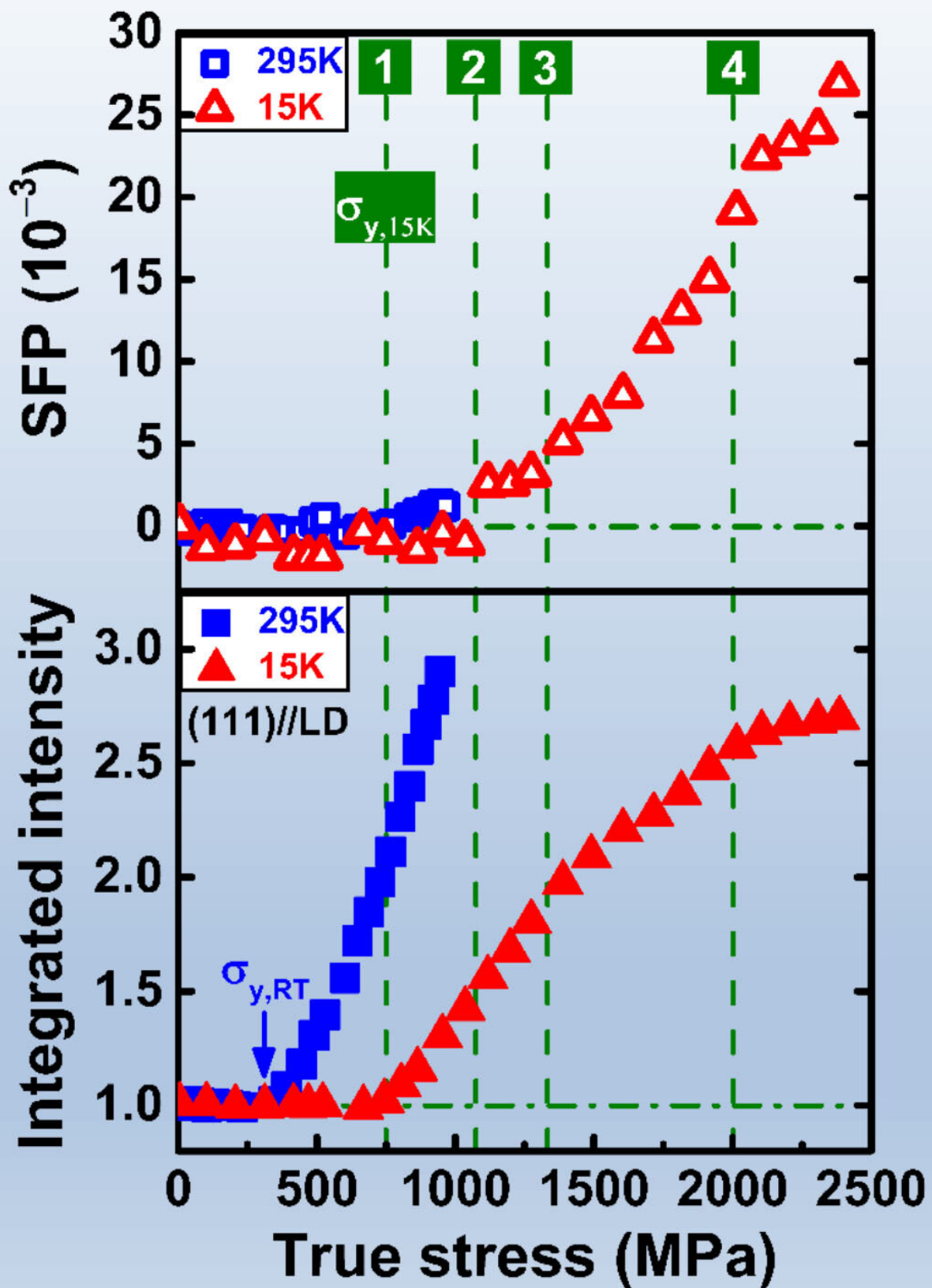


# **Multi-stage deformation process in high-entropy alloys at ultra-low temperatures revealed**

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Deformation pathway of CrMnFeCoNi HEA sample at 15 K. Vertical dashed lines are drawn to pinpoint the changes in the deformation behaviour: (1) Start of dislocation slip; (2) start of stacking faults; (3) first sign of serrations; and (4) massive serrations coincided with the saturation of dislocation slip. Credit: © City University of Hong Kong / Science Advances

An international research team led by scientists from City University of Hong Kong (CityU) has recently discovered that high-entropy alloys (HEAs) exhibit exceptional mechanical properties at ultra-low temperatures due to the coexistence of multiple deformation mechanisms. Their discovery may hold the key to designing new structural materials for applications at low temperatures.

Professor Wang Xunli, a newly elected Fellow of the Neutron Scattering Society of America, Chair Professor and Head of Department of Physics at CityU, collaborated with scientists from Japan and mainland China in conducting this challenging study on HEAs' deformation behaviors at ultra-[low temperatures](#). Their research findings were published in the latest issue of the scientific journal *Science Advances*, titled "Cooperative deformation in [high-entropy alloys](#) at ultralow temperatures."

## **Neutron scattering: a powerful measurement tool**

HEAs are a new class of structural materials with favorable mechanical properties, such as an excellent strength-ductility combination, high fracture toughness, and resistance against corrosion. It consists of multiple principal elements, contributing to complex deformation behaviors.

Materials normally become brittle at low temperatures because the atoms are "frozen" and lose their mobility. But HEAs demonstrate high ductility and can be stretched to a large deformation at low temperatures. "This phenomenon was first discovered in 2014, but the [mechanism](#) behind it is still unknown. It's intriguing," said Professor Wang, who has been studying the mechanism since then and is the corresponding author of the paper.

To solve this puzzle, the research team led by Professor Wang made use of the in-situ neutron diffraction technique to study the deformation process of HEAs. "Neutron diffraction measurement is one of the few means to observe what's going on during the materials' deformation. We can see every step: which mechanism kicks in first, and how each of them interacts with the others, which is not feasible by conventional experimental methods like [transmission electron microscopy](#)," Professor Wang explained.

"More importantly, it can conduct measurements at ultra-low temperatures, i.e., near absolute zero. And the measurements are representative of the bulk of the sample rather than from the surface or localized area, providing microscopic information like how different grains of the materials interacted with each other," he added.



Muhammad Naeem prepares the experiment at TAKUMI, an engineering materials diffractometer at Japan Proton Accelerator Research Complex (J-PARC) used to perform in-situ neutron diffraction measurements multiple HEA samples, which all showed a multi-stage deformation process. Credit: © Professor Wang Xunli / City University of Hong Kong

## Sequence of deformation mechanisms revealed

Using this technique, the sequence of deformation mechanisms in HEAs at ultra-low temperatures are revealed for the first time. The team found out that at 15 Kelvin (K), the HEA deforms in four stages.

It begins with the dislocation slip, a common deformation mechanism for face-centered-cubic materials, where the planes of the crystal lattice slide over each other. While the dislocations continue, stacking faults gradually become active and dominant where the stacking sequence of crystal lattice planes are changed by the deformation. It is then followed by twinning, where the misorientation of lattice planes occurs, resulting in a mirror image of parent crystal. Finally, it transits to serrations where the HEA shows big oscillations of deforming stress.

"It is interesting to see how these mechanisms become active and cooperate with each other when the material deforms," said Muhammad Naeem, a graduating Ph.D. student and senior research assistant from CityU's Department of Physics, who is the first author of the paper.

In their experiments, they found that the HEAs showed a higher and more stable strain hardening (in which materials become stronger and harder after deformation), and exceedingly high ductility as the [temperature](#) decreased. Based on the [quantitative analysis](#) of their in-situ experimental data, they concluded that the three observed additional deformation mechanisms—stacking faults, twinning, and serrations—as well as the interaction among these mechanisms, are the source of those extraordinary mechanical properties.

## **A new terrain: deformations at ultra-low temperatures**

The whole study took the team almost three years, and will continue studying the phenomenon. "Complicated deformation mechanisms in HEAs at ultra-low temperatures is new terrain that very few people have explored before. The findings of this study only show the tip of the iceberg," said Professor Wang.



For their next step, the team will further investigate when stacking faults will appear in other alloys, and analyze their deformation mechanisms at different temperatures. "Understanding deformation mechanisms will facilitate the design of new alloys. By deploying different mechanisms in synergy, we can tune them to achieve better mechanical properties for applications at low temperatures," said Mr Naeem.

**More information:** "Cooperative deformation in high-entropy alloys at ultralow temperatures" *Science Advances* (2020). [DOI: 10.1126/sciadv.aax4002](https://doi.org/10.1126/sciadv.aax4002) , [advances.sciencemag.org/content/6/13/eaax4002](https://advances.sciencemag.org/content/6/13/eaax4002)

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