# Paragraph Ran in the Queries

**Paper Title:** Enhance the mechanical properties of CoCrFeNi high entropy alloy: Rare-earth element Gd was employed as a "cladding structure" to refine grains
**Content :**

## Mechanical properties

The nanoindentation testing is an effective way to characterize the micromechanical properties of materials, especially suitable for testing the nanohardness and Young's modulus of materials with high accuracy [46], [47]. The nanoindentation *P-h* curve of Gd2 alloy is shown in Fig. 10(a). Under the same loading conditions, the indentation depth of the FCC phase and the HS phase is about 250 nm and 100 nm, respectively. Obviously, the FCC phase shows better plasticity under external conditions, while the HS phase is more resistant to deformation, and exhibits a higher hardness.

In this study, the test results of nanohardness and Young's modulus of FCC phase and HS phase are shown in Fig. 10. The average nanohardness of the HS phase distributed along the FCC phase grain boundary is about 9 GPa, which is almost 3 times that of the average nanohardness of the FCC phase (3 GPa), highlighting the strengthening effect of HS relative to the grain boundary. It is worth noting that this strengthening effect contributes to the improvement of alloy strength. In addition, the average Young's modulus of the HS phase (~ 183 GPa) is also higher than that of the FCC phase (~ 167 GPa), so the HS phase is more resistant to deformation. This is because the HS phase is a simple hexagonal structure of $CaCu_5$, and the number of slip systems is less than that of the FCC structure. Therefore, the HS phase contributes to some extent to the increased brittleness of the alloy.

The compressive stress-strain curves of $(CoCrFeNi)_{100-x}Gd_x$ HEAs at room temperature are shown in Fig. 11. The relevant mechanical data of $(CoCrFeNi)_{100-x}Gd_x$ HEAs obtained from the compression test are shown in Table 4. Gd0 shows excellent plasticity and remains unbroken for more than 66 % of the compressive deformation, but the yield strength is only 235 MPa, therefore Gd0 alloy has a good work hardening ability. The increase of Gd content in the alloy significantly improves the yield strength of the alloy (local amplification in Fig. 11). It is worth noting that the yield strength of Gd0 is 235 MPa, while that of Gd2 and Gd3 is increased to 520 MPa and 650 MPa respectively (see Table 4). However, the addition of Gd increased the brittleness of $(CoCrFeNi)_{100-x}Gd_x$ HEAs, and the fracture strain of Gd1, Gd2 and Gd3 is reduced to 43.76 %, 41.46 % and 36.40 %, respectively.

## Analysis of mechanical properties

The enhancement of macroscopic mechanical properties in $(CoCrFeNi)_{100-x}Gd_x$ HEAs is closely related to the evolution of its microstructure. First of all, the average grain size of FCC phase of Gd3 is significantly refined compared with that of Gd0. Obviously, grain refinement directly contributes to the strength improvement of the alloy and plasticity retention. As can be seen from Fig. 12(a), the average grain size of FCC phase of Gd3 is 25.70 μm and the yield strength of Gd3 is 650 MPa, especially compared with the super-large grain size of Gd0 and the yield strength of 235 MPa, the higher yield strength of Gd3 is ensured by the grain refinement degree of the microstructure. Secondly, the solid solution strengthening caused by Gd added to CoCrFeNi alloy also improves the strength of the alloy to a certain extent. In addition, compared with Gd0, Gd05, Gd1 and Gd2, the content of HS phase in Gd3 is higher as shown in Fig. 12(b). Although the HS phase shows a certain brittleness, which slightly impacts the material plasticity, the strength of HS phase reaches a remarkably high level, and it also important in improving the strength of Gd3.(Fig. 13, Fig. 14)

## Strengthening mechanisms

Due to the addition of Gd, the microstructure of $(CoCrFeNi)_{100-x}Gd_x$ HEAs undergoes significant changes which directly affects the mechanical properties of the alloy. From the perspectives of microstructure refinement, solid solution strengthening and second phase strengthening the yield strength of $(CoCrFeNi)_{100-x}Gd_x$ HEAs has been significantly improved without impairing ductility.