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Article

Two-Dimensional Evolution of Thermomechanical Interfacial Stripping in Ultrafast Laser Processing of Metal/Polymer Layered Systems

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Supporting Information

Section S1. Measurement Methodology and Standardization Process for Groove Profiles and Depths

To ensure the reproducibility and accuracy of the geometric characterization, a standardized measurement protocol was established to extract the groove profiles, average depths, and uniformity as shown in Figures 6 and 7 of the main text. As shown in Figure S1a, the 3D surface topography and raw depth data were acquired using a laser scanning confocal microscope, followed by a leveling and tilt-correction procedure. To minimize artificial or random sampling errors, a multi-section averaging method was implemented. As illustrated in Figure S1b, cross-sectional profiles perpendicular to the groove scanning direction were extracted at an interval of 5 μm. A total of 220 parallel cross sections were captured, constituting the entire measurement range of 1100 μm, and these profiles were subsequently averaged to generate a single representative average profile. The definitive groove depth was then determined by measuring the vertical distance between the baseline of the pristine material surface and the lowest point of this average profile.

The shaded error bars plotted alongside the removal depth in Figure 7b serve as a metric for depth uniformity along the longitudinal direction of the groove, which was obtained with the arithmetic mean roughness (R_a) of the groove bottom along the laser scanning path (Figure S1c,d). During the initial ablation stage, the material was removed uniformly, yielding a negligible roughness (Figure S1c); consequently, the depth distribution remained highly consistent, resulting in negligible and invisible error bands in Figure 7b. In contrast, during the over-ablation stage, the underlying woven glass fiber reinforcement within the substrate became fully exposed. The intrinsic checkerboard-like structural distribution of the woven glass fabrics induced highly nonuniform material removal, leading to a sharp increase in the bottom roughness (Figure S1d) and a correspondingly wider variation in the groove depth, ultimately manifesting as prominent shaded error bars in Figure 7b.

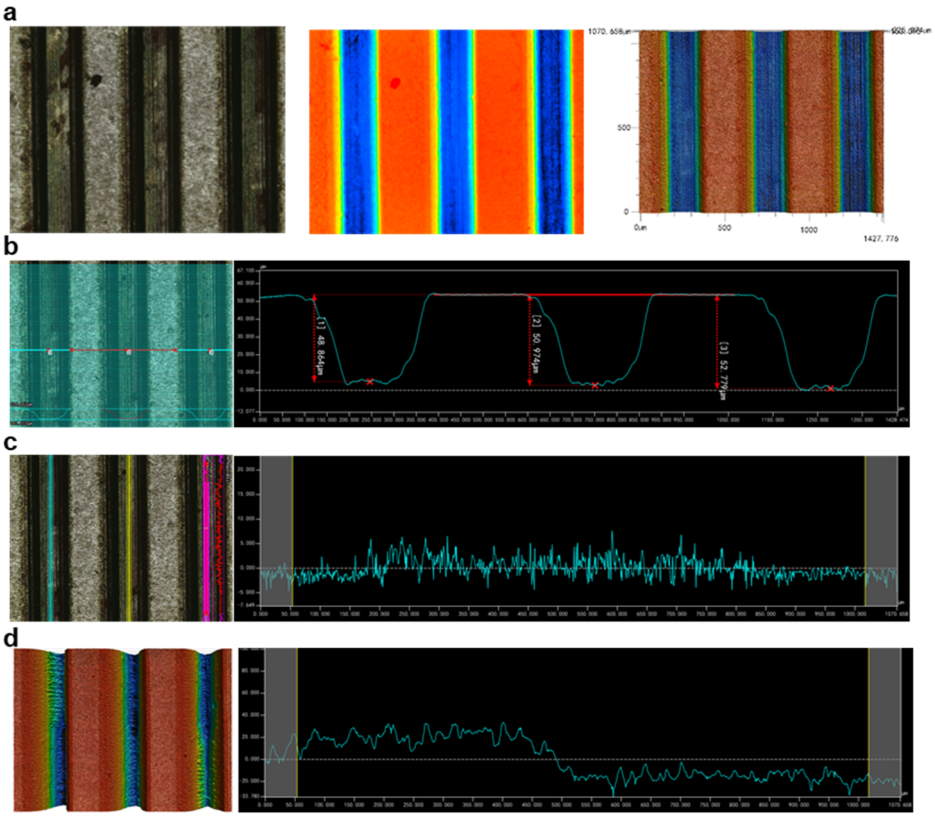


Figure S1. Standardized measurement protocol for groove depth and uniformity. (**a**) Surface topography and raw depth data of the groove. (**b**) Standardization of the cross-sectional profile averaging method. (**c**,**d**) Assessment criteria for depth uniformity based on the bottom roughness (R_a) along the groove scanning direction.

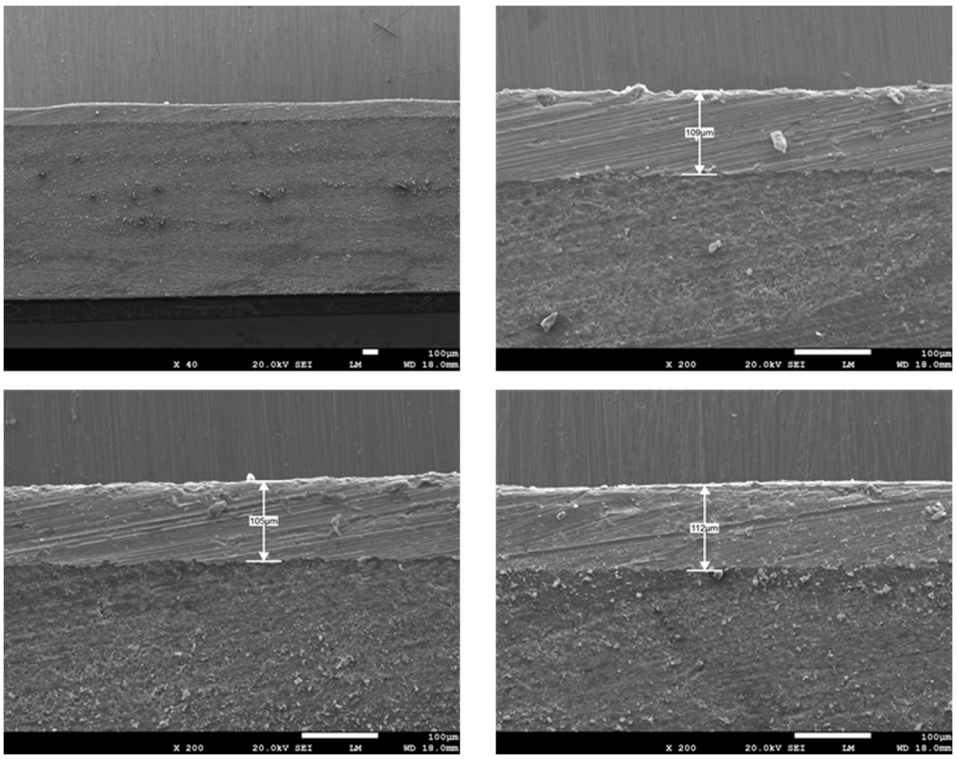


Figure S2. Cross-sectional micrograph for measuring the thickness of the Cu film layer (with a thickness range of approximately 105–112 μm).

Table S1. Lennard–Jones (12-6) potential parameters for Al, Ni, and Cu (metal units) [1].

Metal	r_0 (Å)	ε_0 (eV)	A (eV·Å^{12})	B (eV·Å^6)
Al	2.925	4.02	1,577,000	5,035
Ni	2.552	5.65	431,100	3,121
Cu	2.616	4.72	484,800	3,026

Table S2. Thermodynamic parameters of metal.

Parameter		Unit	Al	Cu	Ni
Electron density	n_e	1/Å^3	0.181	0.085	0.183
Electron heat capacity	C_e		The C_e for Al, Cu, and Ni is temperature-dependent and was obtained by fitting based on Reference [2]		
Electron thermal diffusivity	D_e	Å^2/ps	311,767 [3]	413,400	5261[3]
Electron-phonon coupling factor	G	W/(m^3·K)	3.0×10^{17} [4]	1.0×10^{17} [5]	$3.0–8.0 \times 10^{17}$ [4]
Optical penetration depth	δ_p	nm	8 [6]	14 [7]	13.5 [8]

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