Microstructure analysis and crack nucleation in TWIP steel tube at expansive deformation

ChunYuan Liu, KaiHong Song, Wei Wu, Ping Jiang, YanFei Jiang, XingChuan Xia and Bo Liao

1 School of Material Science and Engineering, Hebei University of Technology, Tianjin, 300400, People's Republic of China
2 National Engineering Research Center for Technological Innovation Method and Tool, Hebei University of Technology, Tianjin, 300400, People’s Republic of China
* Author to whom any correspondence should be addressed.

E-mail: Kevin_skh@126.com

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Abstract

The expansion test of twinning induced plastic (TWIP) steel tube was carried out at room temperature. Cracks appeared inside the tube edge when TWIP steel tube expands by 15.6%. The microstructure evolution, deformation mechanism and crack generation of TWIP steel after expansion were investigated by XDR OM TEM and EBSD. The results show that TWIP steel tube still austenite phase after expansion at room temperature; a great deal of dislocations are gathered around the grain boundaries and twin boundaries, the integral number of twins is high, and the mechanism of expansion deformation is the joint action of dislocations slip and deformation twins; Twins produce a large number of finer secondary or even multiple twins, intersecting each other; After expansion, the silk texture with direction of \(\langle 111 \rangle || X_0 \) dominated by rotating brass texture \(\langle 110 \rangle \) \(\langle 111 \rangle \) is gradually produced through grain deformation and rotation; The proportion of small angle grain boundaries increased greatly; It is deduced that the criterion of crack nucleation is based on the difference between the dislocation pile-up energy (DPE) and the crack nucleation energy (CNE), and the expansion deformation process of TWIP steel satisfies the condition of crack nucleation.

1. Introduction

Expandable tubular technology is considered to be one of the core technologies in oil drilling and production industry in the 21st century, and the choice of tube is always the research hotspot in this field [1]. The higher the yield strength of most high strength steels is, the lower the elongation will be, but the twinning induced plasticity (TWIP) steel is an exception, which not only has high yield strength, but also has quite superior plasticity, which meets the requirements of high strength and high plasticity of expansion tube materials [2–4]. Since the concept of TWIP steel was proposed, scholars at home and abroad have studied the microstructure and properties of TWIP steel under different deformation modes from different perspectives, which provides a certain theoretical basis for the development of TWIP steel as expandable tube material.

Peng Mengdu et al studied the conditional tensile behavior of high-nitrogen austenitic steel and found that the tensile strength of TWIP steel after solution could reach 911 MPa and the elongation after fracture could reach 62% [5]. Zhou Xiaofen et al [6] mainly studied the microstructure and mechanical properties of steel. The study showed that with the increase of deformation degree, the density of twins increased, and the mechanical properties index also increased. Frederike Brasche et al [7] studied mechanical twinning and texture evolution of high manganese steel during asymmetric hot rolling, the results show that the yield strength of high manganese steel after hot rolling reached 1047 MPa due to a high density of dislocations and stacking faults on the one hand and a reasonably high ductility (30%) on the other hand. Rajib Kalsar and Satyam Suwas [8] studied the texture and microstructure evolution of TWIP steel under large strain deformation at 40%, 70%, 90%, 95% and 98% cold rolling. The results show that twinning is the major mode up to 40% reduction level and the material develops very high in-plane anisotropy above 70% deformation level; A Brass type texture forms and strengthens throughout the
deformation. The deformation mechanism change in 0.98C–8.3Mn–0.04N steel during compressive deformation at room temperature have been studied by T.S. Wang et al [9]. Experimental results show that with the reduction increasing the microstructure of the deformed sample changes from dislocation substructures into the dominant twins plus dislocations, and the plastic deformation mechanism changes from the dislocation slip into the dominant deformation twinning. In addition, temperature, composition, grain size and other factors can also affect the microstructure and mechanical properties of TWIP steel [10–12]. However, there is little research on the microstructure and properties of TWIP steel tubes after expansion deformation.

In order to cope with the complex mining environment of oil fields, Song Kaihong [13] optimized the design of a TWIP steel 30Mn25Cr10n2MoNbRe with good strain hardening performance and it is suitable for preparing the expansion tube with large expansion percentage. Yang Yang [14] pointed out in research on the material selection of expansion tube that cracks appeared at the edge of TWIP steel sample tube in the process of 20% expansion, and it was difficult to achieve large expansion forming, which was completely contrary to the high strength plastic characteristics of TWIP steel. Therefore, based on the technical characteristics of expandable tube, this paper studies the microstructure and strain hardening mechanism of TWIP steel tube under the expandable deformation mode and the causes of cracks, providing a theoretical basis for the further development of TWIP steel as expandable tube material.

2. Experimental section

2.1. Material preparation

The raw materials of pure iron, electrolytic manganese, graphite, polycrystalline silicon, aluminum and trace rare earth elements were smelted in a vacuum medium frequency induction furnace with a vacuum degree of $1 \times 10^{-3}$ Pa, and the raw materials were cast into cylindrical ingots; The ingots were diffused annealed in a high-temperature box furnace, and after billet they were forged by a 10 t air hammer free forging machine at an initial and final forging temperature of approximately 1100 °C and 900 °C, respectively, to a cylindrical ingot with an outer diameter of 80 mm and an inner diameter of 50 mm; Then the solution treatment was carried out, that is, the temperature was set at 1050 °C and the heat was kept for 30 min, with water cooling; The surface oil and oxides were removed by the wire cutting machine. Finally, an expandable TWIP steel tube with an outer diameter of 58 mm and a wall thickness of about 3.2 mm was obtained. Its composition is shown in table 1.

2.2. Experimental method

Expansion test was a fixed expansion cone, the selection of cone angle is 8, using WDW-200Y type of electronic universal testing machine for TWIP steel tube expansion test. The lithium molybdenum disulfide grease was

![Figure 1. Schematic diagram of expansion process of TWIP steel tube.](image)

**Table 1. Chemical composition of TWIP steel.**

| Element | C  | Mn  | Cr  | Ni  | Al  | Si  | Mo  |
|---------|----|-----|-----|-----|-----|-----|-----|
| Wt%     | 0.21 | 24.4 | 5   | 2   | 2   | 1   | 0.5 |

...
selected and evenly smeared on the inner wall of the TWIP steel tube and the expansion zone of the expansion cone. The matched expansion cone and TWIP steel tube were placed in the center of the lower pressure plate of the testing machine to ensure that the force mode was positive pressure and the loading rate was $1 \text{ mm min}^{-1}$, until the expansion cone completely entered the TWIP steel tube, figure 1 shows the expansion process of TWIP steel.

According to GB/T 228.1-2010, standard tensile specimens are prepared along the axial direction of the tube, as shown in figure 2(a). The tensile test at room temperature was carried out with a microcomputer controlled electronic universal testing machine WDW-200Y, and the tensile rate was set at $1 \text{ mm min}^{-1}$. The compressed block sample whose thickness was equal to the wall thickness of the tube was taken by wire cutting mechanism, and its size was $10 \times 3.2 \text{ mm}$, as shown in figure 2(b). At room temperature, the compression test was carried out on a universal testing machine of model WDW-200Y with a compression rate of $0.1 \text{ mm min}^{-1}$ and a preset compression rate of 20%.

2.3. Microstructural characterization
Samples are cut off along the axial direction of the tube, and the surface is polished, and radial surface is the test surface, as shown in figure 3. Phase analysis was performed on D500 x-ray diffractometer (XRD) at a scanning
speed of $6^\circ \text{min}^{-1}$. The microstructure was observed by Optical Microscope (OM) DM2700 and the etchant was 5% nitric acid-alcohol solution. Tecnai G2 F30 S-Twin transmission electron microscope (TEM) was used to observe the fine microstructure of the samples, sample preparation steps are as follows: first, square slices with thickness of 300 μm were cut, and then the samples were mechanically thinned; secondly, electrolytic double spray method was used to thin the sample; The electrolyte was 5% perchloric-acid alcohol solution, the electrolytic polishing temperature was controlled at $-20^\circ \text{C}$, the voltage was 40 V, and the current was 120 mA. The FEI Quanta 650F EBSD device was used to analyze the microorientation of the samples and data analysis was performed using TSL (Ten Sem Laboratory) software. The schematic diagram of sample testing is as shown in the figure Figure 3(b), $X_0$ and $Y_0$ are radial tube, and $Z_0$ is axial. Microhardness tests are performed on microvickers hardness tester, the test diagram is shown in figure Figure 3(c). The test load was 0.98 N, the load holding time was 15 s, the distance between hardness test points was greater than 10 μm, and the selected test points are distributed in the inner (1), center (2) and outer (3) regions of the sample radial section.

3. Results

3.1. Expansion properties

Soon after the expansion cone entered the TWIP steel tube, cracks appeared inside the tube edge. It is as shown in figure Figure 4, Table 2 shows the measured values of inner and outer diameter and wall thickness of TWIP steel tube before and after expansion. According to the calculation formula of expansion percentage

$$\varepsilon = \frac{r - r_0}{r_0} \times 100\%$$

Where, $\varepsilon$ is the expansion percentage; $r$ is the inner diameter of the tube after expansion; $r_0$ is the inner diameter of the tube before expansion. The maximum expansion percentage of TWIP steel is 15.6%.

3.2. XRD Analysis

Figure 5 shows the XRD patterns of TWIP steel before and after expansion at room temperature. The figure shows that it is still a single austenite phase after deformation. The intensity of (111) $\gamma$ and (200) $\gamma$ diffraction peaks on each surface of TWIP steel decreases abnormally, the intensity of (311) $\gamma$ diffraction peaks decreases slightly, (110) $\gamma$ diffraction peak disappeared, and only the intensity of (220) $\gamma$ diffraction peaks increases slightly, indicating that the TWIP steel grain internal deflection occurs. In addition, the width of each diffraction
peak increases slightly, because the stacking fault energy of TWIP steel is about 23.3 mJ m\(^{-2}\)\[15\], and dislocation slip is difficult, which promotes the generation of twins and leads to grain fragmentation. The generation of twins and the increase of internal stress together lead to the phenomenon of diffraction peak widening.

3.3. Microstructure

At room temperature, the original structure of TWIP steel tube after heat treatment is shown in figure \ref{fig:6}(a). The matrix is a typical austenite structure accompanied by various forms of annealing twins. Because of the grain orientation deviation, the grains in the optical microscope show different color fields, and there is no obvious carbide precipitation in the grain interior and grain boundary. On the whole, there is no obvious selective orientation of the grains. Figure \ref{fig:6}(b) shows the microstructure of TWIP steel during expansion. In the expansion process, a large number of intersecting, blocking and cutting deformation zones appear in the matrix under the action of external axial pressure, meanwhile, larger annealing twins can be clearly seen, as shown in figure \ref{fig:6} (c). Moreover, they are more likely to occur at grain boundaries or trigeminal grain boundaries and terminate at grain boundaries. Since deformation twins are more likely to occur at grain boundaries where stress

![Figure 5. XRD patterns of TWIP steel tube (a) Before expansion; (b) During expansion; (c) After expansion.](image)

![Figure 6. Microstructure diagram of TWIP steel (a) Before expansion; (b) (c) During expansion; (d) (e) After expansion.](image)
concentration occurs, the strip structure can be identified as deformation twins \[16\]. After expansion, deformation twins are generated in each grain in the matrix, and the integral number of twins is further increased, as shown in figure 6(d). In figure 6(e), a large number of finer secondary or even multiple twins are produced between the twins, and the austenite grains are segmented so as to refine the grains \[17\].

In order to explore the deformation mechanism of TWIP steel tube in the expansion process, TEM was used to characterize the microstructure evolution and twins formation of TWIP steel tube in different expansion stages. Figure 7 shows the TEM microstructure of twins and dislocations in the expansion process of TWIP steel. When the tube begins to expand, dense dislocations are generated at the grain boundaries to gather and intertwine with each other as shown in figure 7(a), forming a stress concentration area and promoting the generation of deformation twins as shown in figure 7(b). With the expansion, the dislocations proliferate, the interaction between dislocations is strengthened, and the deformation twins begin to increase, but the twins are smaller and the twin spacing is larger. A large number of dislocations are still accumulated around the twins, as shown in figure 7(c).

Figure 8 shows the twinning structure of TWIP steel after expansion. After expansion, the number of twins increases further, the twins grows and the twin spacing becomes smaller. In addition, some studies have pointed out that matrix dislocations can enter the twin region after consuming two twin dislocations by means of dislocation reaction \[18\]. When the dislocation reaction is difficult to proceed, the dislocation pile-up at the twin boundaries. Figure 8(b) shows that the interaction between deformation twins is complex, and the twins grow together to form different morphologies with different interactions: 1. Twins prevent the growth of another twin in a different direction completely, terminating at the twin boundary. 2. Twins can change the shape of the twin which hinders its shear, so that the twin interface of the latter has a certain shift. 3. When the twins intersect, it can pass through each other and only produce a certain displacement, and the direction of shear remains unchanged. 4. Twins can cut into another twin to form dislocations and secondary twins. Figure 8(c) shows
Figure 8. TEM microstructure of TWIP steel tube after expansion.

Figure 9. (a)–(c) are \{111\} PF of TWIP steel in the before expansion, during expansion and after expansion; (d) (e) and (f) are distribution of orientation difference of TWIP steel in the before expansion, during expansion and after expansion.
twin thickness and twin spacing are almost the same, indicating that the twins after expansion have more integrals, higher dislocation density, and stronger strengthening effects of dislocations and twins \[19\].

3.4. Texture

The grain orientation affects the deformation mechanism, and the combination of different slip systems and twin systems also affects the fracture of the deformed metal. Twin formation plays an important role in the strong plasticity of TWIP steel, and the amount of twin formation and transformation dynamics are firstly affected by grain orientation, as well as stress variables and orientation changes caused by crystal rotation during deformation \[20\]. The \(\{111\}\) pole figure (PF) of TWIP steel in the expansion process is shown in figure 9, \(X_0\) and \(Y_0\) are radial surfaces of the tube, and different colors represent different densities of orientation. As can be seen from the figure 9, after solid solution treatment, that is, the original TWIP steel, the PF spots are scattered and irregular. During the expansion process, through grain deformation and rotation, the silk texture with the direction of \(\langle 111 \rangle \parallel X_0\), which is dominated by rotating brass texture \(\{110\} \langle 111 \rangle\), is gradually produced. The Schmid factor expression is

\[
m = \cos \varphi \cos \lambda
\]

Where, \(\varphi\) is the included angle between the external load and the normal of the slip plane (or the normal of the twin plane); \(\lambda\) is the included angle between the external load and the slip direction (or twin direction) \[21, 22\].

The Schmid factors of \(\{111\} \langle 110 \rangle\) slip system and \(\{111\} \langle 112 \rangle\) twin system for the texture orientation of rotating brass are calculated, which are 0.27 and 0.31, respectively. When the twinning Schmid factor is larger than the sliding Schmid factor, it is favorable for the formation of twins. With the increase of deformation, TWIP steel gradually formed a strong rotating brass texture, which promoted the formation of deformation twins.

The distribution of orientation difference angle in EBSD can be used to qualitatively determine the dislocation density inside the material. In the TWIP steel before expansion, the grain boundaries between each grain are large angle grain boundaries; As the expansion goes on, the proportion of small-angle grain boundaries increases significantly. Any small-angle grain boundaries can be regarded as a dislocation wall arranged by a series of dislocations. It can be seen that a large number of dislocations exist in the deformed grains \[23\].

4. Discussion

TWIP steel shows high strength and plasticity. The true stress-strain curve is shown in figure 10(a). The ductility of TWIP steel is 64.7% and the tensile strength reaches 1013MPa; The power strengthening model was used to fit the true stress-strain curve, and the change of the work hardening index \(n\) with the true strain was obtained, as shown in figure 10(b). \(n\) is generally regarded as an indicator of metal plastic forming ability \[24\]. With the increase of the expansion percentage, the \(n\) increases, the maximum is 0.65, which is consistent with the high strong plasticity. However, during the expansion process, the plasticity obviously did not reach the expected, and the expansion percentage was only 15.6%. In this regard, the following analysis is made:

As can be seen from the above EBSD and TEM observations, the structure of deformation twins in the process of plastic deformation of TWIP steel is summarized in figure 11. Most twins, such as T1 and T2, intersect with each other. It is shown that part Shockley dislocations sliding on plane \((-11-1)\) will decompose at the
boundary of plane $(-111)$, which will further facilitate the intersection of twins [25]. At the same time, the relatively small T2 and T1 also intersect each other in a stair or ladder, forming a multi-level twin structure. Further, it can be found in the figure that some twins are blocked by the twin boundary, forming secondary twins between the twins [26]. In summary, twins are intersected with each other in a variety of ways, and grains are refined.

Due to the intersection between twins, the grains are divided into twin layers and matrix layers, and it can be seen that there are many grain boundary-twin boundary (GB-TB) intersections and twin boundary-secondary twin boundary (TB-STB) intersections in the twin layers. It is as shown in figure 12. When dislocations glide parallel to twin boundaries, these dislocations do not experience any barrier until they are hindered by grain boundaries. As the deformation goes ahead, dislocations begin to pile up against grain boundaries and produce a stress concentration between dislocations on twin boundaries on grain boundaries, and stress concentration is more obvious. When reaching a critical point, a crack forms to release the stress concentration [27–31]. The calculation formula of dislocation density is

$$\sigma = M \omega \mu b \sqrt{\rho}$$ (1)
Where, $\sigma$ is the stress, $M$ is Taylor factor, $\alpha$ is empirical constant, $\mu$ is shear modulus and is $b$ burgess constant; $\rho$ is the dislocation density.

The expression of unit dislocation elastic energy $W_d$ is

$$W_d = \frac{A\mu b^2}{4\pi K}$$  \hspace{1cm} (2)

Among them:

$$\frac{1}{K} = \cos \varphi \cos \varphi + \frac{\sin \varphi \sin \varphi}{1 - \nu}$$  \hspace{1cm} (3)

$A$, $\varphi$, $\nu$ are the empirical constant, the angle between the dislocation line and Burgess vector, and the Poisson’s coefficient, respectively. The dislocation pile-up energy (DPE) generated by $N$ units of dislocation pile-up.

$$W_D = \frac{A\mu b^2 N}{4\pi K}$$  \hspace{1cm} (4)

The crack nucleation energy (CNE) can be pushed out through the fracture mechanism. In the plane, the release rate of energy per crack length can be expressed as.

$$\frac{\partial E_c}{\partial c} = 2\gamma - G$$  \hspace{1cm} (5)

Where, $c$ is the crack length and $\gamma$ is the surface energy, and the surface energy per unit area

$$2\gamma = 0.2\mu b$$  \hspace{1cm} (6)

Under the assumption of plane strain, only the generation of type I crack is considered, then

$$G = \frac{1 - \nu^2}{E} K_I^2$$  \hspace{1cm} (7)

Where $E$ is Young’s modulus, $K_I$ is the stress field intensity factor of type I crack, and its expression is:

$$K_I = Y\sigma \sqrt{c}$$  \hspace{1cm} (8)

Where $Y$ is constant. By combining equations (5)–(8) the CFE can be deduced.

$$\frac{\partial E_c}{\partial c} = 0.2\mu bc - \frac{1 - \nu^2}{E} Y^2\sigma^2 c^2$$  \hspace{1cm} (9)

The crack length is integrated from 0 to $c$, so equation (9) can be expressed as.

$$E_c = 0.2\mu bc - \frac{1 - \nu^2}{2E} Y^2\sigma^2 c^2$$  \hspace{1cm} (10)

The criterion of crack nucleation is based on the difference between $W_D$ and $E_c$, when $W_D > E_c$, the crack will nucleate. TEM figures and orientation difference distribution of expanded TWIP steel show that the number of dislocations is large enough to satisfy the condition of crack nucleation. At the same time, when there are secondary twins, cracks are more likely to occur. The reason is that dislocation stacking also occurs on the

\[\text{Figure 13. Schematic diagram of stress subjected to expansion process.}\]
boundaries of the secondary twins, which leads to the increase of dislocation stacking energy of the structure [32].

4.1. Stress state
Figure 13 is a schematic diagram of the stresses subjected to expansion deformation. $\sigma_\theta$ and $\sigma_z$ are tensile stresses and $\sigma_r$ are compressive stresses. It can be seen that the expansion behavior shows the thinning of the thickness and the upward elongation of the ring. OM was used to observe the microstructure of TWIP steel with compression deformation and elongation of 10% and 20%, as shown in figure 14. It can be seen from figures 14(a), (b) that under uniaxial compression stress, annealing twins in grains are still clearly visible, the number of grains involved in deformation is significantly less than that of expansion deformation, and the deformation bands in the matrix are in a single group of parallel state and relatively sparse. Figures 14(c), (d) shows that the twins also intersect with others under tensile deformation, but the degree is much lower than that of expansion deformation. It can be concluded that the generation speed and quantity of twins in the expansion deformation process are much higher than that of uniaxial tensile or compression deformation, which further promotes the nucleation of cracks.

4.2. Microhardness
The axial microhardness test results of the pipe are shown in table 3. The test results show that the microhardness of the material increases gradually with the expansion. And the microhardness of the tube shows a decreasing trend from inside to outside, because the outer part of the tube is in a free bulging state, and the inner part is squeezed by the expansion cone and plastic deformation occurs first, and the strength is improved first. As the expansion progresses, the plastic deformation will transfer to the outer side, making the outer

|                | (1)  | (2)  | (3)  | Average |
|----------------|------|------|------|---------|
| Before expansion | 249.8 | 245.8 | 243.7 | 244.1   |
| During expansion  | 374.5 | 356.8 | 346.2 | 349.2   |
| After expansion   | 495.8 | 482.7 | 474.2 | 480.9   |
strength improve, so the inner strength of the tube is higher than the outer, which also explains the crack first appeared on the inner surface of the tube. Tables 4 and 5 show the changes of microhardness after stretching and compression respectively. By comparison, the microhardness of expansion deformation is obviously higher than that of tensile and compression deformation under the same shape variable, so the degree of work hardening of expansion deformation is higher, the generation of twins is faster, and the volume fraction of twins is higher, and it is more prone to crack generation.

5. Conclusions

In this research, the expansion test of TWIP steel is carried out. Based on the experimental results, some conclusions are drawn as follows.

(1) Cracks appeared inside the tube edge in TWIP steel when expansion rate is 15.6%. After expansion, it is still a single austenite structure with no carbide and intermetallic compounds precipitated out. The deformation mechanism of expansion is the joint action of dislocation slip and deformation twins, and a large number of twins and secondary twins are produced in the grain after expansion; Abundant dislocations occur in the grain, and the stress concentration caused by dislocation pile-ups reaches the critical stress value of crystal twinning, thus inducing the formation of deformation twins;

(2) Twins formation is influenced by grain orientation. During the expansion process, \(\{110\} < 111 > \) silk texture in \(< 111 > X_0\) direction is formed; The orientation difference after expansion is mainly small angle grain boundaries, which is due to the formation of dense dislocations and pile-up of small angle grain boundaries;

(3) The grains are divided into twin layers due to twins intersecting; The criterion of crack nucleation is deduced based on the difference between the dislocation pile-up energy (DPE) and the crack nucleation energy (CNE). There are a lot of twins and dislocations in the matrix and the intersected between twins during expansion, which meets conditions of crack nucleation; Due to the combined action of compressive stress and tensile stress in the expansion process of TWIP tube, the twin generation rate, twin volume fraction and work hardening capacity are much higher than those of uniaxial tensile or compression deformation which further indicates that the expansion deformation is easier to meet the conditions of crack nucleation.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

| Table 4. Microhardness of TWIP steel after tensile (unit: HV). |
|-----------------|-------|-------|-------|
| (1)             | (2)   | (2)   | Average |
| Tensile 10%     | 255.5 | 253.4 | 254.4  |
| Tensile 20%     | 300.4 | 302.8 | 306.2  | 303.1  |
| Tensile 30%     | 330.6 | 332.6 | 329.2  | 330.8  |
| Tensile 40%     | 370.4 | 372.3 | 368.4  | 370.4  |
| Tensile 50%     | 411.5 | 410.5 | 414.4  | 412.1  |
| Tensile 60%     | 470.6 | 473.1 | 470.4  | 471.4  |

| Table 5. Microhardness of TWIP steel after compression (unit: HV). |
|----------------|-------|-------|
| (1)            | (2)   | (2)   | Average |
| Compressed 10% | 270.2 | 273.1 | 271.4  | 271.6  |
| Compressed 20% | 344.4 | 346.8 | 346.2  | 345.8  |
Declaration of competing interest

The authors declare no competing financial interest.

ORCID iDs

ChunYuan Liu @ https://orcid.org/0000-0002-1930-0025
KaiHong Song @ https://orcid.org/0000-0003-2210-0574

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