Paragraph Ran in the Queries

Paper Title: Compositional engineering of CoCrCuFeNiAlx high entropy alloys to achieve superior yield strength-ductility synergy
Content :

Mechanical characterization

The mechanical characteristics of the alloys were assessed initially by measuring hardness values using a hardness testing machine (Duramin-40 A2, Struers), equipped with a square base diamond pyramid indenter with a specified angle of 136° between two opposite faces. Hardness measurements were carried out under a constant applied load of 5 kg for a dwell time of 15s. At least ten indentations were made at randomly chosen locations on each polished specimen to ensure accuracy and reported the average result. Following this, uniaxial tensile tests were conducted to evaluate strength and ductility of each alloy composition. Flat dog-bone-shaped tensile specimens (conforming to the sub-size ASTM E8 standard, featuring a 12.5 mm gauge length, a 3 mm gauge-width with a thickness of ~2 mm) were extracted from the as-cast ingots using EDM wire-cut system. Fig. 1 illustrates schematic representations of the tensile specimens and actual experimental specimens used in the study. Tensile tests at room temperature were conducted on these specimens using a 250 kN servo-hydraulic fatigue testing machine (Instron® 8802) with a crosshead velocity of 1 mm/min (strain rate: 0.001 s^{-1}). To ensure repeatability of the data, at least three tensile specimens were tested for each alloy. The yield strength was estimated at 0.2 % plastic deformation.

Study of tensile deformation

Fig. 11 represents engineering stress-strain curves of the cast alloys tested under tensile loading at room temperature. Similar to the observed trend in hardness values, the yield strength (YS, 0.2 offset stress) also could be observed to decrease with a corresponding increase in the ductility as Al concentration decreases. Alloy Al_1 demonstrated a remarkable tensile yield strength of 805 MPa but exhibited an extremely limited ductility (0.9 % only). This limited ductility could be ascribed to its hard BCC matrix phase, as evident from the corresponding EBSD phase map analysis shown in Fig. 5(b). This observation aligns with a separate study reported by Kuznetsov et al. [27], where the same alloy demonstrated a tensile strength of 790 MPa coupled with only 0.2 % ductility. For alloy $Al_{0.8}$, there is a slight increase in the ductility (7 %), but the yield strength drops significantly to a value of 587 MPa. With further reduction in the Al content to $Al_{0.75}$, the ductility increased to 12 %, while yield strength declined further to 544 MPa. However, there is a substantial improvement in ductility for the alloys $Al_{0.7}$ and $Al_{0.6}$, respectively, which recorded values of 32–34 % while maintaining a commendable yield strength of 490 MPa and 480 MPa, respectively. The presence of a composite microstructure comprising a hard Ni-Al intermetallic phase and BCC phase distributed uniformly in a soft FCC matrix contributed to a desirable balance between the strength and ductility. These findings are comparable with the tensile results reported for alloy $Al_{0.5}$CoCrCuFeNi with 500 MPa yield strength and 32 % ductility [28]. The observed variations in strength and ductility can be ascribed to the changes in phase evolution induced by Al content. The presence of a hard BCC matrix, as seen in alloy Al_1, tends to enhance yield strength but severely limits the ductility. Conversely, as Al content decreases, a transition towards a softer FCC matrix occurs, leading to a decrease in the yield strength while enhancing its ductility.

Fractography analysis of tensile fractured surfaces could provide valuable insights about the failure mechanisms and mechanical behavior of the materials. Fig. 12 represents SEM fractographs of the tensile fractured samples. Fig. 12(a) and (b) show morphology of fractured surface of the alloy Al_1, which includes cleavage facets and river patterns without any slip marks such as dimples. The granular surface and absence of dimples indicate minimal plastic deformation prior to failure, resulting in brittle fracture. Fractography analysis of the alloy $Al_{0.8}$ sample revealed predominantly poor ductile behavior characterized by the presence of quasi-cleavage regions along with a very small number of dimples, as demonstrated in Fig. 12(c) and (d). With decrement in Al content, an increase in ductility was recorded during tensile deformation. Fractographs of alloys $Al_{0.75}$ (Fig. 12(e) and (f)), $Al_{0.7}$ (Fig. 12(g) and (h)) and $Al_{0.6}$ (Fig. 12(i) and (j)) revealed quasi-cleavage regions and dimples, indicating a mixed mode ductile-brittle fracture, revealing predominantly ductile fracture for the low Al content alloys. The dimples are less pronounced and less uniformly distributed in case of the alloy $Al_{0.7}$ compared to alloy $Al_{0.6}$. The well-defined dimples correspond to higher ductility and are indicative of higher energy absorption, which can be clearly observed from extensive plastic deformation marks along with more dimples for the alloys $Al_{0.7}$ and $Al_{0.6}$. Conversely, the absence of dimples and the prevalence of river-like patterns correlated well with insignificant ductility for the HEAs Al_1 and $Al_{0.8}$.