# Paragraph Ran in the Queries

**Paper Title:** Enhancement of strength-ductility trade-off in Al5Fe25Cr25Ni42.5Ti2.5 high entropy alloy through annealing twins
**Content :**

## Strengthening mechanism of alloys

The yield strength (YS), tensile strength (UTS) and elongation at break (UE) of AC, CR-900 and CR-1000 HEA are listed in Table 2. We use the structure-based strength model to explain the strengthening mechanism of CR-900 and CR-1000 HEAs, namely:

in the formula,

is the yield strength of NiFeCr MEA [44], which represents the lattice friction.

,

,

representing strengthening contributions from solutes, grain boundaries, dislocations, respectively.

$Al_5Fe_{25}Cr_{25}Ni_{42.5}Ti_{2.5}$can be regarded as a pseudo-ternary alloy Al5MTi2.5 (M is a mixed solvent composed of Cr, Fe and Ni), and the solid solution strengthening effect caused by Al and Ti can be estimated by traditional formula [45], [47]:

in the formula, the shear modulus G is 87.5 GPa, using the shear modulus of $Ni_{50}Fe_{25}Cr_{25}$ MEA [48], c is the atomic fraction of Al and Ti in the alloy, and the Taylor factor

[16]. The interaction parameter

is expressed as:

The formula combines the size mismatch $\varepsilon_\alpha$ and elastic mismatch $\varepsilon_G$:

where *a* is the lattice constant. It has been reported that if the solute element is in the matrix,

is proportional to $c_{1/2}$ [49]. Lu et al. calculated experimentally that the caused by the addition of Al and Ti in $Ni_{46}Cr_{23}Fe_{23}Al_4Ti_4$ alloy was 52.8 MPa. Therefore, the

value of CR-900 HEA and CR-1000 HEAs is 49.5 MPa.

Due to the heterogeneous structure in CR-900 HEA, grain boundary strengthening needs to consider the contribution of the proportion of LAGBs, HAGBs and TBs to the yield strength:

In the formula,

and

are the strengthening contributions of LAGBs and HAGBs + TBs, respectively. $M$, $\alpha$ and $G$ are Taylor factor, constant and shear modulus, respectively. Taylor factor

. For FCC alloy, $\alpha$= 0.2[50]. the shear modulus $G$ is 87.5 GPa, using the shear modulus of $Ni_{50}Fe_{25}Cr_{25}$ MEA. $S_v$ is the boundary area of LAGBs per unit volume ($2/d_{LAGBs}$), $f_{LAGBs}$ is the area fraction of LAGBs, k is the strength contribution coefficient,

[51], $f_{HAGBs+TBs}$ is the relative area fraction of HAGB and TB, $\theta_{LAGBs}$ is the average orientation difference in the range of 2-15°. And $d_{HAGBs+TBs}$ represents HAGBs grain size.

Due to the high density of annealing twins in CR-1000 HEA, grain boundary strengthening includes two strengthening contributions: (1) grain boundary strengthening (

); (2) Twin boundary strengthening (

). It can be expressed by formula:

In the formula, the Hall-Petch coefficient

, $d$ = 12.17 μm is the average grain size considering the annealing twin boundary, and $d_0$ =19.43 μm is the average grain size (when calculating the grain size, the annealing twin is not considered as a grain). and the

value of CR-900 HEA and CR-1000 HEAs is estimated to be 434.5 MPa, 141.6 MPa.

The contribution of dislocation strengthening

can be estimated by Taylor 's hardening law [52]:

$M$, $\alpha$, $G$, $b$ and $\rho$ are Taylor factor, empirical constant, shear modulus, burgers vector and dislocation density, respectively. Taylor factor

. For FCC alloy, $\alpha$= 0.2. the shear modulus G is 87.5 GPa, using the shear modulus of $Ni_{50}Fe_{25}Cr_{25}$ MEA, $b$=0.251 nm. Therefore, the contribution of dislocation strengthening to yield strength of CR-900 and CR-1000 HEAs is 518.8 MPa and 105.8 MPa, respectively. The total strengthening estimated by Eq. (3) is shown in Fig.17, and the total yield strength of CR-900 HEA and CR-1000 HEA is 1082.8 MPa and 376.9 MPa, respectively. It is close to the experimental value of 1072MPa, 392 MPa.