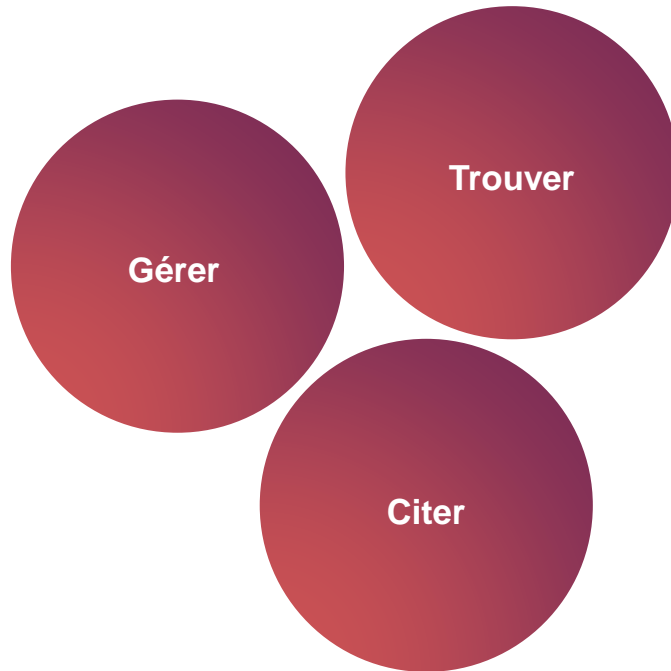


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Towards a self-healing aluminum metal matrix composite: Design, fabrication, and demonstration

David Svetlizky^a, Baolong Zheng^b, Xin Wang^b, Sen Jiang^b, Lorenzo Valdevit^b, Julie M. Schoenung^{b,c}, Enrique J. Lavernia^{b,c}, Noam Eliaz^{a,*}

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ARTICLE INFO

Keywords:

Aluminum metal matrix composite
Core/shell powder
Self-healing metal-matrix composites (SHMMCs)
Spark plasma sintering (SPS)
Transient liquid phase bonding (TLPB)

ABSTRACT

This paper presents a novel approach to designing and synthesizing a self-healing aluminum-based metal matrix composite (MMC) at the macro-scale. The composite comprises an Al 5083 matrix embedded with low melting point particles (LMPPs) that act as healing agents. A two-step electroless micro-encapsulation process is developed to create LMPPs with a diffusion and thermal barrier designed to protect the Zn-Sn core with a Co-P shell. The MMC is fabricated using spark plasma sintering. Following controlled total fracture under tension, external compressive force is applied during heat treatment to heal the fracture effectively. The evolution of phases and interfaces is characterized using electron microscopy, and transient liquid phase bonding (TLPB) is identified as the fracture-healing mechanism, facilitated in areas with sufficiently high Zn concentration to fill the crack. The design can be expanded to incorporate other matrix and LMPP materials, mechanical crack volume reduction by integrating shape memory alloy (SMA) reinforcement during MMC synthesis, and processing of the self-healing MMC using Directed Energy Deposition additive manufacturing.

Ramification: Editeur, Journal, Volume, Issue, Année, Numéro d'article, Page

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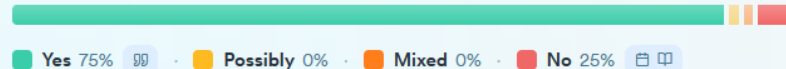
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Yes, electric current can promote diffusion. This phenomenon is observed across various systems where the application of electric current enhances the diffusion process.

Mechanisms of Enhanced Diffusion

- Electromigration:** In systems like the W-Ti during spark plasma sintering, electric current significantly increases the interdiffusion coefficient due to electromigration. The electron wind force accelerates atomic movement, enhancing diffusion without changing the activation energy ¹.
- Electrotransfer:** In bimetallic composites such as the Cu-Al system, electric current accelerates the growth of the diffusion layer significantly, demonstrating the impact of electrotransfer on diffusion kinetics ².
- Ion Transport in Glass:** In S78-5 glass, electric current affects the diffusion of ions, with diffusion coefficients observed during annealing at constant temperatures ³.
- Electroconvection:** At ion-selective surfaces, intensive electric currents generate electroosmotic flow, which enhances ion transport by mixing the depleted solution layer, thus reducing diffusion limitations ⁴.

Applications and Implications

- Polymer Electrolytes:** In polymer electrolytes, electric fields influence ion transport, with models predicting ion velocities and limiting currents, crucial for battery performance ⁵.
- Multicomponent Systems:** In systems like $\text{H}_2\text{O} + \text{CaCl}_2 + \text{HNO}_3$, electric current influences the formation of sharp moving boundaries, demonstrating the interplay between electric conduction and diffusion ⁶.



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1. Le titre
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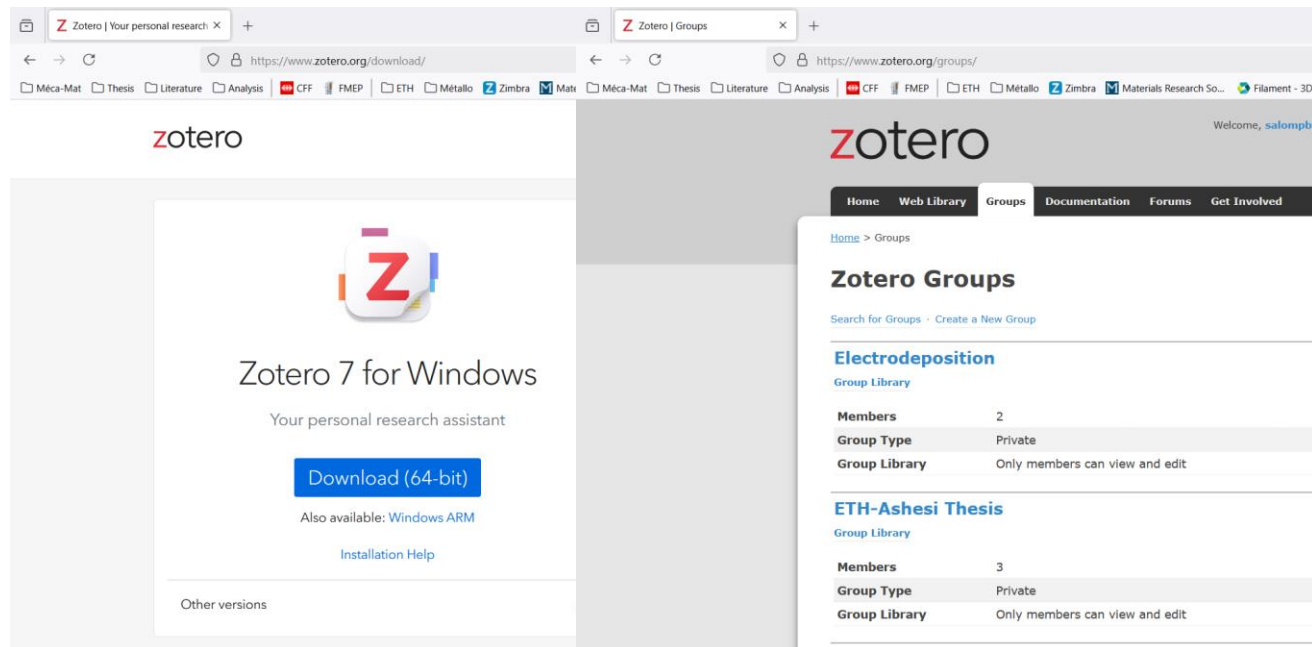
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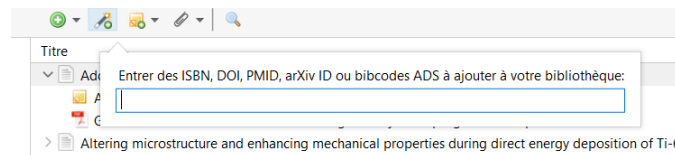
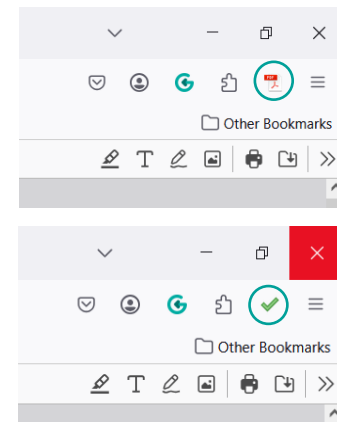
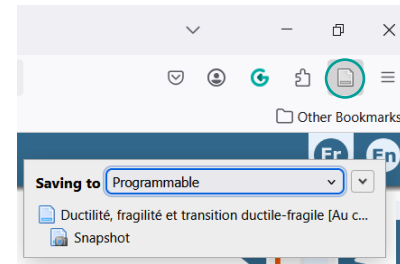
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thickens equals that of the individual microstructure layers. The more practical limit, however, is set by the spatial resolution of LPBF machines (of the order of 100 μm along the build direction in this work), which is a function of melt pool size and laser parameters employed. When attempting to produce an architecture with 19 interfaces, we find that the recrystallized microstructure expands beyond the initial design, yielding connected regions of recrystallized material that limit the maximum attainable strength (Supplementary Fig. 10b).

Discussion

In this work, we focus on the capability to engineer the mechanical properties of SS316L using our LPBF strategies to program the thermal stability of SS316L and create layered microstructure architectures. We use these results as a demonstration of the potential of our microstructure control. However, the differences in crystallographic texture, grain structure, and grain boundary character distribution which result from recrystallization may also inspire other microstructure designs that lead to superior performance or novel functionalities. Programmable, site-specific recrystallization could be used to optimize materials resistance against failure as a result of fatigue³³ or hydrogen embrittlement³⁴, for instance. In that regard, we expect our strategy to

Electron microscopy characterization

We prepared the cube samples for microstructure analysis following standard metallographic procedures. We assessed the microstructure using a JOEL JSM-7800F Prime field emission scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD) detector (Oxford Instrument, Symmetry). We acquired EBSD measurements using a step size 0.5 μm for as-built, heat-treated, and tensile samples. We employed a step size of 5 μm step size for the sample shown in Fig. 1d, and of 1.5 μm for the samples shown in Figs. 1e and 5a and Supplementary Fig. 10. We analyzed the EBSD data using the software AZtecCrystal (by Oxford Instruments) and MTEX 5.6, which is a comprehensive MATLAB toolbox for analyzing and plotting crystallographic quantities³⁵. We classified GBs according to their misorientation into low-angle grain boundaries (LAGBs, from 2° to 15°), high-angle grain boundaries (HAGBs, >15°), and twin boundaries (TBs, 60° about <111>). To reveal the solidification structure of SS316L produced by LPBF, we etched the polished samples in a bath of hydrofluoric and nitric acid (HF:HNO₃:H₂O = 1:4:5) for 20 min.

To estimate relative changes in GND density from EBSD measurements, we used strain gradient theory^{27,34}:

$$\rho = \frac{2\theta}{Xb} \quad (2)$$

Here, θ is the average local misorientation angle measured in KAM maps, X corresponds to the scan step-size (0.5 μm for this analysis), and b is the magnitude of the Burgers vector.

To characterize the solidification structure, we relied on bright-field (BF) and high-angle annular dark-field (HAADF) imaging using a JEM-GrandARM aberration-corrected transmission electron microscope (TEM) operated at 300 kV in scanning transmission electron microscopy (STEM) mode. We carried out STEM energy-dispersive X-ray spectroscopy (EDS) to map the elemental micro-segregation at cell boundaries. TEM lamellae were cut from the etched sample surface by focused ion beam (FIB) using a gallium ion source on a ZEISS Crossbeam

were produced using the same laser power of 60 W, scanning speed of 600 mm/s, scan rotation of 90°, and powder layer thickness of 10 μm .

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