TechScape: The Science, Technology and Education Journal of IIT Jodhpur
Volume 01, Issue 03, August 2021

Damage Tolerant High Entropy Alloys: Technological Possibility for Sustainable Human Life

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Research Snippets

Introduction of metals to the mankind was a major breakthrough to levitate the human life by overcoming environmental as well as economical concerns. However, most of these metals either exhibit very high strength or exceptional ductility as a result of strength-ductility tradeoff. All the existing materials such as steels, Al alloys and Ti alloys which are getting frequently used in a day-to-day application display this inverse strength-ductility relation which result in sudden failures of these materials during service [1-2]. As a result, material designers worked in this direction so that a cost-effective strategy can be developed for realizing strong as well as ductile material for engineering applications to minimize/delay failures in them during service. This attempt gave birth to very advanced materials for the human community such as advanced high strength steels, Twinning/Transformation induced plasticity assisted steels, ultralight Mg-Al-Ca alloys and so on. However, they also exhibited strength-ductility dilemma though in a minimized way [1-2].

Continuous evolution in the alloy design research focusing on this everlasting issue in metallic materials led to discovery of all together new class of metallic alloys termed as High Entropy Alloys (HEAs). The entire effort of high entropy alloy (HEA) design was based on obtaining an alloy composition that have higher tensile strengths with greater elongations. Conventional materials failed to attain these unconventional properties; hence, the concept of the equiatomic addition of elements attracted researchers in a very short time span. Earlier work on equiatomic HEAs showed uncommon mechanical, wear and fatigue properties that were attributed mainly to the complex concentrated solid solutions formed (by suppressing brittle intermetallic compounds) in the material [2-3]. Further development in this field brought to the floor dual-phase non-equiatomic HEAs, that displayed extraordinary work hardening because of the synergistic activation of dislocation, transformation and twinning effects during deformation. An additional benefit of non-equiatomic HEA design was to devise a huge compositional space (away from the centre of the phase diagram) for developing new alloys which was not explored before. Therefore, researchers realized that, non-equiatomic HEA design approach will enable the material to deform with multiple deformation mechanisms at room temperature so that it will not only show higher strength but also work hardening ability which is necessary for having good ductility. Thus, various attempts were made towards this direction giving rise to various types of HEAs such as FeMnCoCrNi based equiatomic HEAs, AlxCoCrFeNi based, FeMnCoCr based and FeMnCoCrSi based non-equiatomic HEAs [2-4].

Recent work by Z. Li, D. Raabe and his Group [4] at Germany utilized the metastability of phases synergized with high entropy to tune the deformation mechanisms and thereby yield an extraordinary combination of strength and ductility for non-equiatomic dual-phase HEAs (DP-HEAs). Thus, they claimed that the material can be ductilized with steady increase in strength through sustained work hardening (WH) during deformation. Our work further elevated this effort by redefining the metastable dual-phase high entropy alloys (HEAs) design with a motive that they would exhibit properties of stainless steel, TRIP steel and electrical steel in synergy in a cost-effective manner. This was realized by adding light weight non-transition element Si into Fe-Mn-Co-Cr matrix with further alteration with minor additions of Cu and Al. The alloy chemistry in combination with friction stir processing, showed an excellent combination of strength, ductility and corrosion resistance and concurred the conventional strength-ductility tradeoff as shown in Figs. 1 (a-e) [1-8]. We attributed these unconventional properties of these HEAs to the adaptive phase evolution in them leading to optimum grain and phase proportions of ï’-f.c.c. and Îµ-h.c.p. phases in the microstructures with varying alloy chemistry (Figs. 1 (a-d)) as well as processing conditions (Fig. 1). This adaptive phase stability not only promoted the flexibility in microstructural evolution but also empowered the material in selection of multiple deformation mechanisms for attaining good plasticity at room temperature [5-10].

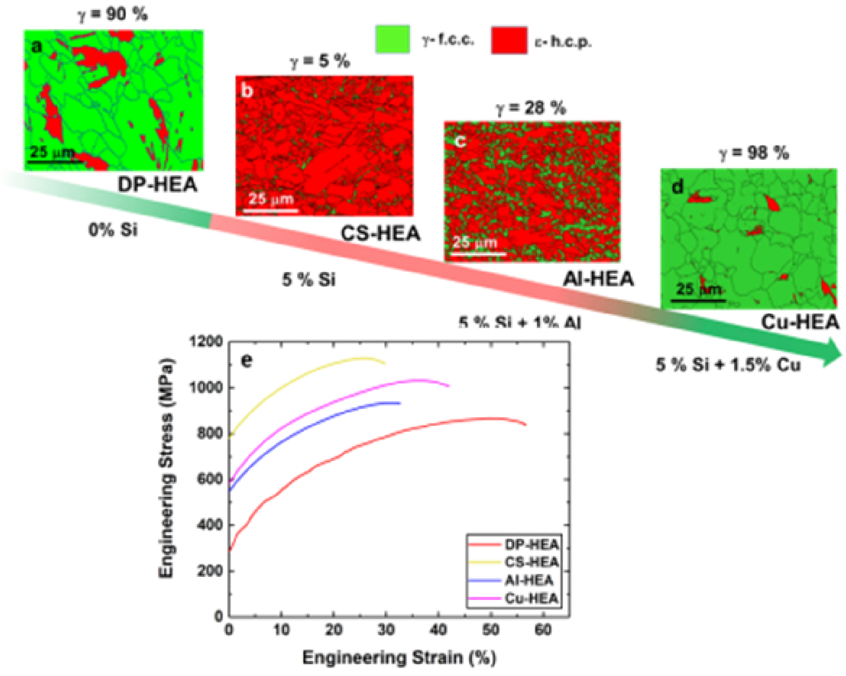

Fig. 1: (a-d) Design of microstructurally flexible high Entropy alloys namely, $Fe_{50}Mn_{30}Co_{10}Cr_{10}$ (DP-HEA), $Fe_{40}Mn_{20}Co_{20}Cr_{15}Si_5$ (CS-HEA), $Fe_{39}Mn_{20}Co_{20}Cr_{15}Si_5Al_1$ (Al-HEA) and $Fe_{38.5}Mn_{20}Co_{20}Cr_{15}Si_5Cu_{1.5}$ (Cu-HEA). (All elemental content is in atomic %), (e) Tensile properties of all these HEA after perfoming friction stir processing at 350 rotations per minute (RPM) [5].

Moreover, we found that these materials exhibited extremely high resistance to failure under cyclic loading due to localized ï’â†’ Îµ transformation within the crack tip plastic zone which delayed the crack propagation and improved the fatigue life. This controlled transformation activity was mainly attributed to the engineered ï□§ matrix stability and stress concentration within the crack tip plastic zone. Fig.2 (a) display the dramatically improved fatigue endurance limit of the $Fe_{38.5}Mn_{20}Co_{20}Cr_{15}Si_5Cu_{1.5}$ HEA whereas Fig. 2 (b) display the localized ï’â†’ Îµ transformation near the fatigue crack tip in the interrupted fatigue specimen of the same HEA in electron back scattered diffraction (EBSD) phase map (Figs 2 b_1-b_3). Fig. 2 (c-c_1) clearly indicates the crack path deviation supporting the region-specific plastic deformation during fatigue deformation by dual phase strengthening within the crack tip plastic zone [11].

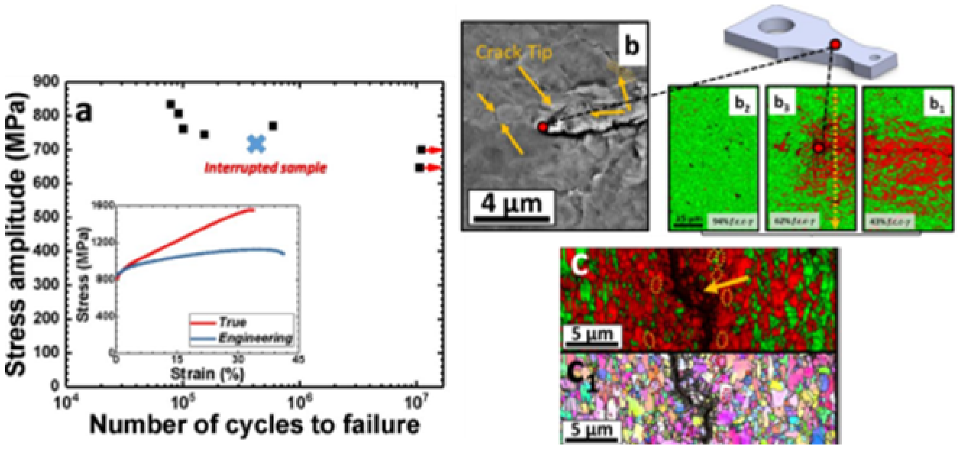

Fig. 2: (a) S-N curve for ultrafine grained $Fe_{38.5}Mn_{20}Co_{20}Cr_{15}Si_5Cu_{1.5}$ HEA, (b) EBSD image quality, and (b_1-b_3) phase map showing localizedï’ â†’ Îµ transformation near the fatigue crack tip, (c) EBSD phase, and (c1) IPF map showing crack path deviation [11].

I am currently working towards correlating this metastable HEA design approach with the defects inherently present in the material for realizing new damage tolerant materials. All the metallic materials inherently contain defects which are known to be sites for local stress concentration. In metastable HEAs, this local variation in stress near the defects can additionally activate ï’ â†’ Îµ transformation based on the tuned metastability of the matrix phase. As a result, this localized phase transformation would deviate the crack path due to increased strength of the region via plastic deformation ahead of the crack front. This crack path deviation can cause crack branching at the crack front during the propagation which can further delay the overall fracture in the material. Therefore, this minor increase in plasticity before failure due to the presence of peculiar type of defects in these metastable HEAs is termed as defect induced plasticity (DIP). This DIP effect in these metastable HEAs not only enhances the damage tolerance of the material but also delays the sudden failures in materials like Fatigue. This work thus will involve synergistic research done by mechanical engineering, computational materials and metallurgical community such that a new material can be designed in a most effective way. Further, this work can be easily extended to metal additive manufacturing research since defects are inherently present in all 3D printed products and hence limit their usability in engineering applications.

In summary, DIP effect in metastable HEAs gives the benefit to utilize defects (which are considered as detrimental sites for failure in conventional materials) for improving their failure resistance in engineering applications for sustainable human life.

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