Supplementary Discussion 1: Relative strength of binary and ternary junctions

As a useful reference point, consider first a single dislocation line connecting two end points that are fixed (or pinned) in space. When left alone under zero stress, the dislocation stretches between its end points along the straight line minimizing its own line energy; however, under the action of increasing external stress, the line begins to bow out until, at stress σ_0, it reaches an unstable configuration of a semi-ellipse (Fig. SD1.1). Beyond this instability, the semi-loop yields to stress expanding indefinitely: this is the so-called Frank-Read mechanism of dislocation multiplication. The magnitude of yield stress σ_0 depends on the direction of applied stress and on the length and orientation of the line. In this study we computed σ_0 for a family of dislocation lines of initial length 1000 (in the units of cubic lattice constant) with Burgers vector ½$[1\bar{1}1]$. All lines were parallel to the $(10\bar{1})$ plane but formed different angles θ with respect to the [111] direction. Two stress directions were tested for the sake of this discussion, namely uniaxial tension stress along $[1\bar{1}0]$ and [100] axes. For a given line orientation angle θ, the yield stress is the same for two selected stress directions.

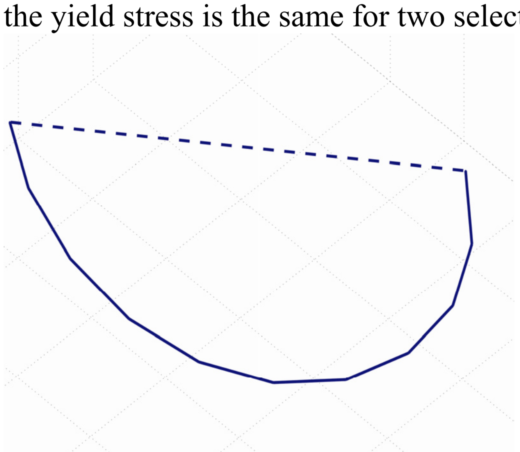

Figure SD1.1: Yielding of a single dislocation line. Initially the line is straight under zero stress (dashed line) but under critical stress σ_0 it bows out and reaches an unstable configuration (solid line). From this state on, the line yields by bowing around its end points indefinitely.

When two or more dislocations interact, the constraining effect of their interaction can be quantified by the minimal stress σ required to make each line yield. In a large network of interacting dislocations, the yield stress is a very complicated function of network geometry. Here we consider a few relatively simple geometries that are representative of the range of behaviors observed in large dislocation networks under stress. In the DD simulations of dislocation collisions, the lines are initially brought to intersection at their mid-points and positioned at the same incidence angles θ with respect to the common intersection line of their glide planes. Figure SD1.2 below illustrates the geometry for the case of a binary collision. As before, each line has initial length 1000 and forms angle θ to the [111] direction. With the choice of Burgers vectors and glide planes described in the main text, all collisions are attractive but their outcomes (junction or cross) depend on the incidence angle while their yield strengths σ depend also on the stress direction. A given collision makes dislocation motion more difficult only when $\sigma > \sigma_0$. Repulsive collisions result if one of the Burgers vectors of the colliding lines is inverted: such configurations are not discussed here.

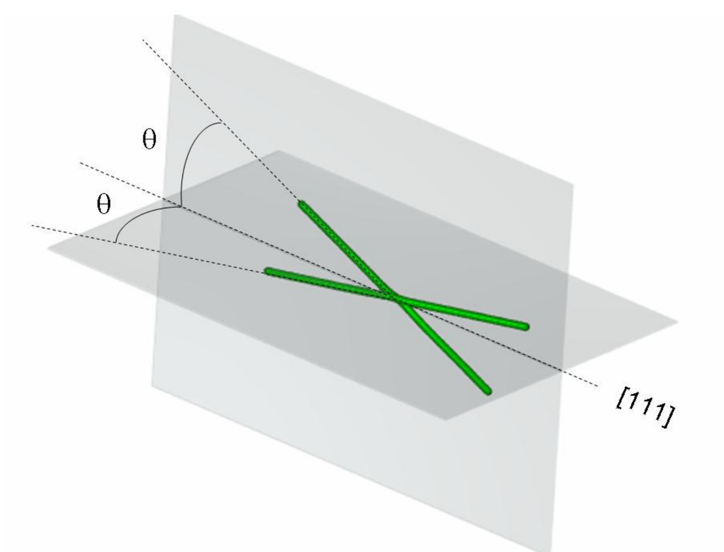

Figure SD1.2: Geometry of a binary dislocation collision. Both lines are fixed at their ends and are initially straight. Under the action of their interaction forces and applied stress, the lines can move but only along their respective glide planes (shaded).

As illustrated in the Figure SD1. 3 below, binary junctions of the kind shown in Figure 1(b) of the main text form, or *zip*, only in a limited range of collision angles, between 0 and 50 degrees. The stress required to disentangle two dislocations by unzipping a binary junction increases with the decreasing incidence angle. At higher collision angles, from 60 to 90 degrees, the lines do not zip junctions but stay crossed: such weakly attractive configurations have been previously termed "crosses" (Wickham *et al*. 1999). It takes a small stress (close to zero) to separate two crossed lines in such cases.

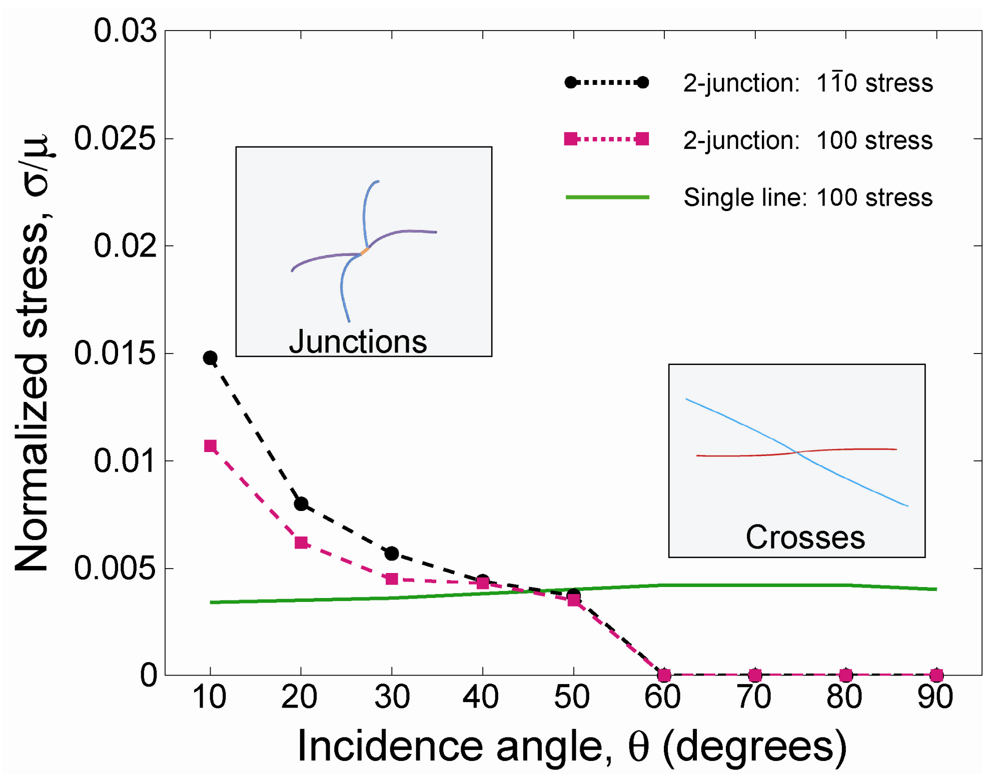

Figure SD1. 3: Formation and strength of binary junctions. The data points show the magnitude of stress required to separate two interacting dislocations as a function of incidence angle θ. Binary junctions zip only for collision angles between 0 and 50 degrees. At higher angles, the lines stay crossed as shown in the right inset. The crossed states are weakly attractive but have no strength since it takes only a small stress to separate two crossing lines. The junction-forming collisions are strongest at small incidence angles whereas the junction formed at collision angles around $\theta = 50^o$ are weak and offer no additional resistance to dislocation motion because they yield by unzipping under stress below the yield stress σ_0 of a single line (green solid line). The strength of a given junction depends on the direction of applied stress: when stress is applied along [1-10] direction (black filled circles and black dashed line) the binary junctions hold dislocations stronger than when stress is applied along [100] direction (magenda filled squares and magenda dashed line). A snapshot of a binary junction during unzipping is shown in the left inset. The yield stress of a single line (green solid line) is weakly dependent on the line orientation angle θ but, for a given θ, is the same for both tested stress directions.

To investigate the strength of ternary reactions, here we consider simple collision geometry in which the glide planes of three colliding lines intersect along a common [111] line. As before, each line has initial length 1000, intersects two other lines at the midpoint and forms angle θ to the [111] line. It turns out that ternary collisions studied here do not produce crosses but zip multi-junctions in the entire range of incidence angles, from 0 to 90 degrees. Figure SD1.4 shows how much stronger the multi-junctions are compared to the binary junctions, over the entire range of collision angles. Even at high collision angles, from 60 to 90 degrees, the multi-junctions show considerable strength, substantially higher than σ_0. In contrast, binary junctions do not zip at high angles at all. At angles below 50 degrees both binary and multi-junctions zip, but the latter hold the reacting lines considerably stronger (compare the multi-junction strength data shown in red to the binary strength data shown in black and magenda).

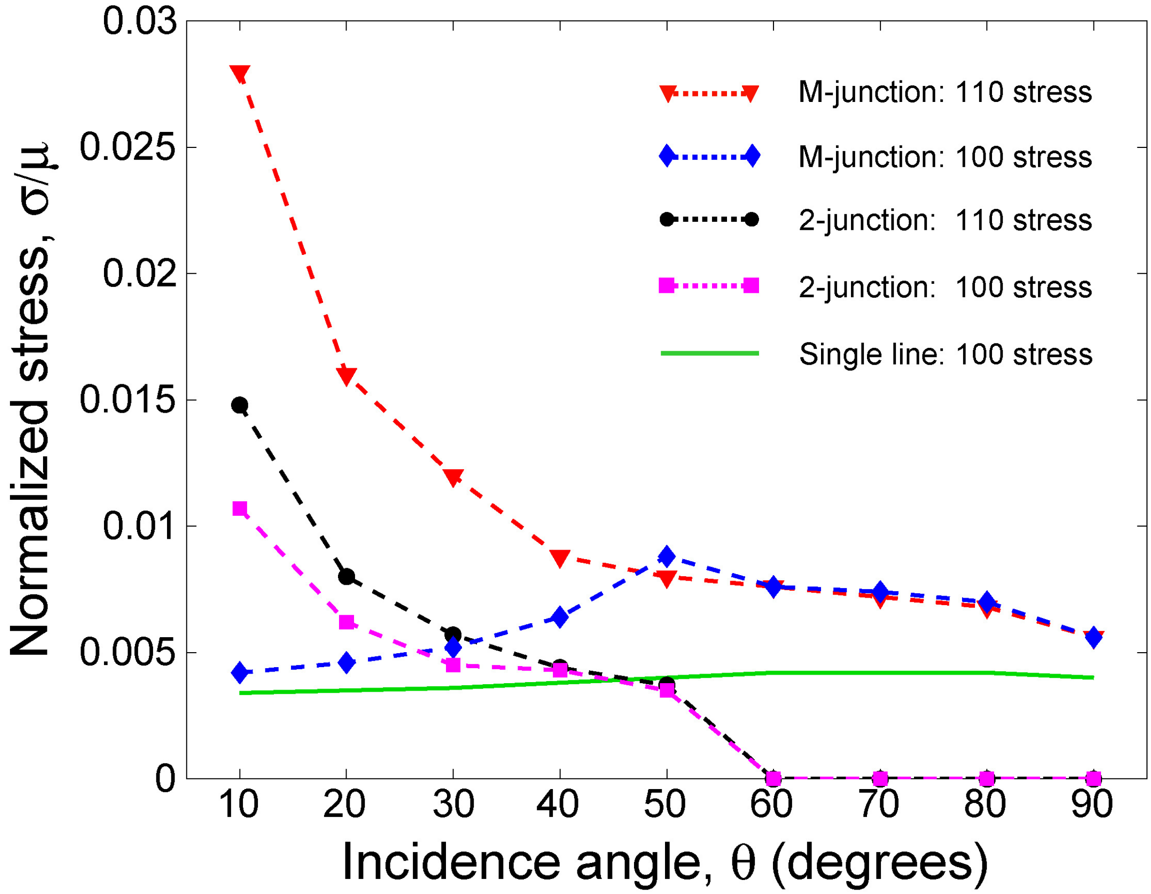

Figure SD1.4: Stress required to unzip a junction as a function of collision angle.

It may appear that, when stressed along [100] direction, the multi-junctions are strongest for angles around $\theta = 50^o$ (the data shown in blue). The meaning of the apparent reduction in the multi-junction yield strength for collision angles below 50 degrees is discussed in the caption to figure SD1.5.

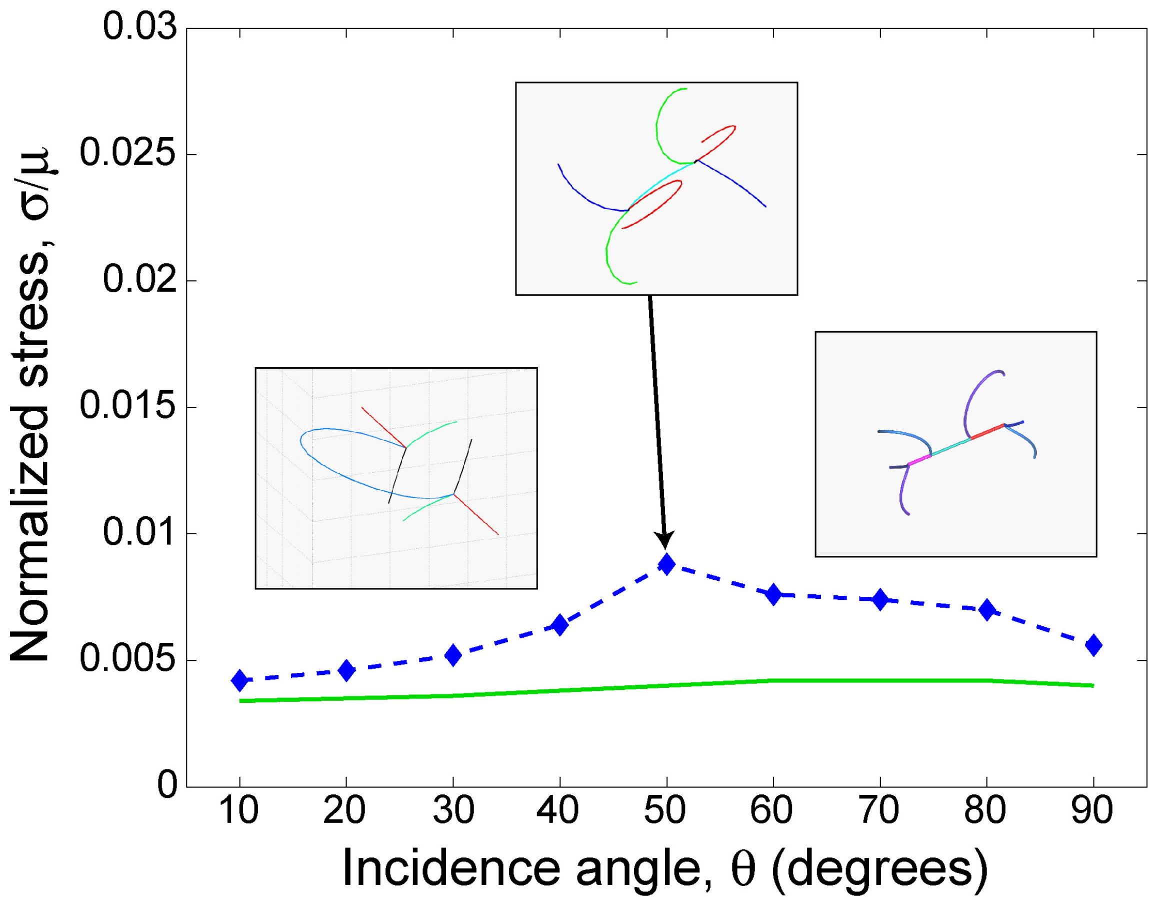

Figure SD1.5: Yield of multi-junctions under [100] stress. Multi-junctions formed at high incidence angles, between 60 and 90 degrees, tie dislocations together with considerable strength. A snapshot of a multi-junction unzipping under stress is shown in the lower right inset. That the multi-junctions appear strongest at θ=50^{o} is a manifestation of a cross-over to a different mode of yielding response taking place at this incidence angle. Now, rather than unzipping under stress, the multi-junctions hold dislocations so strongly that the segments of the parent lines reach instability, bow around the 4-nodes and eventually produce closed dislocation loops concentric with the multi-junction. An early stage of such source activation is shown in the middle inset where two line segments (red) will eventually produce two new dislocation loops (not shown). At still lower incidence angles, between 0 and 40 degrees, the junction line itself (magenda line in the left inset) yields to stress by bowing about its two 4-nodes and producing a concentric dislocation loop. Remarkably, each time a new dislocation loop is emitted, the whole configuration regenerates itself so that the multi-junction is never destroyed (see Supplementary Video 4).

References

Wickham, L. K., Schwarz, K. W., and Stolken, J. S. Rules for forest interactions between dislocations. *Phys. Rev. Lett.* **83**, 4574 (1999).