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***Review:***

# Correlated necklace dislocations in highly oriented nanotwinned metals*

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**Abstract:** In this paper, we review recent progress in the understanding of a novel dislocation mechanism, named correlated necklace dislocations (CNDs), activated in highly oriented nanotwinned (NT) metals under monotonic and cyclic loading applied parallel to the twin boundaries (TBs). This mechanism was initially revealed to be responsible for the continuous strengthening behavior of NT metals when the TB spacing ($\lambda$) is reduced to around 1 nm. It was later found that the presence of a crack-like defect could trigger the operation of CNDs at much larger TB spacings. Most recently, atomistic modeling and experiments demonstrated a history-independent and stable cyclic response of highly oriented NT metals governed by CNDs formed in the NT structure under cyclic loading. CNDs move along the twin planes without directional lattice slip resistance, thus contributing to a symmetric cyclic response of the NT structure regardless of pre-strains imposed on the sample before cyclic loading. We conclude with potential research directions in the investigation of this unique deformation mechanism in highly oriented NT metals.

**Key words:** Nanotwinned (NT) metals; Correlated necklace dislocation (CND); Twin boundary (TB); Size effect; Cyclic response
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## 1 Introduction

Nanotwinned (NT) metals have gained substantial attention owing to their superior mechanical and physical properties, including high strength and hardness (Lu et al., 2004; Ma et al., 2004; Tian et al., 2013; Huang et al., 2014) and resistance to fracture and fatigue (Qin et al., 2009; Zhou et al., 2010; Shute et al., 2011; Pan et al., 2013). A typical NT structure exhibits a lamellar anisotropic structure within the grain: a large density of coherent twin boundaries (TBs) is incorporated in a polycrystalline grain structure with nanoscale spacing between the adjacent TBs and an average grain size of up to tens of micrometers. By the controlled introduction of the nanoscale TBs into the microstructure, the strength can be enhanced without a significant degradation of the work hardening ability of materials, providing a promising route for the design of nanostructured metals with high strength and desirable tensile ductility (Lu K et al., 2009). Numerous studies have also been performed to understand the mechanics of NT nanopillars and nanowires (Jang et al., 2012; Wang et al., 2013).

Recently, highly oriented NT structures have been widely synthesized in pure metals, alloys, and bi-materials using electrodeposition and magnetron sputtering (Zhang et al., 2006; Hodge et al., 2008; Wang et al., 2010; Shute et al., 2011; Bufford et al., 2016). The length, thickness, and orientation of nanotwins can be controlled by changing the deposition and sputtering parameters, including temperature, current density, cathode potential, and substrate rotation speed. Furthermore, preferentially oriented

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NT bundles with a large density of nanoscale deformation twins can be introduced in metallic materials with low and medium stacking fault energy, including pure Cu, Cu-Al alloy, Cu-Zn alloy, 316 stainless steel, and austenitic Fe-Mn steel, through the technique of dynamic plastic deformation at high strain rates and cryogenic temperatures (Li et al., 2008; Zhang et al., 2011; Yan et al., 2012, 2014).

The mechanical behavior of highly oriented NT metals is governed by the interactions between dislocations and TBs (Wu et al., 2009; Zhu and Gao, 2012; Lu et al., 2017). Depending on their orientations relative to the TBs, the 12 slip systems in face-centered cubic (FCC) metals pertain to three categories: Mode I slip with inclined slip plane and Burgers vector relative to the TBs, leading to dislocation pile-ups against the TBs (Fig. 1a); Mode II slip with inclined slip plane relative to the TBs and the Burgers vector parallel to the TBs, forming threading dislocations gliding within the twin layers (Fig. 1b); Mode III slip with parallel slip plane and Burgers vector relative to the TBs, referred to as twinning partial dislocations gliding along TBs (Fig. 1c). When the direction of the applied load is nearly parallel to the TBs, numerous experiments and simulations have shown that the glide of Mode II dislocations (threading dislocations) prevails in the twin/matrix lamellae (Beyerlein et al., 2014; Lu et al., 2017).

Recently, it was found that a very small twin thickness (typically around 1 nm), a sharp crack-like defect, and cyclic deformation could trigger the formation of a novel type of TB-related dislocation mechanism, named correlated necklace dislocations (CNDs) (Fig. 1d), in highly oriented NT metals (Zhou et al., 2014; Zhou and Gao, 2015; Pan et al., 2017, 2019). Atomistic simulations revealed that threading dislocations in neighboring twin layers could be correlated through either cross slip (Fig. 1e) or linking by twinning partial dislocations (Fig. 1f) to form CNDs. In this paper, we review recent progress in the understanding of this unique dislocation mechanism, which has been demonstrated to play particularly critical roles in the plasticity of highly oriented NT metals.

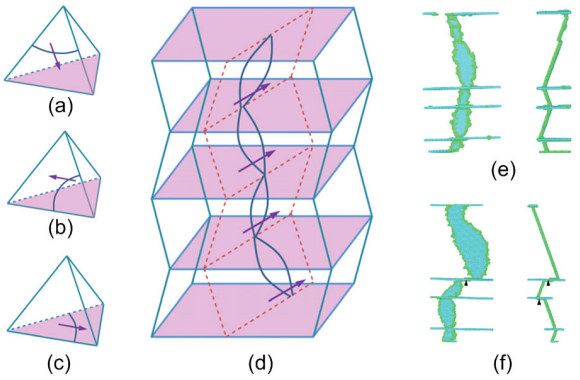


**Fig. 1 TB-mediated dislocation mechanisms in highly oriented NT FCC metals**

(a) Mode I slip mode with inclined slip plane and slip direction with respect to TBs; (b) Mode II slip mode with slip plane inclined to TBs and Burgers vector parallel to TBs; (c) Mode III slip mode with both parallel slip plane and slip Burgers vector with respect to TBs; (d) CND spanning across multiple TBs formed through either cross slip (e) or linking by twinning partial dislocations (f). The black triangles in (f) indicate the twinning partial segments on the twin planes. Figs. 1a–1d are reprinted from (Zhou and Gao, 2015), Copyright 2015, with permission from ASME. Figs. 1e and 1f are reprinted from (Pan et al., 2017), Copyright 2017, with permission from Springer Nature

## 2 Formation of CNDs

A double Thompson tetrahedron is shown in Fig. 2a to illustrate the slip systems in the upper matrix (M in short in Fig. 2) and the lower twin (T in short in Fig. 2). Suppose there are two individual threading dislocations with the same Burgers vector of $\boldsymbol{CB}$ in the deformed NT structure. One is gliding in the matrix while the other is gliding in the neighboring twin (Fig. 2b). They have the same Burgers vectors. The misfit segments (tails) of the threading dislocations left on the TBs can split into pairs of twinning partial dislocations with Burgers vectors of $\boldsymbol{\delta B}$ and $\boldsymbol{C\delta}$ (Fig. 2c). Note that the tails of the threading dislocation in the matrix and those from the twin have opposite line directions. During cyclic deformation, these tails can easily merge on the twin plane given that there exists an attractive force between them (Fig. 2d, and highlighted by black triangles in Fig. 1f). The formation of CNDs in the highly oriented nanotwins under cyclic loading is governed by this linkage mechanism of misfit tails from neighboring threading dislocations (Figs. 1f and 2e). A CND is therefore composed of three types of dislocation segments. The first type consists of Mode II slip segments (e.g. threading dislocations) gliding on inclined slip planes (such as *BCD*) within the twin

layers. The Burgers vectors of these Mode II dislocation segments (such as ***CB***) are parallel to the twin planes. The second type consists of Shockley partial dislocations (such as ***δB*** and ***Cδ***) gliding on twin planes (*ABC*). These two types of dislocations join together at the intersections of the TBs and the inclined slip planes by unit jogs, which represent the third type of stair-rod dislocations (such as ***αδ***).

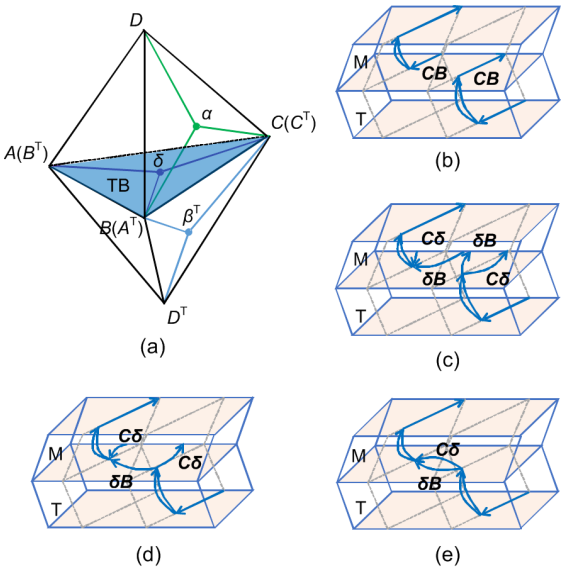


**Fig. 2 Double Thompson tetrahedron showing the slip systems in the upper matrix and lower twin (a), and four stages of CND formation (b)–(e) through linkage of misfit tails from two individual threading dislocations gliding in the upper matrix (M) and the lower twin (T) on twin planes. Reprinted from (Pan et al., 2017), Copyright 2017, with permission from Springer Nature**

Molecular dynamics (MD) simulations of uniaxial loading on samples with extremely fine nanotwins or sharp defects indicated that threading dislocations can also cross the twin planes into adjacent twin layers, leading to the formation of a slightly different CND structure with only threading segments and stair-rod segments (Fig. 1e). In Sections 3 and 4, we will see that this direct slip transfer mechanism is most likely to occur at high stress levels and accounts for the continuous strengthening and crack tip plasticity of the highly oriented nanotwins. In Section 5, we will see that the tail-linkage formation mechanism of CNDs is widely observed under cyclic loading without the presence of extremely small nanotwins and crack-like sources.

## 3 Strengthening by nanotwinning

In highly oriented NT metals with the external load parallel to the TBs, pile-up dislocations at TBs and partial dislocations along TBs are greatly suppressed. The activation and movement of Mode II dislocations shown in Fig. 1b are confined between neighboring TBs. Each threading dislocation contains two misfit tails pinning on the TBs and a pair of partial dislocations bridging across the twin lamellae. It is generated from grain boundaries and glide along inclined slip planes across the grain before absorbed by the opposite grain boundaries. Threading dislocations were previously reported in thin films and nanolayered metallic composites (Was and Foecke, 1996; Nix, 1998; Misra et al., 2005; Li and Zhang, 2010). The confined layer slip (CLS) model of threading dislocations was used to explain the increased strength of these layered materials as the layer thickness was reduced (Misra et al., 2005; Li and Ghoniem, 2009; You et al., 2011). As a threading dislocation moves along the slip plane, the length of its misfit segments on the TBs increases. Therefore, the CLS model contains a logarithmic term which originates from the fact that the total length of the misfit tails increases as the threading dislocations move forward along the twin planes, as shown in Fig. 2b.

Recent uniaxial tensile simulations on highly oriented NT Cu samples (Fig. 3a) showed that as the TB spacing $\lambda$ is refined below a range of 2–5 nm, the governing plastic deformation mechanism transits from Mode II threading dislocations to CNDs (Zhou et al., 2014). A single CND consists of multiple extended dislocations gliding on inclined slip planes relative to the TBs (Fig. 3b). Every extended segment contains a pair of Shockley partial dislocations separated by an intrinsic stacking fault ribbon. The segments are joined to one another by stair-rod unit jogs at the TBs (Fig. 3c). The motion of CNDs is therefore featured by the coordinated movements of multiple Mode II dislocations and unit jogs along the highly oriented TBs. The formation of CNDs below a critical twin thickness could be energy favorable. For the motion of a single threading dislocation, a sufficiently large applied stress is required to drag two misfit tails along the TBs. If the threading dislocations in the

adjacent twin/matrix lamellae share a misfit tail, like a stair-rod unit jog, the dislocation energy could be reduced dramatically.

MD simulations also showed that the strength of highly oriented NT metals increases with deceasing TB spacing (Fig. 3d). This continuous strengthening effect observed at extremely small twin thicknesses is completely different from the softening behavior of nanotwins revealed in equiaxed nanotwins (Li and Ghoniem, 2009; Lu L et al., 2009). Moreover, the traditional CLS model of threading dislocations fails to capture the size dependence of material strength in Fig. 3d. When the TB spacing is refined to a certain value, the CLS predicts a sudden drop in stress, which is contradictory to the continuous strengthening behavior.

The TB-related continuous strengthening behavior observed in the small range of twin thickness must be associated with the motion of CNDs. As revealed by MD simulations, the motion of a constituent dislocation segment in the CND involves the motion of the extended dislocation in the twin interior and the de-pinning of stair-rods on the twin planes. To overcome the pinning force, $f_{\text{pin}}$, from the TBs, a Peach-Koehler force, $f_{\text{PK}}$, must be applied on the threading segment (Fig. 3e), leading to the following balance equation:

$$f_{\text{pin}} = f_{\text{PK}} = (\tau - \tau_0) b_{\text{f}} \lambda, \tag{1}$$

where $\tau$ represents the resolved shear stress on the inclined slip planes along the Burgers vector of the threading dislocation, $\tau_0$ is the lattice friction, and $b_{\text{f}}$ is the magnitude of the Burgers vector of the threading dislocations. The CND-governed size dependence of material strength can be obtained as (Zhou et al., 2014)

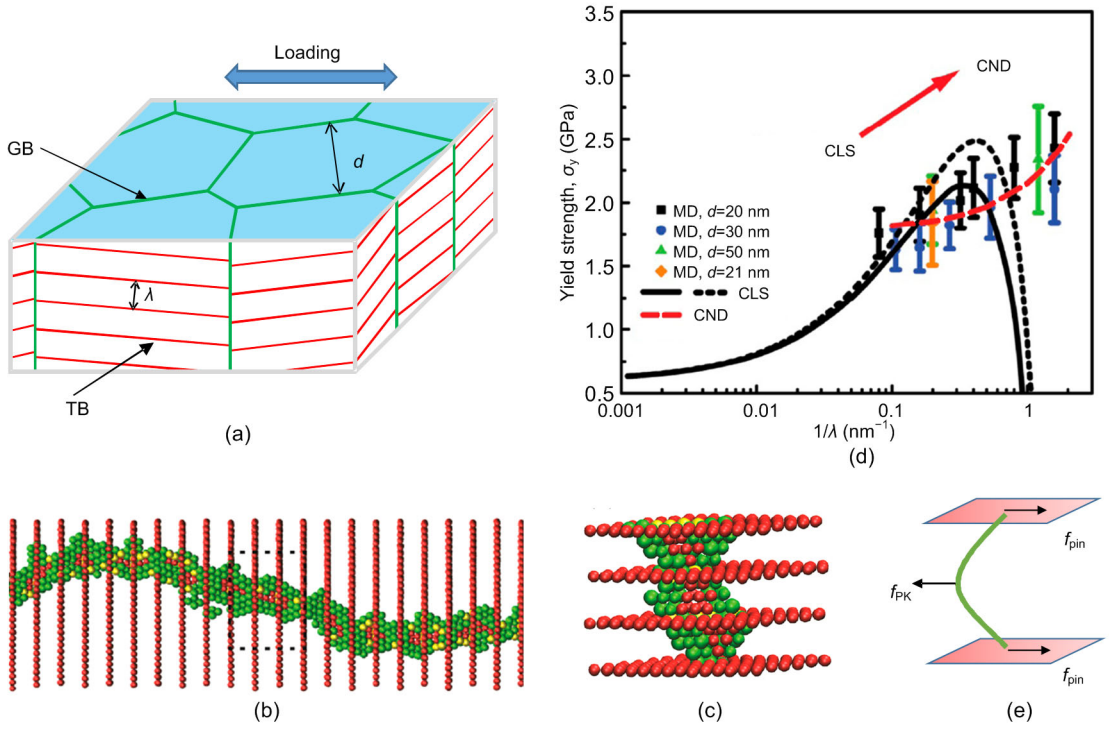


**Fig. 3 (a) Typical microstructure of highly oriented NT metals with uniaxial loading applied parallel to the TBs (*d* is the grain size; GB is the grain boundary); (b) Atomic configuration of a CND formed in a highly oriented NT sample with a twin thickness of 0.83 nm; (c) Magnified view of the dislocation segments highlighted by the dashed box in (b); (d) Twin size dependence of material strength in highly oriented NT metals with the loading axis parallel to the TBs (a transition from CLS to CND with reduced twin thickness $\lambda$ leads to a continuous strengthening behavior); (e) Free body diagram of a constituent threading dislocation segment confined by two adjacent TBs (the pinning forces exerted by the TBs on the threading segment are denoted by $f_{\text{pin}}$, and the PK force on the threading segment is denoted by $f_{\text{PK}}$). Figs. 3b–3d are reprinted from (Zhou et al., 2014), Copyright 2014, with permission from American Chemical Society**

$$\sigma_{\mathrm{CND}} = M\left(\frac{f_{\mathrm{pin}}}{b_{\mathrm{f}}\lambda} + \tau_0\right), \tag{2}$$

where the Taylor factor $M$=3 has been used to relate the resolved shear stress on the inclined slip plane to the uniaxial tensile stress on the sample. Fig. 3d shows that, below a critical value in the range of 2–5 nm, the continuous strength increase can be well captured by Eq. (2). The fitting parameters are $f_{\mathrm{pin}}$= $3.148\times10^{-11}$ N and $\tau_0$=0.59 GPa. In contrast to threading dislocations, the atomic structure of CNDs is symmetric. During their formation, the misfit tails from neighboring threading dislocations connect with one another, leading to pairs of twinning partial dislocations on TBs (Fig. 2e). During cyclic deformation, the twinning partial dislocations move along the twin planes without a net increase in their total length. This might explain the absence of the logarithmic term in Eq. (2).

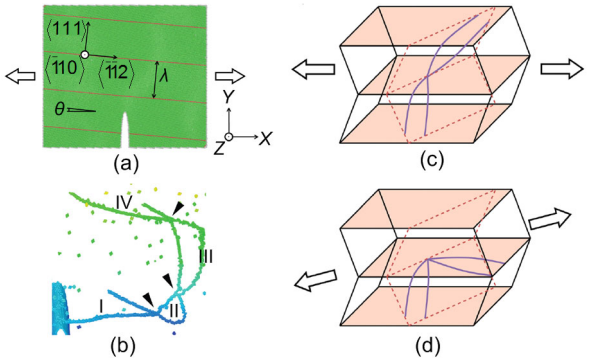


**Fig. 4 Formation of CNDs at a crack tip in highly oriented NT Cu**

(a) Simulation setup; (b) CND with multiple dislocation segments formed at the crack tip through cross slip (dislocation segments gliding on TBs are labelled I and IV, those gliding on inclined slip planes in twin interiors are labelled II and III, and stair-rod dislocations are marked by black triangles); (c) CND with dislocation segments on the inclined slip planes; (d) CND with dislocation segments on both the inclined slip plane and TB. Reprinted from (Zhou and Gao, 2015), Copyright 2015, with permission from ASME

## 4 Crack tip plasticity in nanotwins

Although CNDs have been found in highly oriented NT structures below a critical TB spacing, an open question is whether or not this dislocation mechanism can be operative in more general conditions. Recent studies on highly oriented NT Cu showed that crack-like defects facilitate CNDs at much larger twin thicknesses near stress concentrators (Zhou and Gao, 2015). To demonstrate this, MD simulations were performed on 3D nanocrystals with a size of 30 nm×50 nm×40 nm and a twin boundary spacing of $\lambda$=10 nm (Fig. 4a). The twin planes were inclined to the uniaxial tensile loading axis ($X$-axis) by a small inclination angle $\theta$. An atomically sharp crack was introduced in the $Y$-direction with an initial length of 10 nm. Due to the concentrated stress, an extended dislocation was emitted from the crack tip, transferred across the twin plane adjacent to the crack tip, and formed an embryo of the CND, which was composed of two extended dislocations and a stair-rod dislocation pinning at the TB. The embryo CND moved along the TB and expanded into neighboring twins with continued loading, leading to the formation of a mature CND with multiple dislocation segments (Fig. 4b).

Two different configurations of CNDs were revealed as the inclination angle of the twin planes was changed. When the loading direction was nearly parallel to the twin planes, resolved shear stress is negligible on the TBs. Only inclined slip planes were activated (Fig. 4c). On the other hand, both parallel and inclined slip planes were activated when loading was tilted relative to the twin planes. In such cases, the CND consists of threading dislocations and twinning partial dislocations (Fig. 4d).

The simulations of crack tip plasticity in highly oriented NT metals suggest that there does not seem to be any constraint on TB spacing. In addition, they confirm that the mechanism is insensitive to crack geometry and TB orientation. Therefore, CNDs may be critical in the plastic deformation of NT metals, especially near crack-like sources.

## 5 Cyclic response of the highly oriented nanotwins

### 5.1 History-independent cyclic response governed by CNDs

In the above sections, CNDs were observed in the highly oriented NT metals under static loading.

The formation mechanism of CNDs is mainly through cross slip, which requires a very small TB spacing (typically of the order of 1 nm) or a crack-like sharp source. Important open questions include whether and how CNDs form in nanotwins under cyclic loading, and how they influence the cyclic response of highly oriented NT metals.

To address these questions, tension-compression cyclic loading experiments and simulations were performed on highly oriented NT Cu samples with variable strain amplitudes (Pan et al., 2017). Both the experiments and simulations demonstrated a history-independent cyclic response in the highly oriented nanotwins. Fig. 5a shows a simulated NT sample containing four $[1\bar{1}\bar{1}]$-textured grains with a grain size of 40 nm. The twin thickness was 5.5 nm in each grain. The number of atoms was about 12 million. Uniaxial tensile loading with a total strain of 15% was first applied parallel to the twin planes to introduce an initial distribution of threading dislocations in the individual twin layers. After unloading to zero stress, a stepwise tension-compression cyclic loading was applied to the sample using two different total strain amplitudes, $\Delta\varepsilon_t/2$=0.01 and 0.015 (Fig. 5b). Fig. 5c shows the relationship between the measured stress amplitude $\Delta\sigma/2$ and the cycle number $N$. After six cycles of deformation at a larger strain amplitude of $\Delta\varepsilon_t/2$=0.015 and another six cycles at $\Delta\varepsilon_t/2$=0.01, the final stress amplitude was close to that recorded for the first six cycles at $\Delta\varepsilon_t/2$=0.01, indicating a history-independent cyclic response of the nanotwins. Fig. 5d shows that the hysteresis loops from different loading steps overlapped with one another, which is typical of the Masing-like behavior.

The deformation mechanism of the history-independent cyclic response of highly oriented NT Cu was revealed as the formation and motion of CNDs during cyclic loading. Fig. 5e shows a cross-sectional view of a grain in the cyclically deformed NT Cu sample. Since the direction of the tension-compression cyclic loading is parallel to the TBs, threading dislocations are activated in pre-tension. During cyclic deformation, separate threading dislocations in individual twin layers are observed to correlate with each other through the linking of the twinning partial dislocations, forming CNDs in multiple TBs (Fig. 5e).

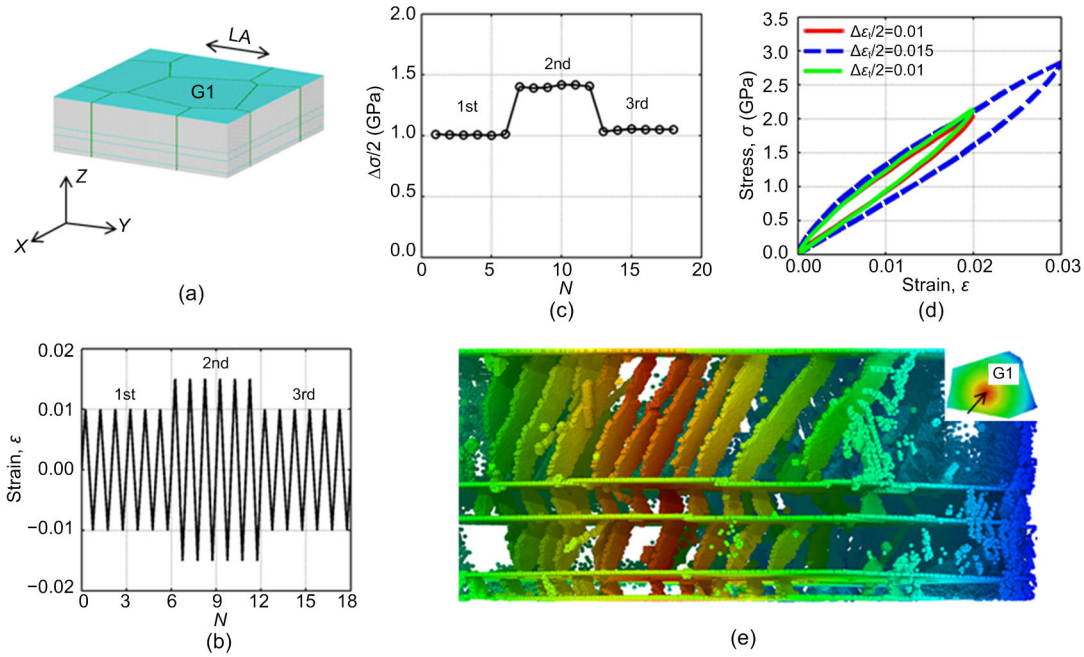


**Fig. 5 Cyclic deformation simulation of NT Cu**

(a) Columnar-grained NT Cu sample with $[1\bar{1}\bar{1}]$-texture; (b) Three-step cyclic loading scheme with strain amplitudes of $\Delta\varepsilon_t/2$=0.01 and 0.015; (c)–(d) History-independent cyclic response of the simulated NT Cu; (e) Deformation pattern of the cyclically deformed NT Cu governed by CNDs. LA stands for the loading axis; G1 is the center grain. Reprinted from (Pan et al., 2017), Copyright 2017, with permission from Springer Nature

A single CND formed by cyclic loading contains threading dislocations in the twin interior, twinning partial dislocation pairs on TBs, and a stair-rod dislocation (Fig. 1f).

During cyclic deformation, the movement of CNDs is fully reversible. The density of CNDs at a given strain amplitude is thus stable. The movement of CNDs does not destroy the coherency and stability of the TBs. Since these dislocations can reversibly move along TBs, they do not accumulate on TBs or block other dislocations. The basis for the history-independent cyclic response of NT Cu is therefore related to the stabilization of dislocation structure by correlating plasticity in neighboring twin/matrix lamellae. The super-stable CNDs can move along the TBs in a highly reversible manner, with negligible effect on the TBs. This gives rise to a unique cyclic deformation mechanism which is fundamentally different from the formation of dislocation patterns in monocrystal and coarse-grained (CG) metals, as well as shear localization and grain coarsening in ultrafine-grained (UFG) and nanocrystalline (NC) metals (Hanlon et al., 2003; Mughrabi and Höppel, 2010; Pineau et al., 2016).

### 5.2 Asymmetric to symmetric transition in the cyclic response

Recent studies found that highly oriented nanotwins subjected to pre-deformation (schematics in Fig. 6a) would exhibit an asymmetric cyclic response during symmetric cyclic loading (Pan et al., 2019). Fig. 6b shows the stress-strain hysteresis loops of a simulated pre-tensioned NT Cu at different cyclic strain amplitudes. The stress ratio of the maximum stress ($\sigma_{max}$) to the minimum stress ($\sigma_{min}$) measures the degree of tension-compression asymmetry of the pre-deformed sample. Fig. 6c shows the relation between the stress ratio and the cycle number $N$. The cyclic response of the pre-deformed sample exhibits clear asymmetry at $\Delta\varepsilon_t/2$=0.005 and 0.01. As the strain amplitude is increased to 0.02, the stress ratio decays. Additional simulations on pre-deformed twin-free Cu samples show much smaller cyclic asymmetry than that observed in pre-tensioned NT Cu (Fig. 6c), indicating the critical role nanotwins play in the cyclic asymmetry of the pre-deformed nanotwins.

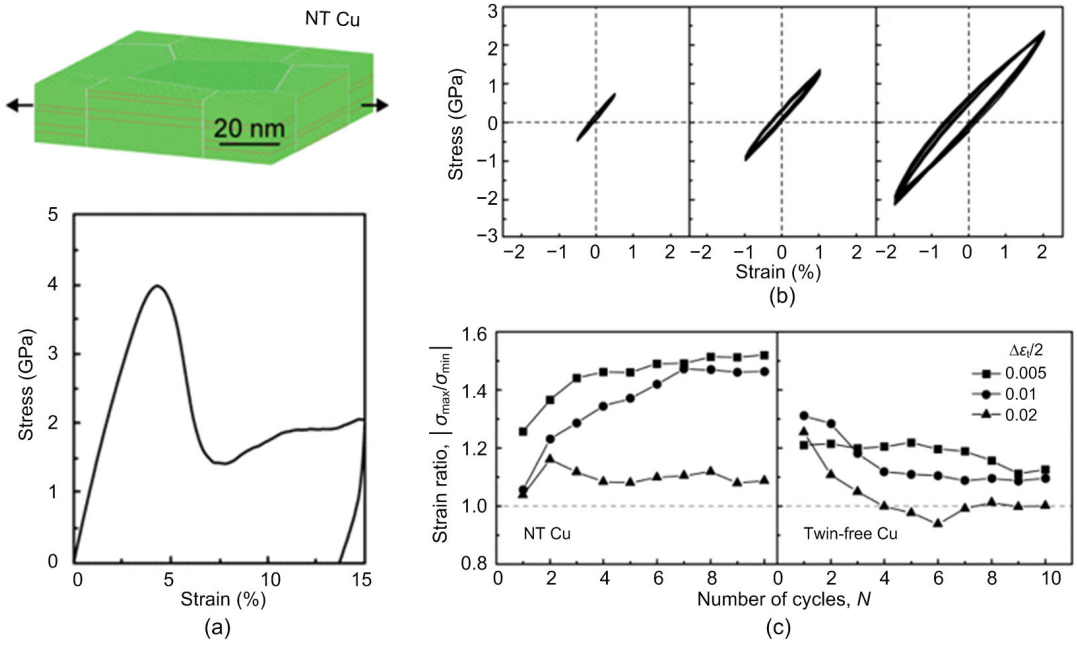


**Fig. 6 (a) Tensile pre-deformation on a highly oriented NT Cu sample; (b) Stress-strain hysteresis loops at total strain amplitudes of 0.005, 0.01, and 0.02; (c) Variation in the stress ratio, $|\sigma_{max}/\sigma_{min}|$, with respect to the number of cycles at different strain amplitudes measured for the simulated NT and twin-free Cu samples. Reprinted from (Pan et al., 2019), Copyright 2019, with permission from Acta Materialia Inc.**

The strong asymmetric response of pre-deformed NT Cu at $\Delta\varepsilon_t/2$=0.005 and 0.01 is related to the directional resistance of threading dislocation (Fig. 7a). During pre-deformation, threading dislocations are activated in individual nanotwins. During tension stage, the threading dislocations move forward and extend their misfit tails on the TBs, which is energetically less favorable and requires a larger stress. During compression, the threading dislocation withdraws its misfit tails as it moves backwards, which is energetically more favorable and requires a smaller stress. The reduced cyclic asymmetry at $\Delta\varepsilon_t/2$=0.02 is caused by the formation of CNDs and the exhaustion of threading dislocations during cyclic loading (Fig. 7b). In contrast to threading dislocations, CND exhibits a symmetric atomic configuration without directional shear resistance. The total length of misfit tails of CNDs is stable during cyclic deformation.

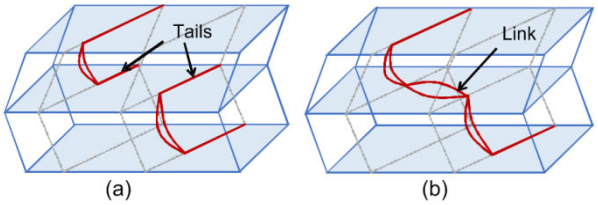


**Fig. 7 Cyclic asymmetry governed by the directional movement of separate threading dislocations in individual nanotwins (a) and by the symmetric movement of CNDs connecting neighboring nanotwins (b)**

## 6 Conclusions

In conclusion, we have reviewed recent advances in the understanding of the formation of CNDs and the associated mechanical behavior of highly oriented NT metals. Experiments and simulations have demonstrated that a large stress at an extremely small twin spacing, stress concentration at a crack tip, and cyclic deformation facilitate the linking of threading dislocations in neighboring layers to form CNDs. This mechanism correlates the plastic deformation in separate nanotwin layers, leading to continuous strengthening, crack tip plasticity, and a history-independent cyclic response in the highly oriented nanotwins. This unique monotonic and cyclic behavior of highly oriented NT metals not only advances the scientific understanding of the deformation mechanism in nanostructured metals, but also sheds light on potential ways to tailor-design the microstructure of engineering materials with targeted mechanical properties.

Finally, we point out a number of unresolved issues on the topic of CNDs for future research. The structure of CNDs and their reversible movement have been confirmed only by atomistic simulations. Direct experimental characterization of the 3D structure of CNDs is extremely challenging. In addition, the activation of slip systems in NT metals is dependent on the orientation of the loading direction with respect to the TBs (Lu et al., 2017). MD simulations have demonstrated that CNDs may be dominant in highly oriented nanotwins as long as the loading direction is within 15° with respect to the TBs. Further studies are needed to explore whether CNDs exist for other orientations.

The formation of CNDs in highly oriented nanotwins is strongly related to the activities of threading dislocations. Threading dislocations exist ubiquitously in nanolayered alloys and thin films (Was and Foecke, 1996; Nix, 1998; Misra et al., 2005; Li and Zhang, 2010). This leads to a natural question whether CNDs exist in nanolayered materials with coherent or semi-coherent interfaces. Further experiments and simulations are required to study the presence of CNDs in such materials.

Finally, a physically-based constitutive model which captures the unique monolithic and cyclic response of highly oriented nanotwins is currently lacking. Such a constitutive model is expected to include the fundamental deformation mechanism of CNDs and the structural heterogeneity of the highly oriented nanotwins.

### Contributors

Haofei ZHOU conducted the literature survey, wrote the first draft of the manuscript, and revised and edited the final version. Pan-pan ZHU assisted with the literature survey, and document delivery and arrangement. Haofei ZHOU and Pan-pan ZHU read and approved the final manuscript.

### Conflict of interest

Haofei ZHOU and Pan-pan ZHU declare that they have no conflict of interest.

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## 中文概要

**题　目：择优取向纳米孪晶金属中的“链式”关联位错**

**概　要：**本文综述了择优取向纳米孪晶金属中“链式”关联位错（CNDs）的研究进展。当拉伸方向与孪晶界方向水平，且孪晶厚度（$\lambda$）为 1 nm 左右时，关联位错会大量开动，引起材料持续强化。在较宽的孪晶片层中，裂纹等初始缺陷可引起应力集中，诱发关联位错形核。此外，循环变形也会促进关联位错在纳米孪晶结构中的形成，使后者具有与历史无关、稳定和拉压对称的循环响应。最后，本文提出了择优取向纳米孪晶金属中与“链式”关联位错相关的潜在研究方向。

**关键词：**纳米孪晶金属；“链式”关联位错；孪晶界；尺寸效应；循环响应