between fatigue performance and defect statistics. A comprehensive analysis of defect characteristics between NP and RP specimens revealed insightful patterns in their distribution and morphology (Fig. 3). CT scan data showed comparable total defect counts (NP: 650, RP: 627), with RP exhibiting 25.6% fewer surface defects (99 vs 133) but slightly higher internal defects (402 vs 392). Both specimens demonstrated uniform spatial distribution of defects throughout the volume, with no significant clustering observed in either vertical or cross-sectional views. Sphericity analysis indicated marginally superior characteristics in NP specimens (0.9556 ± 0.0490) compared to samples manufactured using RP (0.9469 ± 0.0560) (Fig. 3(d)). Distribution analysis showed both batches maintained high sphericity, though the NP batch exhibited tighter clustering around the mean with fewer outliers, indicating more consistent spherical morphology. The observed higher sphericity and reduced variation in the NP batch suggest better control over particle formation compared to the RP process. Interestingly, fatigue performance data revealed that RP specimens maintained higher stress coefficient (~143 MPa) compared to NP (~134 MPa), with both materials showing gradual decline in fatigue strength over increasing cycles. The improved fatigue performance of the samples fabricated using RP despite slightly lower sphericity suggests that other important parameters, i.e., microstructure, defects' alignment, oxides, inclusions, loading frequency might have significant impact on the fatigue performance of L-PBF AlSi7Mg samples. It is important to note that the statistics for the defects shown here are only for two samples (one from each powder condition). Future CT analysis of more samples for each powder condition including heated recycled powder will provide additional insights into the relationship between processing conditions, defect characteristics, and fatigue properties.

IV. CONCLUSIONS

The fatigue performance analysis of L-PBF AlSi7Mg samples manufactured under three different powder conditions revealed distinct behavioral trends. Recycled powder samples exhibited the highest fatigue performance compared to new powder and heated recycled powder samples. Heated recycled powder demonstrated the lowest fatigue performance behavior. Defect analysis showed comparable total defect counts between the samples manufactured using new and recycled powder, with variations in defect distribution patterns. New powder exhibited higher surface defects while recycled powder showed slightly higher internal defects. The powder morphology analysis confirmed that both new and recycled powders maintained excellent sphericity characteristics.

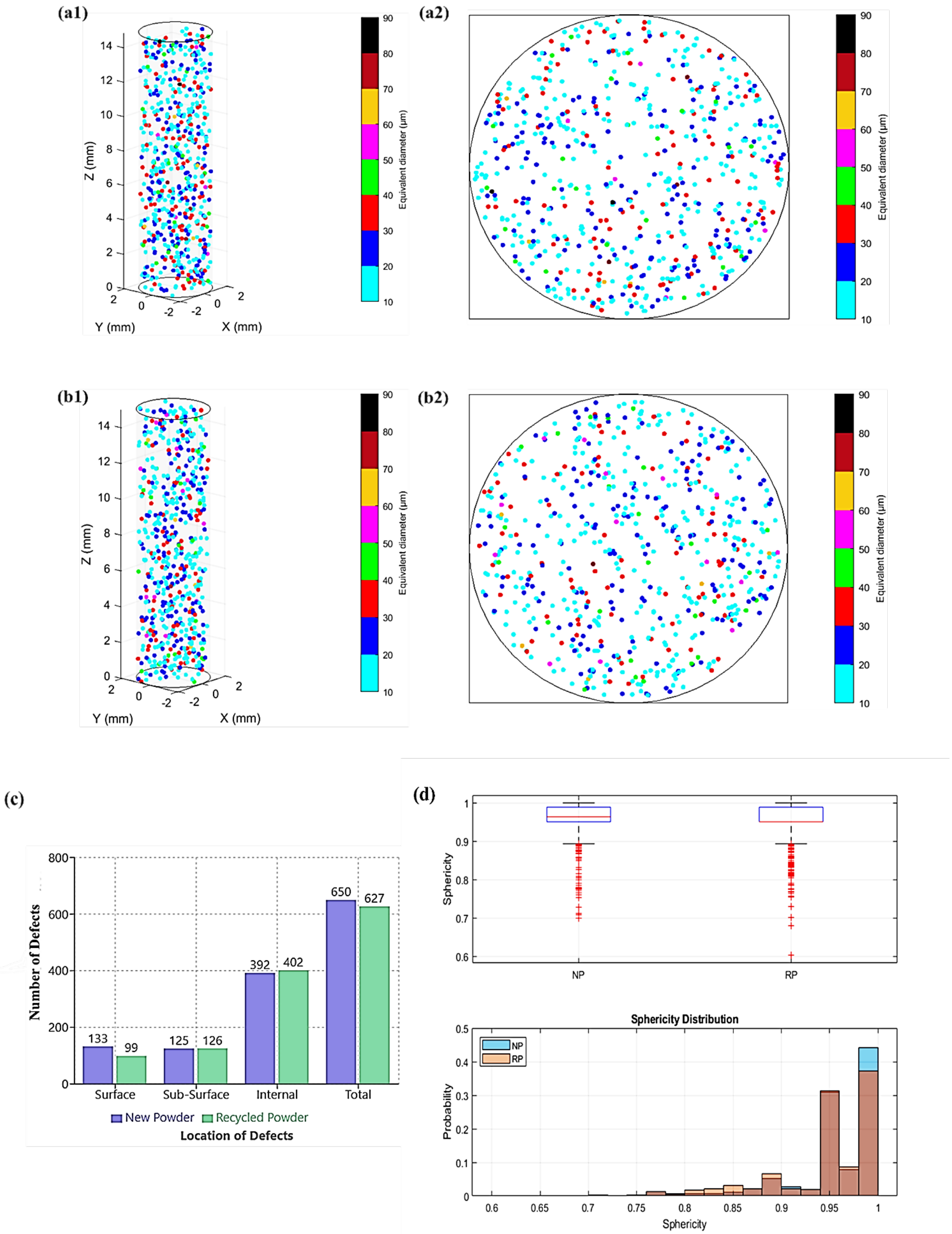

Fig. 3. Defects statistics (a) NP (b)RP (c) Location of the defects (d) Sphericity of the defects. Here, 1 and 2 stands for Front view and Top view respectively.

However, the analysis suggests that powder condition alone is not the dominant factor influencing fatigue performance. Other factors such as microstructural characteristics (grain size, characteristics of Si boundary), defect characteristics (defect count, defect type, position, alignment of the defects relative to the loading), oxidation state of the powder, particle size distribution, loading frequency likely play crucial roles in determining fatigue behavior. This indicates that while powder recycling and heat treatment of the recycled powder may influence fatigue properties, their effects are potentially overshadowed by other parameters. These findings highlight the complexity of fatigue behavior in L-PBF manufactured AlSi7Mg alloy and suggest that a more comprehensive investigation of processing-structure-property relationships would be beneficial for optimizing fatigue performance of L-PBF AlSi7Mg samples. Future work will include testing more samples, μ-CT defect analysis, microstructure and fracture surface studies to better understand crack initiation and propagation behaviors for samples fabricated from different powder and heat treatment conditions.

Acknowledgment

The authors gratefully acknowledge the financial assistance provided by the NSERC (Natural Sciences and Engineering Research Council of Canada) (DGECR-2018-00232) in supporting this research project. The authors express their gratitude to FusiA impression 3D M´etal Inc., located at 180 Boulevard Industriel, Saint Eustache, Qu´ebec, J7R 5C2, for their assistance in supplying the fabricated and treated cylindrical samples. The authors would also like to acknowledge the technical support provided by Ecole de Technologie Superieure for μ-CT imaging.

References

[1] Tusher, M.M.H. and A. Ince, High Cycle Fatigue and Very High Cycle Fatigue Performance of Selective Laser Melting Ti-6Al-4V Titanium Alloy—A Review. Mat Perform Charact., 2023. 12(2).

[2] Tusher, M.M.H. and A. Ince, Effect of stress relieved heat treatment on very high cycle fatigue performance of additive manufactured Ti‐6Al‐4V alloy. Fatigue & Fracture of Engineering Materials & Structures, 2023. 46(10): p. 3982-4000.

[3] Tridello, A., et al., Size-effects affecting the fatigue response up to 109 cycles (VHCF) of SLM AlSi10Mg specimens produced in horizontal and vertical directions. International Journal of Fatigue, 2022. 160: p. 106825.

[4] Tusher, M.M.H. and A. Ince, A systematic review on high cycle and very high cycle fatigue behavior of laser powder bed fused (L-PBF) Al-Si alloys. Engineering Failure Analysis, 2023: p. 107667.

[5] Tusher, M.M.H. and A. Ince, Exploring VHCF response in L-PBF AlSi7Mg Alloy: Influence of T6 heat treatment on microstructural characteristics and defect distribution. International Journal of Fatigue, 2024: p. 108471.

[6] Li, D., et al., Effect of heat treatment on AlSi10Mg lattice structure manufactured by selective laser melting: Microstructure evolution and compression properties. Materials Characterization, 2022. 187: p. 111882.

[7] de Menezes, J.T.O., E.M. Castrodeza, and R. Casati, Effect of build orientation on fracture and tensile behavior of A357 Al alloy processed by Selective Laser Melting. Materials Science and Engineering: A, 2019. 766: p. 138392.

[8] Lorusso, M., et al., A357 Alloy by LPBF for industry applications. Materials, 2020. 13(7): p. 1488.

[9] Carrion, P.E., et al., Powder recycling effects on the tensile and fatigue behavior of additively manufactured Ti-6Al-4V parts. Jom, 2019. 71(3): p. 963-973.

[10] FusiA Inc. Available at: https://www.fusia-inc.com/ [Accessed: Jan. 28, 2025].

[11] Dragonfly 2024.1 [Computer software]. Comet Technologies Canada Inc.: Montreal, Canada; software available at https://www.theobjects.com/dragonfly [Accessed: Jan. 28, 2025].