# Microstructure and Mechanical Properties of Magnetic Levitation Fabricated Cu-Ni-Co Multi-principal Element Alloys

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**Abstract:** The $Cu_{35}Ni_{35}Co_{30}$ multi-principal element alloy (MPEA) with dual-FCC phase structure was prepared by magnetic levitation melting. Single-phase face-centered cubic (FCC) structure was obtained by heat treatment at 1030 °C for 15 h. Cold rolling and post-deformation annealing (PDA) heat treatments were used to produce heterogeneous grain structures (HGS). X-ray diffraction (XRD), scanning electron microscope (SEM) equipped with an energy-dispersive spectrometry (EDS) detector were used to characterize the microstructure and phase composition of the alloys and to determine their room temperature tensile properties in different states. The room temperature tensile test was used to determine their mechanical properties in different states. HGS could be achieved in PDA-treated sample at 1030 °C for 60 s. This sample exhibits excellent combination of strength and ductility, showing a tensile yield strength of 562 MPa, an ultimate strength of 758 MPa and a total elongation of 29.9 %.

**Keywords:** Multi-principal element alloy, magnetic levitation melting, Mechanical properties

## 1 Introduction

The concept of multi-principal element alloys (MPEA) was introduced by Yeh et al [1] in 2004, which consists of solid solution phases. Until now, the FCC MPEA have been widely studied for their properties such as good plasticity and excellent corrosion resistance [2]. However, FCC-structured MPEA exists the strength-ductility trade-off [3]. Fortunately, heterogeneous structural architectural strategies, such as bimodal structures, heterogeneous layered structures, gradient structures， have been reported to be effective strategies for realizing strength-toughness synergies in metals and alloys. Heterogeneous structures introduced by cold rolling and post-deformation annealing (PDA) heat treatment is an effective and simple way to realize the perfect combination of strength and ductility in FCC structured MPEA.

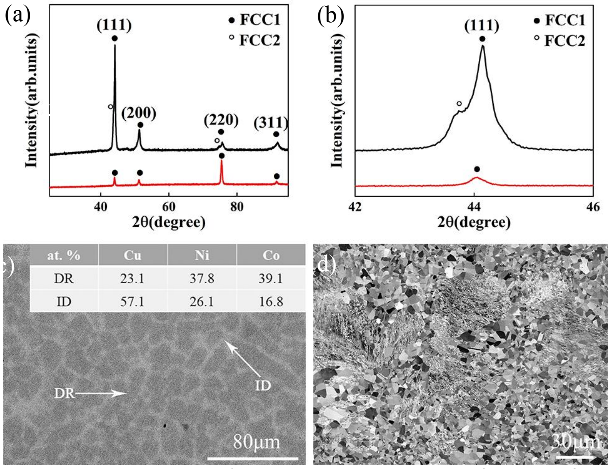
Therefore, $Cu_{35}Ni_{35}Co_{30}$ MPEA was chosen as an ideal prototype in this study. The material was cast by magnetic levitation melting, followed by heat treatment and cold rolling, and finally PDA heat treatment to obtain a heterogeneous grain structure (HGS) that produces a synergistic strengthening effect. The phase compositions, microstructures and mechanical properties of the as-cast and PDA states were investigated.

## 2 Experimental procedure

The $Cu_{35}Ni_{35}Co_{30}$ MPEA was prepared by magnetic levitation melting. After solidification, the ingot was homogenized in an electric-resistant furnace at 1030 ℃ for 15 h followed by water quenching. Then, cold rolling process was conducted on the homogenized ingot with a thickness reduction of 75 %. Finally, PDA heat treatments were performed on the as-rolled samples at 1030 °C for 60 s, followed by water quenching. The crystalline structure was identified by X-ray diffraction (XRD). The microstructure was characterized by a scanning electron microscope (SEM) equipped with an energy-dispersive spectrometry (EDS) detector and a backscattered electron (BSE) detector. Tensile tests were carried out on a universal testing machine at a strain rate of $1 \times 10^{-3}$ $s_{-1}$ at room temperature.

## 3 Result and discussion

Fig. 1 (a) shows the XRD patterns of the as-cast $Cu_{35}Ni_{35}Co_{30}$ MPEA, and the high-magnification image of (111) plane is shown in Fig. 1 (b). As shown by the bimodal (111) plane and (220) plane, the as-cast MPEA exhibit two sets of FCC diffraction peaks. Fig. 1 (c) shows BSE images of the as-cast sample, consisting of two distinct regions with light and dark contrast, showing a typical equiaxed dendritic structure. The inset of Fig. 1 (c) presents the chemical composition of the dendritic regions (DR) and inter-dendritic regions (IR) of the as-cast sample as measured by EDS/BSE. A visual examination of the inset reveals that Cu is rich in the inter-dendritic regions, while Ni and Co are concentrated in the inter-dendritic regions. In order to eliminate segregation and obtain a single FCC phase, the as-cast alloy was held at 1030 °C for 15 h. And to optimize the mechanical properties of $Cu_{35}Ni_{35}Co_{30}$ MPEA, the homogenized samples were cold-rolled with a deformation amount of 75 % and annealed at 1030 ℃ for 60 s. XRD patterns of the cold-rolled and PDA-treated $Cu_{35}Ni_{35}Co_{30}$ sample was shown in Fig. 1 (a). As expected, it is composed of a single FCC phase, suggesting that no phase transformation or precipitation occurred at 1030 ℃. Therefore, XRD results reveal that the $Cu_{35}Ni_{35}Co_{30}$ MPEA possesses a good structural stability against plastic deformation and PDA heat treatments. BSE images of the PDA-treated samples are showed in fig.1 (d). The PDA-1030-60 s sample exhibit notable heterogeneous grain structures. It can be seen that PDA-1030-60 s sample is composed by micro-sized recrystallized grains (MRGs) with an average grain size of ~4 μm and many residual deformed grains (RDGs) in the non-recrystallized regions. The volume fraction of MRGs and RDGs of the sample is estimated to be ~ 77.9 % and ~ 22.1 %, respectively.



| at. % | Cu | Ni | Co |
|---|---|---|---|
| DR | 23.1 | 37.8 | 39.1 |
| ID | 57.1 | 26.1 | 16.8 |

**Fig. 1 (a) XRD patterns of as-cast and PDA-treated Cu35Ni35Co30 MPEA, (b) high-magnification of (111) plane (c) BSE images of as-cast Cu35Ni35Co30 MPEA, (d) BSE images of PDA-treated samples (PDA-1030-60 s)**

**Table 1. mechanical properties at ambient temperature of Cu35Ni35Co30 samples**

| Process | $\sigma_{0.2}$ MPa | $\sigma_{UTS}$ MPa | El % | $\sigma_{t0.2}$ /MPa | $\sigma_{tUTS}$ MPa | $El_t$ % |
|---|---|---|---|---|---|---|
| As-cast | 504 | 686 | 11.0 | 507 | 761 | 10.34 |
| PDA | 562 | 758 | 29.9 | 568 | 964 | 24.22 |

Representative engineering tensile stress–strain curves of the as-cast and PDA heat-treated $Cu_{35}Ni_{35}Co_{30}$ samples at room temperature are shown in Fig. 2. The engineering tensile yield strength ($\sigma_{0.2}$), ultimate strength ($\sigma_{UTS}$) and total elongation (El) of the samples are summarized in Table 1. As shown in Fig. 2 (a) and Table 1, the as-cast sample possesses a good ductility strength but an insufficient ductility, in detail: it shows a $\sigma_{0.2}$ of ~ 504 MPa, a $\sigma_{UTS}$ of ~ 686 MPa and a total elongation of ~ 11.0%. Compared with the cold-rolled sample, PDA-treated sample at 1030 ℃ for 60 s shows distinct recovery of ductility. Specifically, the total elongation of the sample increases dramatically from ~ 11.0 to ~ 29.9 %, while the $\sigma_{0.2}$ was also slightly improved, from ~ 504 to ~ 562 MPa. The excellent combinations of strength and ductility have been achieved in PDA-1030-60 s. The true stress–strain curves of the two samples at room temperature are shown in Fig. 2 (b), while the results of the true tensile yield strength ($\sigma_{t0.2}$), true ultimate strength ($\sigma_{tUTS}$) and total elongation ($El_t$) were listed in table 1. The true stress–strain curves of the two samples at room temperature are shown in Fig. 2 (b), while the results of the true tensile yield strength ($\sigma_{t0.2}$), true ultimate strength ($\sigma_{tUTS}$) and total elongation ($El_t$) were listed in table 1. It can be seen that compared with as-cast sample, PDA heat-treated sample with HGS displays a significant improvement in ductility and $\sigma_{t0.2}$. Figure 2 (c) depicts the strain-hardening rate curves of as-cast and PDA heat-treated samples. It can be seen that the strain hardening rate of as-cast sample first monotonically decreases and then maintains at a relatively low-level work hardening rate as strain increases. However, the strain hardening rates of the PDA-1030-60 s samples first decreases sharply, then tends to increase, and finally decreases linearly with increasing true strain. The sudden increase is due to the presence of twin deformation in the alloy, which increases the work hardening rate of the alloy.

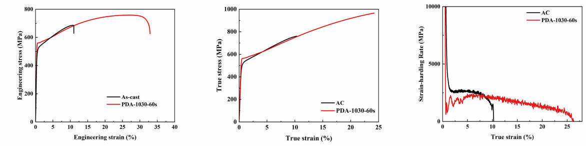


**Fig. 2 Mechanical behavior of Cu35Ni35Co30 MPEA (a) engineering tensile stress–strain curves, (b) representative true stress–strain curves, (c) strain-hardening rate as a function of true strain**

## 4 Conclusion

$Cu_{35}Ni_{35}Co_{30}$ MPEA with dual-FCC phase structure was prepared by magnetic levitation melting. Single-phase FCC sample with heterogeneous microstructure was successfully fabricated via the combination of cold rolling and short-time PDA heat treatments. The PDA-1030-60 s sample exhibits a well combination of strength and ductility, showing a tensile yield strength of ~ 562 MPa, an ultimate strength of ~ 758 MPa and a total elongation of ~ 29.9%. Furthermore, the PDA-1030-60 s sample displays a notable enhancement in ductility when compared with its as-cast counterpart, while simultaneously maintaining a high level of strength.

## References

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