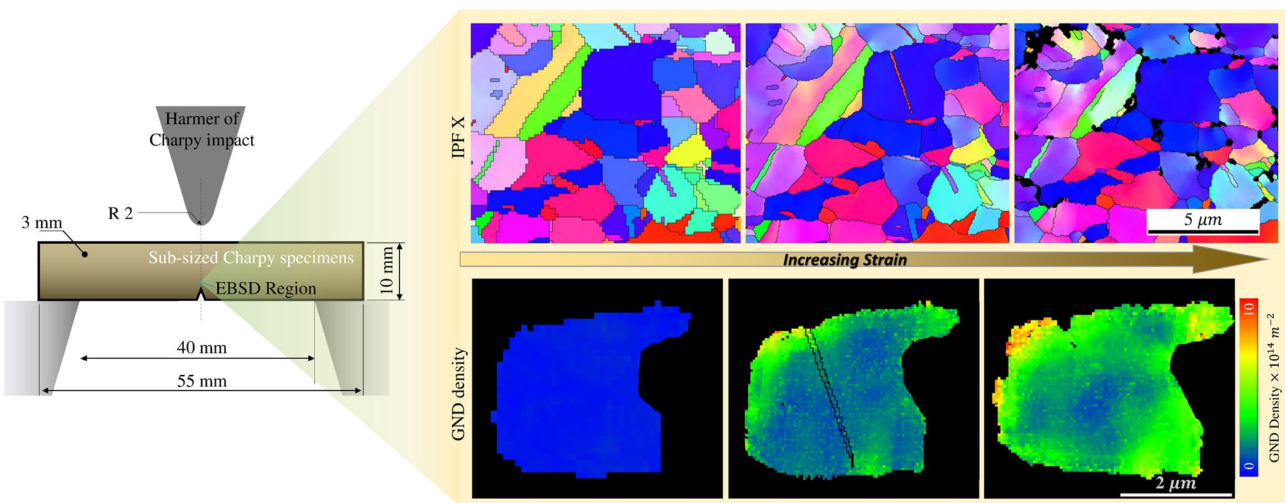
Twin Instability and Its Effect on the Dislocation Behavior of UFG Austenitic Steel Under Charpy Impact Test

MINGHAO HUANG, CHENCHONG WANG, XIAOFEI ZHU, LINGYU WANG, ANNA MOGUCHEVA, and WEI XU

Twinning-induced plasticity (TWIP) steel offers high strength and ductility. However, in this study, deformation-induced detwinning was studied to prove that not all twins significantly benefit the mechanical properties. The quasi *in situ* observation results indicated that submicron-sized twins were unstable during Charpy impact loading. In contrast to the TWIP concept, analysis of the geometrically necessary dislocation evolution associated with detwinning revealed that unstable twins have negligible influence on the pile-ups of dislocations, offering a limited strengthening effect.



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OWING to their combination of strength and toughness, ultrafine-grained (UFG) austenitic steels have been widely used in critical applications, such as liquified natural gas (LNG) tanks.[1,2] The superior properties of austenitic steel are partially due to mechanical twinning, that is, the twinning-induced plasticity (TWIP) effect.[3] Deformation-induced twinning enables back stress hardening, and twin boundaries efficiently reduce the mean free path of dislocations; both contribute considerably to the flow stress. Tailoring the steel microstructure to produce a significant number of twins has been regarded as an efficient strengthening strategy and has received increasing attention.

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Most previous studies suggested that twins are stable and effectively hinder dislocation gliding, like grain boundaries. Hence, extensive effort has been devoted to promoting twin formation before and during loading tests.[4,5] In contrast to conventional observations, some recent studies revealed that detwinning occurs under several specific load situations, such as tension-compression cycle loading[6–8] and dynamic plastic deformation (DPD).[9] These observations raise an interesting question, as to whether twins are mechanically stable throughout loading. Compared to twinning, detwinning has received lesser attention. High strain rates make it difficult to characterize the detwinning behavior under dynamic loading conditions. Dynamic loading is one of the most extensive applications of austenitic steel. The fabrication of UFG alloys is also related to dynamic loading processes, such as severe plastic deformation treatment.[10] On the material fabrication side, detwinning would be undesirable for grain refinement. In terms of material strengthening, it remains to be elucidated as to whether the twins are sufficiently mechanically stable and provide an effective barrier to hinder dislocation gliding during the dynamic test.

To address the aforementioned challenges, the Charpy impact test was selected in this study. It is one of the most common dynamic loading tests, characterized by a strain rate in the range of 10^2–10^3 s^{-1}. In this study, the detwinning behavior of UFG austenitic steel during interrupted Charpy impact loading was directly observed, and its effect on dislocations was quantitatively studied.

A commercial SUS 321 austenitic stainless steel (Fe–17.56Cr–9.34Ni–0.021C–0.578Si–1.38Mn–0.252Ti, wt pct) was selected as the experimental material. The received steel plates were cold-rolled from 12 mm to 3.5 mm, followed by reverse annealing at 900 °C for 90 seconds, resulting in a UFG microstructure, as shown in Figure 1(a). The equiaxed grains were characterized by a mean grain size of 1 μm. To interpret the microstructure evolution, a quasi *in situ* electron backscattered diffraction (EBSD) study was carried out by controlling the Charpy impact energy. Interrupted Charpy testing was performed using an MTS impact tester (SANS ZBC2452-C) with a 1 J solution. The testing method and characterization region are schematically shown in Figure 1(b).

EBSD mapping was focused on the area 100 μm directly above the V-notch, and was performed using a scanning electron microscope (GeminiSEM 300) equipped with an EBSD detector (NordlysNano, Oxford Instruments). The Charpy specimen was carefully electrolytically polished at − 20 °C and a voltage of 20 V for 20 seconds. The EBSD data were analyzed using AZtecCrystal 2.0 analysis software. The nominal strain was calculated as $\varepsilon = (L - L_0)/L_0$, where L_0 and L are the distances between two specified points before and after Charpy impact, respectively, as reported in our previous study.[11]

The microstructural evolution during the Charpy impact tests is shown in Figure 2. Figures 2(a), (b), and (c) show the IPF X maps of austenite, captured after 0, 3.24, and 6.78 pct nominal strain, respectively. The IPF maps indicate the disappearance of twins along with a change in the orientation of the grains (Figure 2(j)). This is consistent with the experimental results of Zhang *et al.*,[12] who reported that detwinning is related to grain rotation. To verify the detwinning results, Figures 2(d), (e), and (f) show the corresponding IPF Z maps of the same area. Meanwhile, Figures 2(g), (h), and (i) show that the misorientation angle changes between 3.24 and 6.78 pct nominal strain, as indicated by the black arrows in Figure 2(e). The detwinning phenomenon is quantized, as confirmed in Figures 2(g), (h), and (i). For ease of description, the twins/matrices are denoted as T1/M1, T2/M2, and T3/M3, respectively (Figure 2(e)). In the IPF maps, the thickness of T3 gradually decreases with increasing strain, but the lamellar morphology is retained. The fragmented T1 is shown in Figure 2(f); notably, a short segment of T1 remains inside the core region, which presents an intermediate stage of detwinning. The measurements show that among the three analyzed twins, T2 nearly completes detwinning. Based on these observations, it is concluded that detwinning might be a result of the progressive thinning of twins. The three twins mentioned above represent three

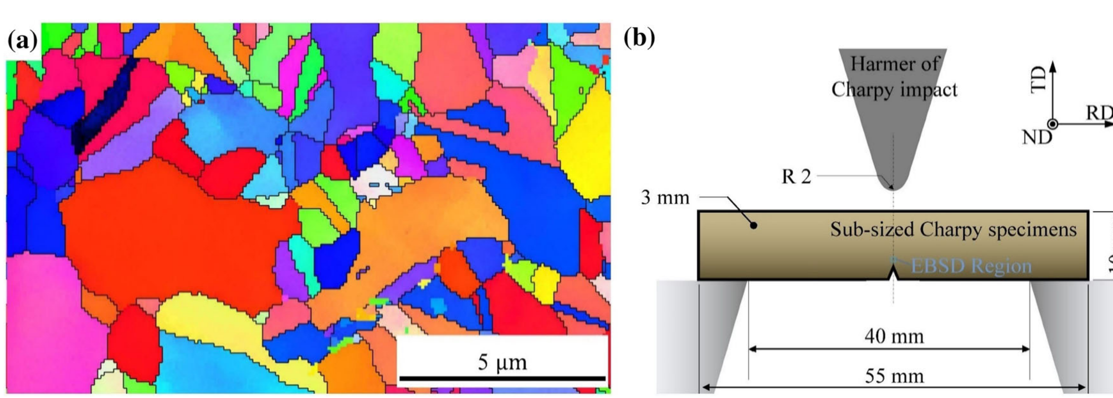

Fig. 1—(*a*) IPF Z map associated with grain boundaries of fabricated UFG steel. (*b*) Schematic of the loading condition and characterization region. RD, TD, and ND represent the rolling, transverse, and normal directions, respectively.

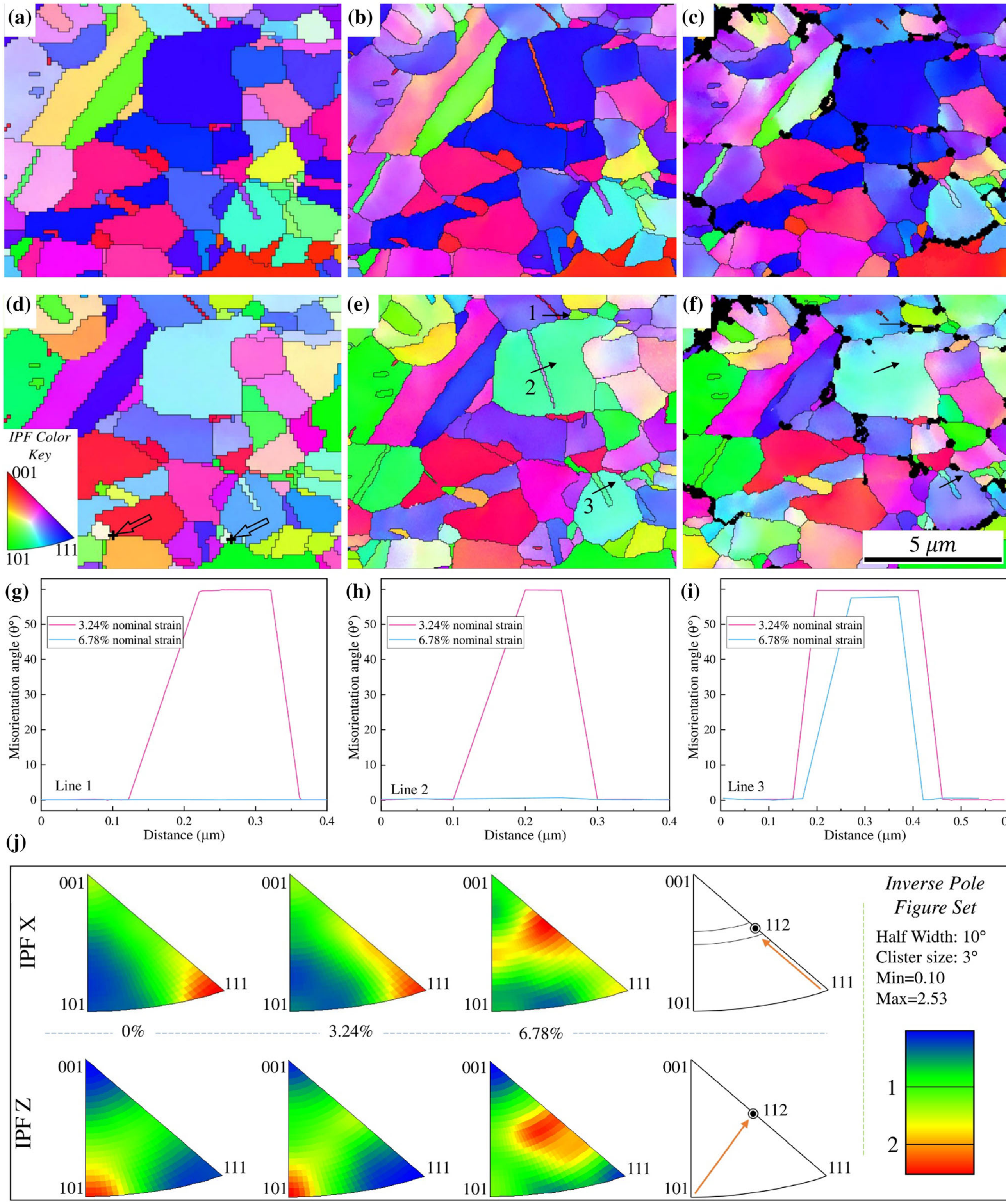

Fig. 2—Microstructure evolution during the Charpy impact test. (*a*, *b*, *c*) IPF X maps of austenite with 0, 3.24, and 6.78 pct nominal strain, respectively. (*d*, *e*, *f*) IPF Z maps of austenite with 0, 3.24, and 6.78 pct nominal strain, respectively. The nominal strain was measured by the distance between two specified points, indicated in (d) with hollow arrows. In addition, the black areas in (c) and (f) represent unindexed pixels. (*g*, *h*, *i*) The misorientation angle changes along the black arrows in (e) at 3.24 and 6.78 pct nominal strain for lines 1, 2, and 3 respectively. (*j*) Grain rotation during Charpy tests in which deformation occurs by duplex slip. (Note: EBSD tests were performed with a 0.13 μm step size for the 0 pct nominal strain sample, and 0.05 μm step size for the 3.24 and 6.78 pct nominal strain samples).

statuses: thinning (T3) → broken (T1) → disappearance (T2). Besides the three twins shown in Figure 2, there are also other individual tests that validate the detwinning phenomenon during the Charpy process (as shown in the appendix). And similar detwinning phenomena have been previously investigated in Cu-Al systems using TEM.[9]

In contrast to previous studies, which described detwinning in TWIP steels under cyclic loading conditions, the present study directly reveals the detwinning behavior occurring in austenitic steel under dynamic loading conditions.

Detwinning behavior in face-centered cubic (fcc) crystals has been reported previously, especially in Cu alloys,[13] and several possible mechanisms for the detwinning behavior have been considered. The first and most accepted mechanism is detwinning induced by twin-slip interaction.[14–17] Therefore, it is worth analyzing the grain rotation and dislocation slip behavior during Charpy impact. As indicated in Figure 2(j), the grains rotate from the initial orientation to an orientation close to (112), indicating the occurrence of duplex slip,[18] where intense dislocation slip occurs. Shockley partial dislocations are the products of twin-slip interactions, and glide along the twin boundaries, resulting in locally thinned twins. The difference in crystal orientation between the twin and matrix leads to varied Schmid factors (Figure 3(a)). The difference between the Schmid factors of the twins and matrix causes the concentration of high-level shear stress in the twin boundaries.[19] To release the shear stress and coordinate the shear strain, dislocation reactions with the twin boundaries are initiated.[20,21] The dislocations promoted by these internal strains make the twin plates thinner.[22] With increasing shear stress, detwinning occurs until the twins disappear. A higher difference in the Schmid factor between the matrix and twins indicates a higher shear stress, which is important for detwinning. The lamella T2 (red-colored), which has the largest misfit of the Schmid factor between the twins and matrix among the three twins, vanishes quickly compared to the others. The second mechanism proposed previously is attributed to secondary twinning within the former twin, which can transform former twin orientations to matrix orientations, resulting in detwinning.[23] In the present study, the progressive thinning of the twins suggests that detwinning is governed by the twin-slip interaction. Thus, Shockley partial dislocation reactions are responsible for the observed detwinning. This specific detwinning process is schematically illustrated in Figure 3(b).

The role of mechanically metastable twins in the movement of dislocations also needs to be considered, as they influence the flow stress. Previous studies have revealed that deformation twinning effectively strengthens steels,[3] first because twin formation induces back stress, and second because twins confine dislocation gliding by reducing the mean free path of dislocations. For UFG steel, grain refinement results in mechanically metastable twins with limited thickness,[24] such as T1 and T2. The contribution of the metastable twins to the dislocation movement was studied, and is shown in Figure 4. In Figures 4(a), (b), and (c), with increasing nominal strain, the average value of the geometrically necessary dislocation (GND) density increases steadily.

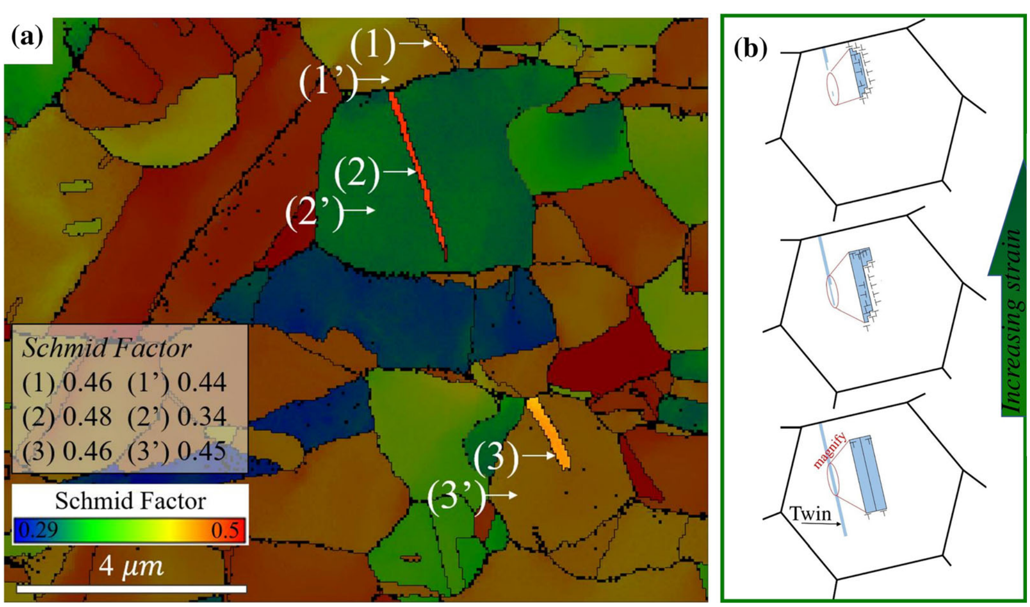

Fig. 3—(*a*) Schmid factor under 3.24 pct nominal strain of the twins and their respective matrices. (*b*) Schematic of the evolution of detwinning with increasing strain.

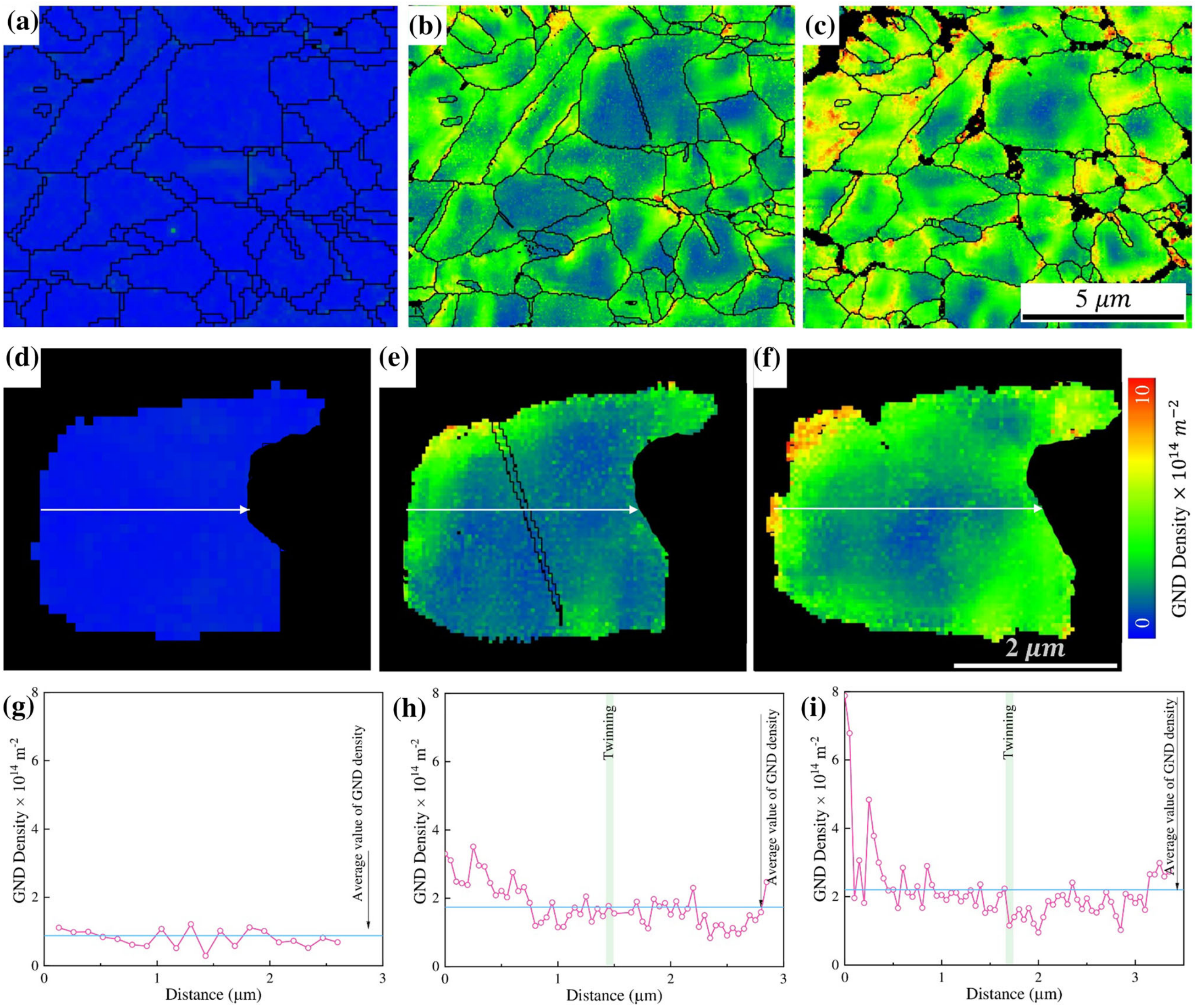

Fig. 4—(*a*, *b*, *c*) Calculated GND density evolution with increasing nominal strain. (*d*, *e*, *f*) Magnified regions of (a), (b), and (c) respectively. (*g*, *h*, *i*) GND density profiles along the white lines in (d), (e), and (f), respectively.

While grain boundaries are strong barriers for dislocations, the thin twins T1 and T2 have a negligible effect on the dislocation pile-up. The GND density profiles along the white lines indicate that T2 has a lesser effect on the dislocation pile-up (Figures 4(g), (h), and (i)). In the present study, the contribution of mechanically metastable twins to flow stress was limited.

UFG austenitic steel typically contains submicron-sized twins due to the limitation of an extremely high nucleation stress. The present results indicate that these types of twins might be mechanically unstable and have a limited effect on the strength of the studied austenitic steel under Charpy impact loading.

This study investigated the detwinning behavior and its contribution to the dislocation pile-up behavior during Charpy impact testing. The detwinning behavior of austenitic steel was directly observed under the one-direction dynamic loading process. The mechanically metastable twins did not strengthen the UFG steel during Charpy impact tests. Based on the presented results, the following conclusions were drawn: (1) Induced and existing submicron-sized twins are unstable during Charpy impact loading. (2) Deformation-induced detwinning occurs more completely in twins with a higher Schmid factor misfit with the matrix. (3) In contrast to the traditional TWIP concept, twins with a limited thickness play a negligible role in work hardening, as they fail to obstruct the gliding of dislocations.

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MH: Conceptualization, Methodology, Investigation, Writing—original draft. Chenchong Wang: Writing—review and editing. XZ: Writing—review and editing. LW: Writing—review and editing. AM: Supervision. WX: Supervision, Project administration, Writing—review and editing, Funding acquisition.

The raw data required to reproduce these findings are available upon reasonable request.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX

See Fig. AI; Table AI.

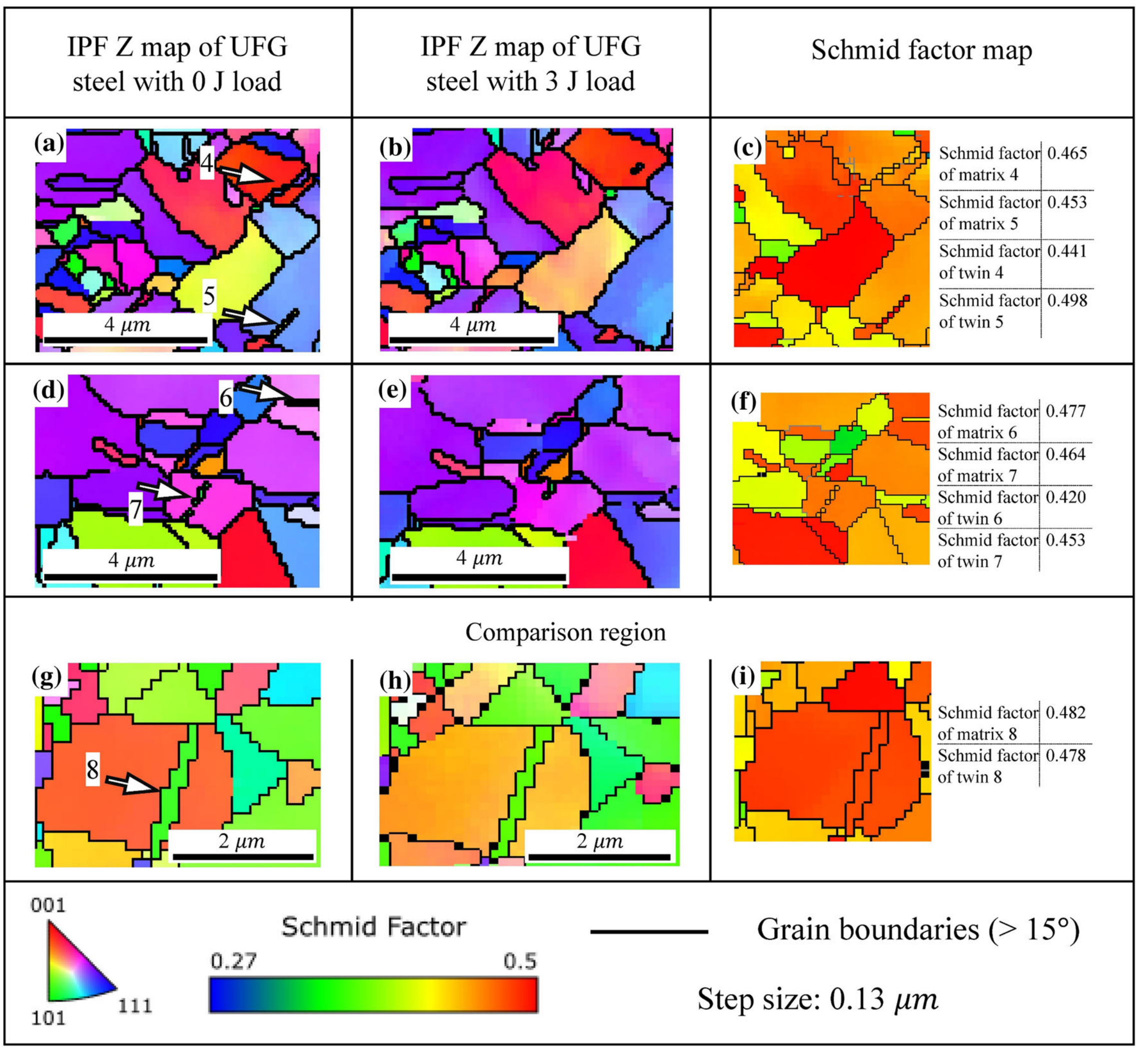

Fig. AI—Microstructure evolution during the Charpy impact test. (*a*, *d*, *g*) IPF Z maps of austenite under 0 J Charpy energy. (*b*, *e*, *h*) IPF Z maps of austenite under 3 J Charpy energy. (*c*, *f*, *i*) Schmid factor maps of austenite under 0 J Charpy energy. The loading energy was controlled by the Charpy impact tester. In addition, non-indexed pixels are shown in black.

Table AI. Summarize the Schmid Factor of Twin/Matrix With Different Extent of Detwinning

Twin/Matrix Number	Schmid Factor of Twin	Schmid Factor of Matrix	Misfit of the Schmid Factor	Extent of Detwinning
1	0.46	0.44	0.02	broken
2	0.48	0.34	0.14	disappearance
3	0.46	0.45	0.01	thinning
4	0.441	0.465	0.024	broken
5	0.498	0.453	0.045	disappearance
6	0.420	0.477	0.057	disappearance
7	0.453	0.464	0.011	broken
8	0.478	0.482	0.004	no detwinning

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