TWIP/TRIP assisted quinary HEAs/CCAs: design, microstructure and properties

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Outline

I Background – a brief reminder

II Motivation – what is the target?

III Experimental – design and results

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Background – Quaternary TRIP CCAs/HEAs

Lower stacking fault energy (SFE)

TRIP: transformation induced plasticity

TWIP: twinning induced plasticity

Improved strength and ductility

Li et al., Nature 2016
Gludovatz et al., Science, 2014

TRIP: transformation induced plasticity

Li & Raabe, JOM 2017

Fe\textsubscript{50}Mn\textsubscript{30}Co\textsubscript{10}Cr\textsubscript{10}

Δ\text{G}\textsubscript{FCC\rightarrow HCP}, J/mol

Li et al., Nature 2016

Fe\textsubscript{80-x}Mn\textsubscript{x}Co\textsubscript{10}Cr\textsubscript{10}

Fe\textsubscript{37}Mn\textsubscript{43}Co\textsubscript{10}Cr\textsubscript{9} (f.c.c.)

Fe\textsubscript{50}Mn\textsubscript{30}Co\textsubscript{10}Cr\textsubscript{10} (f.c.c. + h.c.p.)
Background – Quaternary iCCAs/iHEAs


+ 0.5% C

Interstitial C addition

TRIP
TWIP

Interstitial SSS

Nano-particles

iCCAs/iHEAs: Improved strength-ductility

SSS: solid solution strengthening

\[
\varepsilon_{\text{loc}} = 10\% \\
\varepsilon_{\text{loc}} = 40\% \\
\varepsilon_{\text{loc}} = 60\% \\
\varepsilon_{\text{loc}} = 90\%
\]

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SPP subgroup meeting, 2018, Bayreuth
Motivation – what is the target?

- quaternary to quinary
- C and N in matrix
- nano-carbides/nitrides
- tuning SFE
- grain refinement

SS: solid solution
Motivation – first stage

- quaternary to quinary
- C and N in matrix
- nano-carbides/nitrides
- tuning SFE
- grain refinement

Strength↑
Ductility↑
Alloy design – Quinary TRIP CCAs/HEAs

Guiding rule: SFE

Quinary CCAs/HEAs with SFE similar to quaternary \( \text{Fe}_{50}\text{Mn}_{30}\text{Co}_{10}\text{Cr}_{10} \)

\[
\text{Co}_{20}\text{Cr}_{20}\text{Fe}_x\text{Mn}_y\text{Ni}_z \quad (x+y+z=60)
\]

\[
\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}
\]

MPIE: Grabowski, Körmann (unpublished)
Alloy design – Quinary TRIP CCAs/HEAs

Co: 20; Cr: 20; Fe: 5~35; Mn: 5~35; Ni: 5~35

Three alloy systems under investigation:

1. $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$

2. $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_{6}$

3. $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{24}\text{Mn}_{30}\text{Ni}_{6}$

Input from $ab\ initio$ calculation
Experimental – alloy fabrication

**Set 1: coarse grains**
- Casting
- Hot rolling @900°C
- Homogenization @1200°C, 2h
- 50% thickness reduction, 10 mm → 5 mm
- Water-quenching (WQ)

**Set 2: refined grains**
- Homogenized state
- Cold rolling 5 mm → 1.5 mm
- Annealing @900°C, 5 min, Ar, WQ
- Annealing @800°C, 10 min, Ar, WQ

Ingot size: 10×50×150 mm³
Co: 20;  Cr: 20;  Fe: 5~35;  Mn: 5~35;  Ni: 5~35

Three alloy systems under investigation:

1. Co$_{20}$Cr$_{20}$Fe$_{34}$Mn$_{15}$Ni$_{11}$

2. Co$_{20}$Cr$_{20}$Fe$_{30}$Mn$_{24}$Ni$_{6}$

3. Co$_{20}$Cr$_{20}$Fe$_{24}$Mn$_{30}$Ni$_{6}$
Co$_{20}$Cr$_{20}$Fe$_{34}$Mn$_{15}$Ni$_{11}$ – tensile properties of samples from different heat treatment conditions

1. Coarse grain alloy has reasonable strength and good ductility.
2. Grain refinements lead to a simultaneous increase of strength and ductility.
I. Homogenized state @1200°C, 2h

- Single FCC phase
- High fraction of annealing twins (~47% twins)
- Average grain size ~156 µm
Experimental – alloy I: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$

Microstructure: homogenized state @80% tensile strain (local strain)

For $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$ alloy, TRIP effect is observed, but TWIP is dominant.
I. Homogenized state @80% tensile strain (local strain)

Experimental – alloy I: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$

Experimental – alloy I: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$
Experimental – alloy I: \( \text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11} \)

I. Homogenized state @ 60% tensile strain (local strain)

At lower strains, TRIP effect is neglectable, and TWIP is dominant.
I. Homogenized state @ 60% tensile strain (local strain)
Co: 20;  Cr: 20;  Fe: 5~35;  Mn: 5~35;  Ni: 5~35

Three alloy systems under investigation:

1. Co$_{20}$Cr$_{20}$Fe$_{34}$Mn$_{15}$Ni$_{11}$

2. Co$_{20}$Cr$_{20}$Fe$_{30}$Mn$_{24}$Ni$_{6}$

3. Co$_{20}$Cr$_{20}$Fe$_{24}$Mn$_{30}$Ni$_{6}$
Experimental – alloy II: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_6$

$\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_6$ – tensile properties of samples from different heat treatment

1. Alloy II ($\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_6$) has higher strength but lower ductility compared to Alloy I ($\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$).

2. Grain refinements lead to a significant increase of strength but a decrease of ductility.
II. Homogenized state @1200°C, 2h before DIC test

- Dual phase material, with a tiny fraction of HCP
- A high twinning fraction: 39.1%
- Bimodal grain size
- Average grain size ~57.6 µm
II. Homogenized state @1200°C, 2h, microstructure after DIC, 40% strain

For alloy II, at intermediate strain, TRIP effect is dominant, and TWIP is neglectable.
Experimental – alloy II: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_6$

II. Homogenized state @1200°C, 2h, microstructure after DIC, 40% strain
**Summary and Outlook**

For alloy I: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$

Grain refinement leads to a **simultaneous increase** of strength and ductility.

**TWIP** effect is dominant for homogenized deformation state.

For alloy II: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_{6}$

Grain refinement **doesn’t** simultaneously increase strength and ductility.

**TRIP** effect is dominant for homogenized deformation state.

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SPP subgroup meeting, 2018, Bayreuth
Summary and Outlook

For alloy I: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{34}\text{Mn}_{15}\text{Ni}_{11}$

- TRIP VS. TWIP
- Deformation mechanism comparison

For alloy II: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{30}\text{Mn}_{24}\text{Ni}_{6}$

Adding C or N

similar SFE, different mechanical behavior?

For alloy III: $\text{Co}_{20}\text{Cr}_{20}\text{Fe}_{24}\text{Mn}_{30}\text{Ni}_{6}$

- For alloy I:
  - Co 20
  - Cr 20
  - Fe 34
  - Mn 15
  - Ni 11

- For alloy II:
  - Co 20
  - Cr 20
  - Fe 30
  - Mn 24
  - Ni 6

- For alloy III:
  - Co 20
  - Cr 20
  - Fe 24
  - Mn 30
  - Ni 6
Thank you for your attention!