Supplementary material

Effect of material removal state on the selection of theoretical models when scratching single crystal copper using the load modulation approach

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To estimate the normal shear angle φ_n, we assumed that the direction of the shear coincided with the direction of the maximum shearing stress for the perfectly plastic material. Then, we found the solution to φ_n through the following method proposed by [S1] as follows:

$$\varphi_n = \frac{\pi}{4} - \frac{\beta_n}{2} + \frac{\gamma_o}{2} \tag{S1}$$

According to [S2], the normal friction angle β_n can be calculated as follows:

$$\tan \beta_n = \tan \beta \cos \eta_c \tag{S2}$$

where β is the friction angle, which can be estimated from the following relations [S3]:

$$\tan\beta = \frac{\tau_1}{p_0}\left[1+\rho\left(1-\left(\frac{\tau_1}{p_0\mu}\right)^{\frac{1}{\rho}}\right)\right] \tag{S3}$$

and

$$\frac{\tau_1}{p_0} = \frac{\rho+2}{4(\rho+1)}\frac{\sin(2(\varphi_n+\beta_n-\gamma_o))}{\cos^2(\beta_n)\cos(\eta_c)} \tag{S4}$$

where τ_1 is the shear yield strength of the sample material along the sticking region [S3], which was close to the cutting edges at the exit of the shear zone; p_0 is the normal pressure at the single-point diamond tip; and ρ is the exponential constant representing the pressure distribution, which is regarded to be 3 on the basis of the experimental work [S4]. Furthermore, μ is the sliding friction coefficient of the tip-sample combination, which is considered to be 1.5. By substituting equations (S1), (S2), and (S4) into equation (S3), we can rewrite equation (S3) in terms of only one unknown variable β_n, which can be solved by using the Newton-Raphson algorithm available in MATLAB [S5].

The associated of cut A can be calculated as follows:

$$A = \frac{h^2}{2}(\tan\delta_1 + \tan\delta_2) \tag{S5}$$

where δ_1 and δ_2 are the specified tool profile angles with respect to the two cutting edges. Moreover, the shear flow stress $\tau = \frac{\sigma_p}{3}$, which is a comparatively accurate estimation accounting for the Taylor factor of crystalline materials [S5].

Next we calculated the edge force as follows:

$$F_{eQ} = h\left(C_{eq1} \tan\delta_1 + C_{eq2} \tan\delta_2 - C_{ep1} \sin\lambda_{s1} - C_{ep2} \sin\lambda_{s2}\right) \tag{S6}$$

where C_{eq1}, C_{ep1}, C_{eq2}, and C_{ep2} are the edge force coefficients for each edge, which we estimated by using the analytical model proposed in [S6] as follows:

$$C_{ep1} = r_{e1}\tau\left(\frac{2\theta_0}{\cos\theta_0} + \pi\sin\theta_0 \tan\theta_0\right) \tag{S7}$$

$$C_{eq1} = r_{e1}\tau\left(2\sqrt{3}\sin\theta_0\right) \tag{S8}$$

$$C_{ep2} = r_{e2}\tau\left(\frac{2\theta_0}{\cos\theta_0} + \pi\sin\theta_0 \tan\theta_0\right) \tag{S9}$$

$$C_{eq2} = r_{e2}\tau\left(2\sqrt{3}\sin\theta_0\right) \tag{S10}$$

where r_{e1} and r_{e2} represent the radii of the cutting edges of the single-point diamond tip [S7 S8], which were 578 nm and 426 nm, respectively, as measured by AFM; θ_0 is the neutral point angle, which was considered to be 14° [S6] in this study. Furthermore, note that this analytical model was developed for machining by the tool with large edges at low cutting depths, taking the rubbing forces into account due to the material plowing state beneath the rounded cutting edges. Moreover, the inclination angles corresponding to the two cutting edges were calculated as follows:

$$\lambda_{s1} = \tan^{-1}\left(\frac{\cos\delta_1 \tan\gamma_o - \sin\delta_1 \sin\lambda_s}{\cos\lambda_s}\right) \tag{S11}$$

$$\lambda_{s2} = \tan^{-1}\left(\frac{\cos\delta_2 \tan\gamma_o + \sin\delta_2 \sin\lambda_s}{\cos\lambda_s}\right) \tag{S12}$$

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