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Fracture resistance of high entropy alloys: A review☆

Weidong Li[a,b,*], Peter K. Liaw[b], Yanfei Gao[b,c,**]

[a] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan, 430070, China
[b] Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN, 37996, USA
[c] Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA

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ABSTRACT

Fascinated by the exceptional mechanical properties of high entropy alloys (HEAs), unremitting endeavors are placed on accelerating their engineering applications in multiple critical fields. As all other structural materials, attaining sufficient fracture resistance is a vital requirement for HEAs, particularly for safety critical applications. Along this line, the fracture resistance of a number of HEAs and medium-entropy alloys (MEAs) had been studied in the past decade. While some exhibit unprecedented fracture toughness akin to the toughest materials ever known, others are just alike brittle materials. Herein, we summarize one decade of investigations of the fracture resistance of HEAs and MEAs, including the characterization of fracture toughness, disclosure of fractographic characteristics, and understanding of fracture micro-mechanisms. The role of alloy composition, temperature, phase constituent, and characterization techniques in altering the fracture toughness are discussed; characteristics of the cleavage and shear fractures are detailed; toughening and weakening mechanisms, from the atomic to the defect level, are reviewed. In the end, some key questions are raised, and the directions for future research are suggested.

1. Introduction

Fracture is a problem that our society faces daily in engineered structural or even non-structural components and materials. Historically, human beings have paid huge costs for disasters caused by unpredicted fracture events [1]. Today, the same stories are being repeated or becoming even worse with evolving technological complexity, despite that our knowledge in this area is much more enriched. Materials can fracture in many different ways, depending on the microstructure, stress state, temperature, loading rate, etc. Broadly, they can be classified into brittle and ductile fracture on the basis of the strain to failure [2]. Brittle fracture usually happens in a catastrophic manner, with no evidence of plastic deformation, and therefore is more of a concern in practice. Ductile fracture, on the other hand, is favorable by triggering appreciable plastic deformation to blunt the crack tip and thus to postpone failure. Nevertheless, strain is not the only factor determining the fracture resistance of a material. It is also closely related to strength. For instance, a material with a high failure strain but extremely low strength may be more prone to fracture than a material with low failure strain but extremely high strength. By fusing the effect from both the strain and strength, the fracture resistance of a material is more meaningfully quantified by the fracture toughness, K_{IC} or J_{IC} [1]. Materials that fail in a "brittle" manner usually has a fracture toughness of below 10 $\mathrm{MPa}\sqrt{\mathrm{m}}$, whereas the value for those "ductile fractured" materials could range from a few tens to hundreds [3–5]. All materials, prior to engineering applications, require extensive characterizations of their fracture resistance. Examples are found in traditional metals and alloys [1,6], superalloys [7–10], and metallic glasses [11–13], among many others.

As materials with superior performance are continuously being searched, a novel alloy concept, termed high entropy alloys (HEAs), is emerging as a new class of metallic materials, which has great potential in structural applications [14–17]. Various terminologies have been used, including concentrated alloys, multi-principle-element alloys, or others. Also derivative alloys such as medium entropy alloys (MEAs) are also widely studied together with the HEAs. Despite debates on the effect of high entropy of mixing, we still customarily denote all these above as HEAs. Very distinct from the conventional physical metallurgy

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* Corresponding author. State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan, 430070, China.
** Corresponding author. Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN, 37996, USA.
E-mail addresses: lei432378yu@gmail.com (W. Li), ygao7@utk.edu (Y. Gao).

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principle in which one or two principal metal elements are utilized for dictating the primary phase and properties, and minor alloying elements are added for modifying the properties towards the desired ones [18], HEAs are formulated by mixing five or more principal elements in equal or near-equal molar ratio [16,19]. This new alloy design strategy essentially shifts our exploration of new metallic materials from the corners and edges of phase diagrams to less exploited centers [19–22]. Interestingly, instead of forming multiple phases or intermetallic compounds as one may expect from the established wisdom, the metallurgy of multi-principal metal elements, in fact, could result in simple solid solution phases, such as face-centered-cubic (fcc), body-centered-cubic (bcc), or hexagonal-close-packed (hcp) structures [23–26]. The formed solid solution phases may be present as the sole phase in alloys or coexist with another to form dual-phase alloys [27–29]. Thermodynamically, the formation of these solid solutions is attributed to the stabilization effect posed by the high configurational entropy (thus the low Gibbs free energy) and sluggish cooperative diffusion [29,30], despite some disputes on the effectiveness of these two factors. Such a revolutionary alloy design strategy opens up enormous possibilities in terms of mechanical and functional properties of alloys by permitting extensive and flexible tuning of alloy compositions. One decade of dedicated research has revealed that many HEAs possess unparalleled properties in comparison with traditionally used alloys, for instance, great thermal and microstructural stability [31], high hardness [32,33], great strength at elevated temperatures [34,35], and excellent resistance to wear, corrosion, fatigue and high temperature softening [36–42]. Given these merits, the application of HEAs in different fields, particularly in the structural engineering (e.g., used for gas turbine engines), is being actively explored [42,43].

In addition to the above listed performance indices, it is also indispensable to gain a complete picture of the fracture resistance of HEAs in order to promote their sophisticated engineering applications. Since 2010s, a number of studies have been conducted to characterize the fracture resistance of various HEA systems and certain MEAs (e.g., $FeCoNiCrCuTiMoAlSiBe_{0.5}$, CrMnFeCoNi, AlCoCrCuFeNi, and CrCoNi (MEA)) [44–52]. The fracture toughness, K_{IC}, of the investigated alloys is found to vary from less than unity [52] to as high as exceeding 200 $\mathrm{MPa}\sqrt{\mathrm{m}}$ [46], depending not only on the composition but also on the phase constituent, temperature, and processing history [44,46,52]. Their fracture modes and underlying failure mechanisms also change from one type to another [45,46,48,49,53,54]. There is no doubt that more fracture resistance characterizations need to be done for pinpointing definite correlations between the fracture toughness and the factors mentioned above. As such, the advances in understanding the fracture behavior of HEAs in the past decade are summarized in this article, with a purpose of providing the directional guidance for future endeavors. The rest of the article is arranged as follows. The fracture toughness documented for varied HEAs is compiled and analyzed in Section 2, and compared with commercially used metals and alloys. In Section 3, different fracture modes are classified and surveyed, followed by unveiling the associated micormechanisms in Section 4. Summary and suggestions for future efforts are provided in Section 5.

2. Fracture toughness of HEAs and MEAs

Fracture toughness is a measure of the resistance of a material to crack extension under the action of loads. Fracture itself can take three basic modes and many possible combinations, but the majority of time that we care most about is the Mode I fracture, as it is the most frequent failure mode in practically used materials [55]. The Mode I fracture toughness can be investigated either quantitatively by the rigorous fracture mechanics methodology, e.g., K_{IC}, *K-R* curve, J_{IC}, and *J-R* curve, or qualitatively by the impact energy absorption, e.g., Charpy and Izod impact tests, and drop weight tests [1]. Measurements of the fracture toughness of HEAs have utilized K_{IC}, J_{IC}, and *J-R* testing in a quantitative sense and Charpy impact testing in a qualitative sense. In the following, the two different methodologies in measuring the fracture toughness of HEAs are discussed separately, given their intrinsic differences. The room temperature fracture toughness will be covered in Sections 2.1 and 2.2, and the temperature effect on the fracture toughness will be treated in Section 2.3. Finally in Section 2.4, the relation between the fracture toughness and the phase constituent will be discussed.

2.1. Quantitative measures

2.1.1. Fracture mechanics methods

When a material behaves in an approximately linear manner with the minimal plasticity prior to failure, from the fracture mechanics standpoint, the plastic zone around the crack tip is small compared to the specimen dimensions. In such a scenario, the fracture toughness of the material can be satisfactorily characterized with K_{IC}, the critical stress intensity factor at which the crack start growing [1]. K_{IC} can be determined by failing a pre-cracked specimen, following the ASTM (American Society for Testing and Materials) standard E399 [56]. Simply put, it is derived by first calculating the provisional fracture toughness, K_Q, followed by checking through the validity criteria. For the most widely used single edge notched bend (SENB) specimen in three point bending tests, K_Q is calculated as

$$K_Q = \frac{P_Q S}{BW^{1.5}} f\left(\frac{a}{W}\right), \tag{1}$$

where B, W, and S are the sample thickness, width, and span, respectively. a is the average crack length, which can be measured from the fracture surface. P_Q is the critical load determined from the recorded load-displacement curve, whose determination method varies among three different curve types [56]. $f\left(\frac{a}{W}\right)$ is a geometry dependent polynomial function that can be looked up from the standard [56].

In order to make the computed K_Q from Eq. (1) to be a valid K_{IC} and reflect the plan-strain fracture toughness of measured materials, it needs to pass a few validity checks, which include

$$0.45 \le \frac{a}{W} \le 0.5, \tag{2}$$

$$B,\ a \ge 2.5\left(\frac{K_Q}{\sigma_y}\right)^2, \tag{3}$$

$$P_{max} \le 1.1 P_Q, \tag{4}$$

where σ_y is the yield strength of materials, and P_{max} is the maximum load on a load-displacement curve.

With single edge-notched bend (SENB) specimens, Roy et al. [45] measured K_{IC} of the as-cast $Al_{23}Co_{15}Cr_{23}Cu_8Fe_{15}Ni_{15}$ HEAs with a bcc phase by strictly following the above procedure and reported an average fracture toughness value of 5.8 $\mathrm{MPa}\sqrt{\mathrm{m}}$. Meanwhile, they also conducted measurements on the same alloy with chevron notched rectangular bar (CVNRB) specimens and found a slightly lowered value of 5.4 $\mathrm{MPa}\sqrt{\mathrm{m}}$. The 7% measurement difference observed was attributed to the fact that the SENB specimens had not been fatigue pre-cracked, which was likely to increase the measured fracture toughness slightly due to the blunter crack tip in comparison with the CVNRB specimens. Chen et al. [51] attempted to follow the same standard to measure the fracture toughness of the as-cast $Al_{18}Cr_{21}Fe_{20}Co_{20}Ni_{21}$, $Al_{15.5}Cr_{22.25}Fe_{20}Co_{20}Ni_{22.25}$, and $Al_{13}Cr_{23.5}Fe_{20}Co_{20}Ni_{23.5}$ HEAs, which is composed of bcc, bcc + fcc, and fcc phase, respectively. The reported values are 9, 11, and 53 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for three alloys. It was thought that these measured values were true fracture toughness given that these three alloys exhibited “brittle” characteristics on the measured tensile stress-strain curves [51]. The validity check was not performed. A simple calculation with Eq. (3) and the documented data in Table 1 indicate that in order to make the measured values a valid K_{IC}, the sample thickness, B, and crack length, a, need to be greater than 0.58,