J. Amorphous and High Entropy Alloys: High Entropy Alloys I
Symposium organizers:
Weihua Wang, The Institute of Physics, Chinese Academy of Sciences, China; Zhaoping Lv, University of Science and Technology Beijing, China; Hidemi Kato, Tohoku University, Japan; Hojin Ryu, Korea Advanced Institute of Science and Technology (KAIST), Korea; Michael Ferry, New South Wales, Australia; Evan Ma, Johns Hopkins University, USA

Monday PM | Room: Room 303 (3rd Floor)
August 19, 2019 | Symposium: J

13:30-14:00 Keynote (1233780)
Self and Interdiffusion in High Entropy Alloys: What We Now Know
Irina Belova, Mohhamad Afikuzzaman, Graeme Murch, The University of Newcastle, Australia

High entropy alloys (HEAs) are a novel class of materials with many atomic components (between 5 and 13) at about equal compositions. One of the important properties of HEAs is slow mass diffusion. This should be vital for enhancing the apparent stability of HEAs as well as their high-temperature technological applications. In this overview, recent experimental and theoretical findings of diffusion in HEAs are presented and discussed. The discussion concentrates on the tracer (or self-) diffusion and inter-diffusion (quasi-binary diffusion couple technique in chemical gradients). The newly developed combination of the standard interdiffusion and radiotracer diffusion technique is also discussed. This technique allows for measurement of tracer diffusion as a function of composition in the interdiffusion sample.

From a theoretical point of view, the diffusion kinetics behaviour of the Onsager phenomenological transport coefficients, interdiffusion coefficients and tracer diffusion coefficients of atomic components in multicomponent alloys is discussed. These are investigated by extending and applying three classical diffusion kinetics approaches in the model case of fcc CoCrFeMnNi HEA. In the case of this alloy, the combined analysis of tracer diffusion coefficients with interdiffusion coefficients is also presented. Furthermore, extensive Kinetic Monte Carlo (KMC) simulation results are used for the testing of the possible interdiffusion composition profiles in a model HEA.

14:00-14:25 Invited (1219317)
Large-Area Synthesis of Freestanding Ultra-Thin Films of Complex Alloys: from Amorphous to High Entropy Alloys
Yong Yang, Tianyu Wang, City University of Hong Kong, China

In this talk, we would like to present a novel and facile method to synthesize freestanding ultra-thin films of complex alloys. This is done through a series of well controlled preparation of hydrogels which have a nanometer scale surface roughness and are bonded to silicon wafers within a carefully selected temperature-time window. Afterwards, metal films are deposited onto the hydrogels through inert gas condensation to form a metal-polymer multilayer, such that a cleave fracture can be triggered along the metal-hydrogel interface once the hydrogels are soaked in water for a limited period of time. The film thickness so obtained can be varied from nanometers to micrometers while the film width can span from a few hundred micrometers to a few centimeters. With the aid of finite element simulations, theoretical modeling and experiments, we also discuss the limitations of this method, focusing on the underlying mechanistic understanding of the interfacial fracture process, which is related to the combined effect of elastic mismatch and toughness of films, hydrogel and their interface. As a demonstration, we will present a few freestanding films of amorphous and high entropy alloys and briefly discuss their structures and basic mechanical properties. In principle, our methods can be extended to diverse materials systems, including molecular glasses, polymers and ceramics. On one hand, the freestanding thin films so obtained provide the model systems to understand the physical/chemical behavior of amorphous and high entropy alloys in a nearly two dimensional space, which is very useful to deepen our understanding of the longstanding issues, such as glass transition, mechanical size effect, surface effect, oxidation and corrosion, which has never been done before with freestanding films; on the other hand, the freestanding thin films could have extensive potential use in a variety of applications, ranging from optical devices, micro-electro-mechanical systems, lubrication and catalysts.

14:25-14:50 Invited (1235370)
Study on Thermodynamic Properties of High Entropy Alloys
Hiroshi Ohtani, Masanori Enoki, Tohoku University, Japan

The objective of the present study is to clarify the thermodynamic properties inherent to the high entropy alloys (HEA) by means of free energy calculations based on the first principles technique. For the
computational method, we employed the cluster variation method (CVM) in which the ordered structures of the base solid solution were divided into various clusters, and the interatomic energies for those clusters were evaluated using the cluster expansion method. The free energy at finite temperatures were calculated from the configurational entropy and internal energies. Understanding of the formation tendency for ordered structures is also significant in HEA, hence the stable structures in the ground state were calculated using the genetic algorithm. In this method, many random structures were generated from the component elements at the beginning. Then structural relaxation was performed on each structure using the first principles technique, and variation operators such as heredity, mutation, permutation, and so on were used to generate offspring from the stable structures. These calculations were repeated until the simulation reached the convergence criteria for the most stable structures. The calculated enthalpies of formation in the ternary and the quaternary systems constituting the Cr-Mn-Fe-Co-Ni alloy indicates that the interactions between neighboring atoms could be almost negligible. On the other hand, the mixing entropy was approximately equal to that of the complete disordered state. These results indicate that this alloy behaves as an ideal solution. Furthermore, the calculation by the genetic algorithm clarified that the formation of compound phases was restricted in each component ternary system. Some other evaluated alloys in which a solid solution appears at the equiatomic compositions showed the similar behavior to that of the Cr-Mn-Fe-Co-Ni alloy.

14:50-15:10 (1254149)
FCC to L12 Ordering Transformation in Equimolar FeCoNiV High-Entropy Alloy
Shubin Wang, Shihao Chen, Da Shu, Yongbing Dai, Baode Sun, Shanghai Jiao Tong University, China; Fuyang Tian, University of Science and Technology Beijing, China

The ordered L12 phase generally appears as dispersed precipitates in FCC high-entropy alloys. In this work, a single L12 ordered intermetallic is obtained in the annealed equimolar FeCoNiV solid solution alloy. Experiments show that the FCC to L12 ordering transformation occurs below 778°C, accompanied by lattice contraction, anti-phase boundaries formation and low-temperature magnetic moment decrease. The L12 ordered alloy exhibits strong linear strain hardening rate up to 5.0GPa during the tensile deformation at room temperature, meanwhile, keeps 20% tensile elongation, although the yield strength is not significantly changed. The ab initio calculations based on the exact muffin-tin orbitals in combination with coherent potential approximation (EMTO-CPA) predict that V atoms prefer to occupy the cubic corner sites of L12 sublattice, and the FCC phase becomes more stable with respect to L12 phase above 849°C considering the competition between enthalpy and entropy. The ab initio molecular dynamic simulations (AIMD) indicate that V atoms prefer to bond with the unlike atoms (Fe, Co and Ni) in liquid FeCoNiV, which is consistent with the cubic corner site occupation of V in L12 ordered structure. The present work demonstrates a new design strategy of high-entropy alloys which focus on single phase ductile intermetallic compounds.

15:10-15:30 (1232793)
Development of High Performance Co-Rich High Entropy Alloys
Daixiu Wei, Weicheng Heng, Yuichiro Koizumi, Hideki Kato, Akihiko Chiba, Tohoku University, Japan; Xiaoping Li, KTH-Royal Institute of Technology, Sweden; Won-Mi Choi, Byeong-Joo Lee, Hyoung Seop Kim, Pohan University of Science and Technology, Korea

Equiatomic FeCoCrNi high entropy alloys (HEAs) have attracted extensive academic interests. Recently, twinning-induced plasticity (TWIP) and transformation-induced plasticity assisted dual phase (TRIP-DP) non-equiatomic Fe-rich HEAs were developed, inspired by the plasticity and strengthening mechanisms in low stacking fault energy (SFE) metals and alloys. The two types of HEAs exhibit high tensile strengths and large elongations that overcome the strength-ductility trade-off. The low SFE of the alloys are gained from tuning the chemical compositions and concentrations. On the other hand, Co-based superalloys have been widely used in manufacturing vanes and metallic orthopedic implants, owing to the superior mechanical properties and corrosion resistance. Generally, the SFE of these alloys is extremely low, reaching negative values at room temperature for some compositions. In the present study, we designed novel Co-rich HEAs with manipulated mechanical properties and deformation behaviors by lowering the SFE and the fcc phase stability, achieved by adjusting the elemental concentrations of the equiatomic CoCrFeNi alloy. We adopted quaternary HEAs described as CoCr25(FeNi)x (x = 25, 35, 45, 55, 65). The Gibbs free energy difference between hcp phase and fcc phase of the various alloys, were calculated using Thermo-Calc software with the TCFE2000 thermodynamic database and its upgraded version. The generalized stacking fault energy of the alloys were calculated by ab initio calculations based on density functional theory (DFT) method, and the Kohl-Sham equations were solved using the exact muffin-tin orbitals method (EMTO). The results indicated that an increase in Co content leads to a decrease in fcc phase (γ phase) stability in the CoCr25(FeNi)x alloys. Moreover, γ phase is more stable at elevated temperatures whereas the hcp phase
(ε phase) tends to be more stable at lower temperatures. On the other hand, it was found that the Fe and Ni stabilize the γ phase in the alloys, and an independent reduction of Ni concentration or an increase in the Co concentration does significantly lower the SFE. Among the alloys, the Co35Cr25Fe20Ni20 and Co45Cr25Fe15Ni15 alloys with metastable single fcc phase possess superior combination of strength and ductility compared to other single fcc phase counterparts, contributing to the TWIP and TRIP effect, respectively. The findings here provide a feasible guideline for developing high performance HEAs.

15:30-16:10 Tea Break

16:10-16:35 Invited (1219561)

Effect of Co Content on the Mechanical Properties of A2 and B2 Phases in AlCoCrFeNi High-Entropy Alloys

Young-Sang Na, Ka-Ram Lim, Jong-Woo Won, Heoun-Jun Kwon, Korea Institute of Materials Science, Korea; MinJu Kang, Johns Hopkins University, USA

High entropy alloys are now offering new exploratory topics and strategies to physical metallurgist since the first announcement of its concept by B. Cantor and J.W.Yeh, separately. High entropy alloys are no longer limited to a single phase system even if it was first suggested that single solid solution like FCC-structured CoCrFeMnNi would be stabilized due to the high entropy effect. Actually, second phases like precipitate is regarded to be essential in metallic systems for strengthening. We dealt with dual-phase high entropy alloys with BCC structure, in this study.

AlCoCrFeNi-based high entropy alloys such as AlxCoCrFeNi, and AlCoCrFeNiTix have been studied as representative BCC HEAs. Despite their high strength and wear resistance, there are practical problems due to the high cost of the alloying elements. In particular, Co is more than six times as expensive as the other elements, and is becoming even more expensive with the growth of the secondary cell industry.

In this study, the effect of Co content on the strengths of the A2 and B2 phases in AlCoCrFeNi high entropy alloys was investigated. The strength of AlCoCrFeNi (x=0, 0.25, 0.5, 0.75, and i) was considerably reduced when the Co content was zero. This was attributed to the low hardness of the A2 phase due to reduced configurational entropy. On the other hand, the ordered B2 phase showed the opposite tendency. In summary, AlCoCrFeNi (x=0.25, 0.5, 0.75, and ii) high entropy alloys showed improved compressive properties as the Co content decreased; however, Co0 exhibited a large drop in yield strength. The subtraction of Co decreased the entropy of the A2 and B2 phases. Lower entropy resulted in the decreased and increased hardness of the disordered and ordered phases, respectively. This result shows that the configurational entropy causes opposing effects on disordered and ordered phases, and the importance of considering the effects of elements and entropy on each phase when an alloy is composed of two or more phases.

16:35-17:00 Invited(1234560)

Competition Between L12 and B2/L21 Precipitation in FCC Based High Entropy Alloys: Multi-scale Microstructures and Tuning Mechanical Properties

Rajarshi Banerjee, Sriswaroop Dasari, Bharat Gwalani, Talukder Alam, University of north texas, America; Yao-Jen Chang, An-Chou Yeh, National Tsinghua University, Taiwan, China; Stephane Gorsse, CNRS, ICMCB, UPR 9048, 33600 Pessac, France

Often the experimentally observed single phase high entropy alloy (HEA) is the result of second phase precipitation constrained by thermodynamic and kinetic factors. This raises some fundamental questions regarding the impact of thermo-mechanical processing on the phase transformation pathways in these HEAs. These pathways lead to different combinations of phases, at multiple length scales, within these alloys. This presentation will focus on investigating and rationalizing how such transformation pathways can dramatically alter the microstructure and mechanical properties in face-centered cubic (FCC) based HEAs. Example systems to be considered include FCC-based 3d transition series alloys, such as Al0.3CoCrFeNi, Al0.5Co1.5CrFeNi1.5, and Al0.2Ti0.3Co1.5CrFeNi1.5. All these alloys inherently exhibit a competition between the precipitation of different ordered intermetallic phases, such as the L12, B2, and L21, within the FCC solid solution matrix. The thermodynamic rationale underlying such competition is the complex interplay between the driving force and the nucleation barrier associated with each of these phases. This interplay will be investigated in detail as a function of different thermo-mechanical treatments, resulting in differences in the homogeneous versus heterogeneous nucleation of the intermetallic phases. The resultant microstructural diversity within the same HEA can lead to dramatically different mechanical properties, as aspect which can be used for tuning their properties for various applications.
High entropy alloys (HEAs) with face centered cubic (FCC) crystal structure have attracted broad scientific interests by showing excellent toughness at both room and cryogenic temperatures. Their yield strength, however, is too low for structural applications, and thus the precipitation-strengthening of FCC HEAs has been widely investigated. The L12 phase-strengthened HEAs keep good ductility but possess modest yield strength. The intermetallic particles lead to high yield strength but relatively bad ductility. Therefore, designing a better reinforcing phase is of great importance for precipitation-strengthened HEAs. In the present work, we demonstrated an overall valence electron concentration (OVEC) strategy to design reinforcing precipitates with excellent strengthening effect. A D022 phase-strengthened HEA has been developed by using the OVEC strategy. Nano-size lenticular precipitates with D022 structure were obtained in a novel Ni2CoCrFeNb0.15 HEA. Different from traditional Ni3Nb-type D022 phase, the current high-entropy D022 phase possesses an stoichiometry of (Ni,Co,Cr,Fe)3(Nb,Fe). TEM inspection indicated there are three different variants with crystallographic orientation relationships of [001]γ // <001>γ and (001)γ″ // {100}γ. The high-entropy D022 phase showed excellent strengthening effect. A small volume fraction of D022 phase (~7%) caused an increase of 670MPa in yield strength, resulting superior yield strength-ductility combination among precipitation-strengthened HEAs. The superb strengthening effect of D022 phase was attributed to the combination of ordering strengthening and coherency strengthening. Our results provided a convenient strategy to design reinforcing phase for HEAs and developed a promising D022-strengthened HEA for structural applications. These findings will not only benefit the development of precipitation-hardened HEAs but deepen the fundamentals of the precipitates design for other complex concentrated alloys as well.
Effects of Al Addition on Hot Deformation Behavior and Processing Maps of CoCrFeMnNi High Entropy Alloy

Hee-Tae Jeong, Woo-Jin Kim, Hongik university, Korea; Hyung-Ki Park, Kwangsuk Park, Tae-Wook Na, Korea Institute of Industrial Technology, Korea

The high-temperature deformation mechanism and processing maps of cast Al0.5CoCrFeMnNi that comprises FCC and BCC phases (where BCC phase is a minor phase) were studied at temperatures in the range of 1023 to 1323K and at strain rates in the range of 10s⁻³ to 10¹s⁻¹. During hot compression, the hard BCC phase provided nucleation sites for dynamically recrystallized (DRXed) grains in the soft FCC matrix through particle stimulated nucleation (PSN). Continuous dynamic recrystallization (CDRX) simultaneously occurred with the PSN-induced DRX. As a result, the fraction of DRXed grains was notably higher and the size of the DRXed grain size was considerably smaller in Al0.5CoCrFeMnNi than those in CoCrFeMnNi with a single FCC phase. The effect of the BCC phase on the fraction of DRXed grains was especially pronounced at high strain rates (10s⁻¹), which is important for the practical use of cast Al0.5CoCrFeMnNi in the hot-working industry. Solute drag creep appeared at low strain rates and at high temperatures as the rate-controlling deformation mechanism due to the presence of Al solutes in the FCC matrix. The activation energy for plastic flow associated with solute drag creep was measured to be 251kJ/mole. This value most likely represents the activation energy for the interdiffusivity of aluminum solutes in Al0.5CoCrFeMnNi. The solute drag creep behavior could be predicted by the Weertman model, indicating that AlCoCrFeMnNi behaves similar to a typical class I solid solution metal alloy.

By adding aluminum to CoCrFeMnNi, the hot workability was greatly improved, according to the processing maps and microstructure analysis. The power dissipation efficiency was increased, and the flow instability regime decreased in size. The instability disappeared at 10s⁻¹ and at 1323K in Al0.5CoCrFeMnNi, agreeing with the microstructural evidence for the occurrence of a considerable extent of DRX at the corresponding condition.
Ten Surprises Confronting Dislocations in High Entropy Alloys

Evan Ma, Qingjie Li, Johns Hopkins University, USA

We present the first atomistic simulations, employing a realistic interatomic potential for the NiCoCr model system, to reveal unusual dislocation behavior in high-entropy alloys. We have found that these high entropy alloys are indeed different from the familiar (such as FCC) metals and solid solutions, in terms of the ruggedness of the energy landscape that governs dislocation activities. These lead to 10 new features, including low and variable stacking fault energy, local anti-phase boundary energy in the absence of a sublattice, difficulty in twin widening, slip localization resulting in "planar slip", wavy dislocation lines, intermittent nanoscale segment detrapping, small activation volume, elevated activation barrier, elevated lattice friction (mechanical strength), and increased temperature and strain rate sensitivity. We show how these new and puzzling options facing dislocations affect the selection of dislocation pathways in slip, faulting, twinning, and martensitic transformation, resulting in behaviors unexpected for conventional FCC metals. We also illustrate how the variation in local environments due to concentrated compositions necessitates a new mechanism for dislocation motion, strengthening the high entropy alloy. All these open a vast playground not accessible to traditional metals and ground-state intermetallics, making HEAs a wonderland for dislocations (and other defects), with rich opportunities to tune mechanical (and possibly transport) properties.
High entropy alloys (HEAs) are chemically complex single- or multi-phase alloys with crystal structures. There are no major components but five or more elements are included with near equiatomic fraction. In such a situation, deformation behavior can no longer be described by conventional solid solution strengthening model. Some HEAs, indeed, show higher strengthening behavior and anomalous slip. However, the mechanisms of these features have yet to be understood. Dislocation structure and motion should be the key to identify the unique feature of mechanical properties of HEAs. In the present study, we investigate the core structure of dislocations in BCC-HEAs using density functional theory (DFT) calculations. Special quasirandom structures (SQS) scheme was employed to construct randomly-distributed five-component MoNbTaVW HEAs with equiatomic fraction. Here, MoNbTaVW alloy is one of the most stable BCC-phase HEAs, and has been actually confirmed by experiments. Dislocation quadrupolar was inserted into the perfect SQS models. DFT calculations were then carried out to obtain stable configuration after fully relaxation. We found that core structure of a screw dislocation is identified as is the case with common BCC metals. On the other hand, dislocation motion should be different from pure BCC metals because of chemical and configurational disorder around dislocation core. We confirmed the specific feature of dislocation motion in HEAs by two-dimensional Peierls potential surface.

First-Principles Predictions of Dislocation Motion in High-Entropy Alloys
Tomohito Tsuru, Mitsushiro Itakura, Japan Atomic Energy Agency, Japan; Koretaka Yuge, Kyoto University, Japan; Yoshiteru Aoyagi, Momoji Kubo, Tohoku University, Japan; Tomotsugu Shimokawa, Kanazawa University, Japan; Shigenobu Ogata, Osaka University, Japan

10:10-10:30(1233837)
Compositional Design of novel High-Entropy Alloys with Enhanced Strength and Plasticity
Rong Guo, Lin Liu, Huazhong University of Science and Technology, China

The improvement in plasticity is usually compensated by the reduction of strength in structural materials, which is a long-standing conflict referred as the strength- plasticity trade-off. In recent years, a new type of structural materials of high-entropy alloys (HEAs) with equiatomic or near-equatomic concentrations have attracted increasing attention due to their unique mechanical and physical properties. However, HEAs with BCC structure exhibit high strength but low plasticity, while the HEAs with FCC structure show inversely high plasticity and low strength. The formation of the complex structures (i.e,
High-entropy alloy (HEA) has attracted increasing attention since it was first proposed due to its unique characteristics and great application potential. Unlike the traditional phase rule, HEA composed of four or more metallic elements forms a single-phase solid solution (SSS) with unordered atom occupation. The unique structure of HEA results in some special performances, such as a low diffusion coefficient, high irradiation resistance, and excellent mechanical properties at extreme environment including low temperature, high temperature and high strain rate. However, the application of HEA is still restricted by the trade-off between strength and ductility, which is the most common dilemma for structural materials. To meet the demand for high strength and ductility, the metastability engineering strategy, which has been widely used in high-Mn steels and titanium alloys, has been used for HEAs. According to metastability engineering strategy, the high-temperature structure of HEAs is destabilized to promote strain-induced transformation. The process of strain-induced transformation results in the uniform plastic deformation by delaying the onset of necking and releasing internal stress and the occurrence of the transformation-induced plasticity (TRIP) effect. Furthermore, the strength of HEA will be significantly enhanced by co-contribution from the interface hardening from the dual phases and the transformation hardening from the metastability (named as transformation-induced strength, TRIS). This combined increase in strength and ductility provides a useful guide for designing HEA and other structural materials.

However, all of the reported TRIP-HEAs are dual-phase alloys to date, which limits the popularization of the metastability engineering strategy. It is possible for strain-induced transformation and then the TRIP effect to occur in single-phase HEA via strain-induced element diffusion. When element diffusion occurs during loading, element segregation and dual-phase microstructures will form in the original metastable single-phase HEA. Thus, the strain-induced transformation and TRIP effect can be facilitated as continuous load is applied. Alternatively, it is possible that a fracture has generated along a brittle region before the TRIP effect works in the HEA composed of ductile and brittle phases. This risk can be avoided in TRIP single-phase HEA. Moreover, the elemental fluctuation caused by element diffusion may result in coherent nano-precipitation, which increases strength without ductility loss. Therefore, it is significant to explore the novel HEA with the SSS structure and TRIP effect.

In this work, a BCC-based AlCoCrFeTi0.5 high-entropy alloy (HEA) was modified by the addition of a certain amount of Ni, the FCC stabilizer, to improve the plasticity. The new HEAs have the composition of AlCoCrFeTi0.5Nix (x=0~3mol%), which were prepared by arc melting following by copper mold casting. The effect of Ni concentration on the microstructures and mechanical properties of AlCoCrFeTi0.5Nix alloys were systematically studied. The result shows that Ni element has the capacity to induce phase transformation from BCC phase containing brittle ordered B2 to FCC phase containing ductile ordered L12 nano-precipitates as the Ni concentration increased from 0mol% to 3mol%. A good combination of strength and plasticity was achieved for the HEA with an optimizing Ni content of 2.5mol%, which has the yield strength of 1.4GPa and compressive plastic strain of 42.7%. The mechanism for the improvement of plasticity of the HEAs is discussed.

10:45-11:05 (1220424)
Novel Metastable Engineering in Single-Phase High-Entropy Alloy
Ruixin Wang, Yu Tang, Shun Li, Hong Zhang, Yuanlin Ai, Shuxin Bai, National University of Defense Technology, China

High-entropy alloy (HEA) has attracted increasing attention since it was first proposed due to its unique characteristics and great application potential. Unlike the traditional phase rule, HEA composed of four or more metallic elements forms a single-phase solid solution (SSS) with unordered atom occupation. The unique structure of HEA results in some special performances, such as a low diffusion coefficient, high irradiation resistance, and excellent mechanical properties at extreme environment including low temperature, high temperature and high strain rate. However, the application of HEA is still restricted by the trade-off between strength and ductility, which is the most common dilemma for structural materials. To meet the demand for high strength and ductility, the metastability engineering strategy, which has been widely used in high-Mn steels and titanium alloys, has been used for HEAs. According to metastability engineering strategy, the high-temperature structure of HEAs is destabilized to promote strain-induced transformation. The process of strain-induced transformation results in the uniform plastic deformation by delaying the onset of necking and releasing internal stress and the occurrence of the transformation-induced plasticity (TRIP) effect. Furthermore, the strength of HEA will be significantly enhanced by co-contribution from the interface hardening from the dual phases and the transformation hardening from the metastability (named as transformation-induced strength, TRIS). This combined increase in strength and ductility provides a useful guide for designing HEA and other structural materials.

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Microstructure and Tensile Mechanical Properties of a CoCrFeNiMn High Entropy Alloy with Secondary Phase Nano-Particles Produced by Powder Metallurgy

Jiamiao Liang, Yuehuang Xie, Jun Wang, Shanghai Jiao Tong University, China; Deliang Zhang, Northeastern University, China

A CoCrFeNiMn high entropy alloy with secondary nano-particles was successfully synthesized by high energy mechanical milling (HEMM) followed by spark plasma sintering (SPS) and hot extrusion (HE). HEMM led to the mechanical alloying of the powders and the formation of a dual phase microstructure including BCC phase and FCC phase in the as-milled powders, and it transformed into a single FCC phase after SPS. Meanwhile, Cr-rich M23C6 carbide particles and spinel (Cr, Mn)3O4 oxide particles were formed during sintering and it transformed into a single FCC phase after SPS. The carbide particles with sizes of 350~550nm were much larger than the oxide particles with sizes of 30~60nm. The as-synthesized alloy exhibited a bimodal microstructure consisting of larger equiaxed grains with sizes of 900~1200nm distributed at the prior powder particles. This alloy had an average yield strength and ultimate tensile strength of 1272 and 1288MPa respectively which are clearly higher than those of most of the CoCrFeNiMn high entropy alloys reported in the literatures. The further improvement of tensile strength was achieved by reducing the grain size. It can be found that the significant refinement of grains lead to a yield drop phenomenon and the critical size to maintain uniform elongation is about 500nm. Intragranular particles may pin dislocations and improve ductility while intergranular particles may have an opposite effect. The analysis of the strengthening mechanisms demonstrated that grain boundary strengthening and Orowan strengthening play a major role in strengthening.

Design of Dual-Phase Refractory High Entropy Alloy

Hosun Jun, Pyuck-Pa Choi, Korea Advanced Institute of Science and Engineering, Korea

Refractory high entropy alloys (HEAs) have received great attention due to their high-temperature mechanical properties (e.g., strength and creep resistance) and hence the potential to be the next generation high-temperature alloys for key engineering applications. It was recently found that Al additions to refractory HEAs with BCC structure could result in a dual-phase B2/BCC microstructure. While most reported B2/BCC refractory HEAs have a brittle B2 matrix with discontinuous BCC precipitates, fabricating refractory HEAs with a ductile BCC matrix and coherent hard B2 precipitates is expected to increase creep resistance at elevated temperatures due to a precipitation hardening effect. In the present study, refractory HEAs with a microstructure consisting of BCC matrix and B2 precipitates were designed by a novel approach of mixing two alloys, namely Ti-25at.\% Nb and HfAl. Their mixing ratio...
was controlled to form a supersaturated solution after homogenization and induce phase separation during the ageing treatments. Ageing temperature and time were altered for systematical studies of elemental partitioning behavior.

The microstructure of the newly designed alloys after heat treatment were studied by multiple characterization techniques including X-ray diffraction, transmission electron microscopy (TEM), and atom probe tomography (APT). TEM and APT characterization showed that refractory HEAs with a BCC matrix and coherent B2 nanoprecipitates of 2~3nm in size could indeed be successfully fabricated.
J. Amorphous and High Entropy Alloys: High Entropy Alloys III
Symposium Organizers:
Weihua Wang, The Institute of Physics, Chinese Academy of Sciences, China; Zhaooping Lv, University of Science and Technology Beijing, China; Hidemi Kato, Tohoku University, Japan; Hojin Ryu, Korea Advanced Institute of Science and Technology (KAIST), Korea; Michael Ferry, New South Wales, Australia; Evan Ma, Johns Hopkins University, USA
Tuesday PM Room: Room 303 (3rd Floor)
August 20, 2019

Chairs:
Xinwang Liu, Huazhong University of Science and Technology, China
Koichi Tsuchiya, National Institute for Materials Science, Kobe University, Japan

13:30-14:00 Keynote (1236045)
Microstructure Control in fcc high entropy alloys - SPD and Phase Transformation
Koichi Tsuchiya, Jian Qiang, Jein Lee, Ivan Guitierrez, Toshiji Mukai, Kobe University, Japan

High entropy alloys (HEAs) exhibit various attractive properties, such as pronounced work hardening and enhanced ductility at cryogenic temperatures, high fracture toughness, high fatigue resistance as well as the creep resistance comparable to nickel-base superalloys. The present talk will focus on fundamental metallurgical aspects of fcc-HEAs, such as i) nanostructure formation by severe plastic deformation (SPD), and ii) effect of stacking fault energy on phase transformation and mechanical properties.

Nanostructure formation by SPD: SPD by high-pressure torsion (HPT) was applied to an Al0.3CoCrMnNi alloy. After 3 rotations of HPT, grains were refined to about 50nm. Micro-Vickers hardness indicated high-work hardening rate compared to conventional fcc metals. Formation of fine lamellar structures by twinning or shear bands may be the key for the nano-scale grain formation. Process of nanograin formation will be compared with other low SFE materials.

Design of fcc HEA with improved strength-ductility balance: It has been demonstrated that CrCoNi HEA has improved strength at 77K over CrMnFeCoNi due to the formation of nanotwin-HCP lamellar. This suggests the possibility to further improve the low temperature toughness by controlling stacking fault energy (SFE) or relative phase stability of fcc and hcp phases. CALPHAD simulation revealed that FCC phase is stable in the Cr20Mn20Fe20Co40-xNi system and Gibbs free energy difference between HCP and FCC phases (ΔGHCP-FCC) decreases as the Ni content decreases, indicating the reduction of SFE. The improved mechanical properties were attributed to the deformation-induced twinning or phase transformation as seen in other low SFE alloys such as TWIP/TRIP steels.

14:00-14:25 Invited(1235260)
Thermophysical Properties of Hexabasic AlxCoCrCuFeNi HEAs
Weili Wang, LiJun Meng, Bingbo Wei, Northwestern Polytechnical University, China

The hexabasic AlxCoCrCuFeNi (x=0.25, 0.5, 1, 2) HEAs were produced by doping the different mole fractions of Al element into the quinary CoCrCuFeNi alloy. The liquidus temperatures decrease with the increase of the Al mole fraction, here the Al mole fractions are less than 2. Once the Al mole fraction attains 2, the liquidus temperature increases rapidly and achieves 1659K. The analyzing of the solidified microstructures show that there are two kinds of phases at the different HEAs: a major high-entropy FCC phase together with a minor interdendritic Cu-rich FCC phase in the AlxCoCrCuFeNi (x=0.25, 0.5) HEAs, and a major high-entropy BCC phase and minor interdendritic Cu-rich phase in the AlxCoCrCuFeNi (x=1, 2) HEAs. The phase composition analysis shows that the elemental contents in high entropy phase have a curtain regularity and close to the original composition of HEAs for the AlxCoCrCuFeNi (x=0.25, 0.5, 2) HEAs, but the elemental contents in the AlxCoCrCuFeNi HEA have the higher random where the Cr and Fe contents exceed the original composition. The relationships of the density and Vickers hardness display the opposite feature that the higher density has the lower Vickers hardness, meanwhile the FCC crystal has the lower Vickers hardness, and the BCC crystal has the higher Vickers hardness. Otherwise, the higher Al mole fraction in HEAs, the higher Vickers hardness and the lower density. The enthalpy and entropy of fusion, element segregation and lattice distortion affect the thermal diffusion coefficient in these HEAs. Otherwise, the enthalpy and entropy of fusion, crystal structure, lattice vibration and elemental segregation have the common effect on the thermal expansion coefficient.

14:25-14:45(1220596)
Columnar to Equiaxed Transition and Grain Refinement of Cast CrFeCoNi High-Entropy Alloys
Xinwang Liu, Lei Liu, Zitian Fan, Huazhong University of Science and Technology, China; Gang Liu, Xi’an University of Technology, China; Easo George, University of Tennessee, USA

High-entropy alloys (HEAs) based on the CrMnFeCoNi system have attracted extensive attention during the
last decade and a half due to their excellent properties. Thermomechanical processing has been used to control the grain size/shape of the alloys and obtain excellent strength and ductility. However, in the cast state, the HEAs in many cases show coarse and anisotropic columnar grains, resulting in inferior mechanical properties. Although there is an extensive literature on grain refinement of dilute alloys (mainly based on binary systems), systematic studies of multi-principal-element alloys (MPEAs) are lacking. Due to their large number of constituent element (solute) species and their high concentrations, the solute effects linked to grain growth are different from those of dilute alloys, e.g., Al, Mg and Fe alloys. The solute effect has been considered to be the most important factor in most approaches of grain refinement. Here, we focus on solute effects on the columnar to equiaxed transition and grain refinement of the MPEAs, which involves the effect of the constituent elements themselves as well as those of externally added alloying elements, and further the interaction between solutes. The grain-refinement parameter related to the constituent undercooling induced by solutes was established for multicomponent alloys first. Then the CrFeCoNi system and its subsets were selected as model alloys to verify the applicability of the grain-refinement parameters by experiments. Based on these studies, several external solutes were high-throughput screened to predict and further verify the grain refinement effect. In the solute interaction paradigm, in addition to their individual effects, the strong mutual affinity between solutes rejected in front of the solid-liquid interface is utilized to restrict diffusion and facilitate constitutional undercooling to achieve finer grains. The results show that grain refinement leads to not only remarkable strengthening of the CrFeCoNi HEAs but also improvement of their isotropy (grain shape), which is significant for engineering applications.

14:45-15:05(1220416)
Dynamic Mechanical Behavior and Microstructure Revolution of NbZrTiTa High-Entropy Alloy
Yu Tang, Ruixin Wang, Shun Li, Yuanlin Ai, Shuxin Bai, National University of Defense Technology, China

In recent years, high-entropy alloy (HEA), a novel design concept, has become a hotpot of metal and structural material due to the unique structure and characteristics. Unlike the traditional alloy design strategy and phase rule, HEA, which is composed of more than four elements, will form a simple solid solution structure with unordered atom occupation, and then HEA exhibits excellent properties including high corrosion resistance, high irradiation resistance, and excellent mechanical properties at extreme conditions, such as high temperature, low temperature and dynamic loading. As most structural materials, HEA faces with the dilemma trading off between strength and ductility. Hence, the metastability engineering strategy, which has been widely used in high-Mn steels and titanium alloys, was introduced in HEAs. According to the metastability engineering strategy of HEA, the high-temperature structure of HEA is metastable, and the strain-induced transformation will be promoted during loading. The process of strain-induced transformation results in the uniform plastic deformation by delaying the onset of necking and releasing internal stress and the occurrence of the transformation-induced plasticity (TRIP) effect. Furthermore, the strength of HEA will be significantly enhanced by co-contribution from the interface hardening from the dual phases and the transformation hardening from the metastability (named as transformation-induced strength, TRIS). This combined increase in strength and ductility provides a useful guide for designing HEA.

In fact, the metastability engineering strategy has been successfully applied into the brittle refractory high-entropy alloy (RHEA), which was proposed as high-temperature structural materials. Huang and coworkers destabilized the high-temperature body-centered cubic (BCC) phase via reducing the Ta content in TaxHfZrTi system, which promotes the TRIP effect and work-hardening capability. Recently, Wang further explored the application of the TRIP effect in single-phase RHEA. As reported, in the NbZrTiTa RHEA with the single solid solution structure and uniform element distribution, two regions with different composition and phase stability forms during loading, due to the dislocation pipe diffusion and the low compatibility of elements. The increasing Ti and Zr content reduces the stability of BCC structure and leads to in-situ structure transformation in the TiZr-rich region. The co-contribution of various metastable-induced mechanisms distinguishes the strength and ductility of NbZrTiTa from those of all the reported refractory systems. Moreover, the risk that fracture has generated along brittle region in the HEA composed of ductile and brittle phases before the TRIP effect works could be effectively avoided in TRIP single-phase HEA. However, there is still more work to do for the application of TRIP HEA. For example, the structural materials bear not only static but also dynamic loads during service. It is known that the mechanical behavior of materials under dynamic loading is quite different from that under quasi-static conditions. During dynamic loading, the deformation mechanism is no longer limited to dislocation movement, other mechanisms, such as twinning and grain refining, will take part in too. Moreover, under high strain rate loading, the strain rate hardening effect, thermal soft effect, and adiabatic shear phenomenon also contribute to the deformation. Therefore, it is significant to study the mechanical behavior and the microstructure evolution of RHEA and explore the availability of metastability engineering strategy under dynamic conditions. But, there are only
two reports concerning the dynamic mechanical behavior of RHEA. In Ti20Hf20Zr20Ta20Nb20 system, the yield strength increases with increasing strain rate and the high dislocation density mainly results in the high flow stress at high strain rates. For the TRIP HfZrTiTa0.53 RHEA, although the TRIP and TRIS effects lead to great quasi-static mechanical properties, the appearance of thermoplastic instability and adiabatic shear band make the fracture strength and strain are just 1570MPa and 12.1% respectively under 2200s⁻¹.

In this work, the TRIP NbZrTiTa RHEA with the excellent quasi-static mechanical properties was selected. Its mechanical behavior and the microstructure evolution during dynamic compressions in a wide range of strain rates (10⁻³~10⁴s⁻¹) were systematically investigated. The deformation and strengthening mechanisms were revealed. Results showed that, at low and medium strain rate, the strength increased while ductility decreased resulting from the strain rate effect. However, at high strain rate, the strength and ductility increased simultaneously as a result of the co-contribution from TRIP effect, TRIS effect and grain refinement. On the other hand, the uniform microstructure and deformation of NbZrTiTa alloy could effectively delay the generation of adiabatic shear band. The adiabatic shear band occurs at a high strain rate of 5200s⁻¹, which is higher than those of other reported RHEA systems and conventional alloy. The true strain of NbZrTiTa at 6500 s⁻1 is greater than 103%, indicating a great potential for the application at high strain rate condition.

15:05-15:25(1235250)

Novel MoxNbTaxTiZr Medium and High Entropy Alloys for Biomedical Implants-A Systematic Approach to Get a Combination of Mechanical Properties

Muhammad Akmal, Ho Jin Ryu, Korea Advanced Institute of Science and Technology (KAIST), Korea

In this research work, MoxNbTaxTiZr (x=0-1) medium and high entropy alloys have been investigated systematically in order to find an optimum alloy for biomedical implants. The arc melted alloys, homogenized at 1400oC, have shown single-phase (bcc1) with a lower amount of Mo and Ta i.e., up to 0.6 molar fraction; however, higher content of Mo and Ta led another bcc phase appears named as bcc2. A logarithmic increase in the yield strength is observed as a function of Mo and Ta content because of immense solid solution strengthening imparted with the addition of Mo and Ta. Mo has the highest value of shear modulus and smallest atomic size among all other elements, hence it is most responsible for solid solution strengthening. Nonetheless, higher content of Mo and Ta incorporated the brittleness in the alloy. A linear increase in elastic modulus with respect to Mo and Ta was evaluated by using nano-indentation results. Potentiodynamic polarization results of all the compositions have shown tremendous passivation in the phosphate buffer solution. An excellent combination of strength, ductility, and elastic modulus was achieved in Mo0.2NbTa0.2TiZr alloy with strength reaching 1200MPa, plastic strain more than 30% under compression and elastic modulus close to 110GPa. This study accomplishes that the addition of Ta and Mo more than a critical value is not required for biomedical perspective as it enhances brittleness, elastic modulus and decreases the ductility of the system. It is, therefore, endorsed that single-phase Mo0.2Nb Ta0.2TiZr is the best candidate for biomedical implants because of its excellent strength and ductility combination in order to avoid any wear at the joint. Furthermore, this alloy has similar elastic modulus and corrosion behavior to commercial biomedical Ti-based alloys.

15:30-16:10 Tea Break

16:10-16:40 Keynote(1234230)

Additive Manufacturing of Metallic Glasses and High Entropy Alloys: Challenges and Opportunities

Xiaopeng Li, The University of New South Wales, Australia;

Bulk metallic glasses (BMGs) and high entropy alloys (HEAs) are both important multi-component alloys with novel microstructures and unique physical and chemical properties, which make them promising for applications in many industries, e.g., aerospace, energy, healthcare and etc. However, certain hindrances have been identified in the fabrication of BMGs and HEAs by conventional techniques due to the intrinsic requirements of BMGs and HEAs. With the advent of metal additive manufacturing such as laser powder-bed fusion (LPBF) techniques, new opportunities have been perceived to fabricate geometrically complex BMGs and HEAs with tailorable microstructure theoretically at any site within the specimen, which are difficult to achieve using conventional fabrication techniques. After providing some background and introducing the conventional fabrication techniques for various BMGs and HEAs, this presentation will focus on the current status, development, and challenges in metal additive manufacturing of BMGs and HEAs including different additive manufacturing techniques being used (in particular electron beam melting and selective laser melting), microstructure design and evolution, as well as properties of the fabricated BMGs and HEAs. A few successful and pioneering examples will be given and discussed. A future outlook of metal additive manufacturing of BMGs and HEAs will also be provided at the end.
High-entropy alloys (HEAs) have been attracting much attention because of their exceptional mechanical properties, such as high strength, good ductility, and superior fracture toughness at cryogenic temperatures. However, HEAs are not always ductile and some of these alloys show poor deformability due to the formation of brittle intermetallic compounds. Furthermore, from the viewpoint of future applications, it is important to explore methods for producing complex shaped products with HEAs. In this study, electron beam melting (EBM), a powder-bed-fusion additive manufacturing (AM) technology, was applied for an equiatomic AlCoCrFeNi HEA, and microstructures, mechanical properties, and corrosion behavior were evaluated by comparing them with those of a conventionally cast specimen.

Microstructural observations revealed that both cast and EBM specimens consisted of a nano-lamellar mixture of disordered body-centered-cubic (BCC) and B2 (ordered BCC) phases. Notably, the EBM process realized rapid cooling during fabrication, resulting in finer grains than those in the cast counterparts. Furthermore, the face-centered cubic (FCC) phase was identified at the grain boundaries of the B2/BCC matrix in the EBM specimen. The fraction of the FCC phase (approximately 30%) at the bottom part of the EBM specimen was higher than that at the top part. The preheating procedure, which is a process unique to EBM, is responsible for the precipitation of the FCC phase, because of the long-term exposure at elevated temperatures. As a result, the EBM specimen exhibited much higher plastic deformability than the cast specimen without significant loss of strength, suggesting that the FCC precipitates accommodate the stress concentration at grain boundaries. Furthermore, potentiodynamic polarization tests revealed a significant improvement in pitting corrosion resistance was identified in the EBM specimen. These results indicate that AM processes are promising for manufacturing as well as optimizing the microstructures of difficult-to-work HEAs.

High-entropy alloy (HEA) is a novel metal material composed of more than four elements and possessing a unique single solid solution (SSS) structure and fully disorder atom occupation. The unique structure of HEA results in the special properties, such as high strength and high corrosion resistance. Among all reported HEAs, the refractory high-entropy alloy (RHEA) which is composed of refractory metal displays a great potential to as the special material working at an extreme environmental, such as high and low temperature structure material and energetic structure material, due to its element characteristics. By far, the main route for fabricating RHEA is liquid mixing, including arc melting, electric resistance melting, inductive melting, etc. Due to the inherent compositional complexity and the huge difference in the melting points between the constituent elements, the liquid mixing is challenging. Significant elemental segregation occurs during melt solidification and cooling. Thus, compared to conventional alloys, the as-cast samples of RHEAs may have obvious casting defects, such as cracks, pores, and residual stresses along with compositional gradients and abnormal grain-size distributions.

In fact, solid mixing, which mainly contains the mechanical alloying and subsequent consolidation process, is another route for preparing HEA. Comparing with liquid mixing, solid mixing has an obvious advantage on preventing casting defects and formation of big and irregular sample. But the high melting point and low diffusion rate will delay the homogenization of refractory elements. According to the thermodynamics and high-entropy effect of HEA, the formation of SSS is mainly caused by the uniform distribution of constituent elements. Indeed, the increase of ball milling time can realize the homogenization of element distribution finally. But it also will lead to the increase of lattice defects and the decrease of crystallization degree. That is to say, the problem that element homogenization rate is lower than the defect increase rate makes the formation of RHEA powder with the uniform element distribution, SSS structure and high crystallization be difficult. Therefore, it is significant to find an effective way to speed up element diffusion and slow down defect generation during mechanical alloying process.

As it is known, the element diffusion will accelerate in the area without complete lattice. And the addition of liquid ball milling medium can increase grain refinement efficiency. The grain refinement will increase element diffusion rate through increasing grain boundary and
reducing lattice completeness before the occurrence of cold welding, during which the element start to mutual diffuse. More important, the presence of liquid ball milling medium will obstruct the direct contact between raw powders and lower the defect generation rate. Thus, some ball milling mediums including liquid and solid were added during the prepare process of NbZrTiTa quaternary RHEA by mechanical alloying. The effect of different mediums on the element homogenization and the formation of SSS were investigated. An effective way to prepare RHEA powder with uniform element distribution and SSS structure was found.

17:25-17:45
Flexible High-Entropy Micro-Fiber for Niche Applications
Dongyue Li, Yong Zhang, University of Science and technology Beijing, China

Increasing demands for stronger and more ductile structural materials have stimulated a vigorous search for novel alloys. The emergence of high entropy alloy is promising to breakthrough this general strength-ductility trade-off. Besides the widely studied bulk high entropy alloy ingots, low-dimensional and flexible high entropy fibers also have extremely broad prospects. In this work, we fabricated FCC-based Al0.3CoCrFeNi micro-fiber of 60μm in diameter by hot drawing. Additionally, appropriate heat treatment and coating can further optimize the performance of mechanical properties. This fiber will position the application of high entropy alloys in high-tech micro-devices. It provides support for the development of a new generation of the niche by precise processing and forming.
High-entropy alloys (HEAs) are attracting an academic interest for their promising and unique properties as structural materials. Particularly, the equiatomic CoCrFeMnNi HEAs have been reported to possess a wide-range of promising properties such as good high temperature structural stability and an excellent balance between strength and ductility, particularly at cryogenic temperatures, typically 77K, the liquid nitrogen temperature. Even though most HEAs have equiatomic or near equiatomic compositions, it is believed that the equiatomic composition would not be the optimum composition for a wide range of material properties. To improve a specific material property, one may have to change the alloy composition from the equiatomic composition. Indeed, there have been many efforts to improve the face-centered cubic (fcc) single-phase stability or mechanical properties of the CoCrFeMnNi HEAs by adjusting the composition or introducing new elements. However, for an efficient alloy design, one would need to understand the reason for the typical HEA properties and the effect of individual elements on them. In the present talk, an alloy design procedure to improve the strength of the alloy will be outlined. The CALPHAD computational thermodynamics technique is used to predict the fcc single phase region and the relative stability of the fcc phase over body-centered cubic (bcc) or hexagonal close-packed (hcp) phases in multicomponent systems. Atomistic simulation based on a newly developed (semi-)empirical interatomic potential is used to estimate the effect of individual elements on the critical resolved shear stress of the multicomponent fcc crystal as well as to understand fundamental materials properties of the fcc HEAs (deformation mechanism, diffusion behavior, etc.). An experimental validation of the computational approaches will be presented. Some examples of the application of the computational approaches to alloy design of HEAs with fcc single phase microstructure, with transformation-induced plasticity (TRIP), twinning-induced plasticity (TRIP) and with optimum amount of second phase will also be presented together with experimental results.
9:25-9:50 Invited (1235069)

**Effect of Nitrogen Content on the Microstructure and Mechanical and Tribological Properties of Magnetron Sputtered FeMnNiCoCr Nitride Coatings**

*Paul Munroe, Chuhan Sha, UNSW Sydney, Australia; Zhifeng Zhou, City University of Hong Kong, China; Zonghan Xie, University of Adelaide, Australia*

Extensive research has been carried out on high entropy alloys (HEAs) in bulk form. These alloys exhibit many attractive physical and mechanical properties, and more recently are being investigated in the form of thin film coatings. In pursuit of improved mechanical performance of HEA coatings, nitrides based on these compositions have been investigated in this study. We have examined a series of FeMnNiCoCr nitride coatings deposited onto M2 steels using a DC closed field unbalanced magnetron sputtering system. The target was composed of a FeMnNiCoCr alloy in equal atomic ratio. The nitrogen content in the nitride coatings was controlled by nitrogen gas flow rate. The phase compositions, microstructure, mechanical, and tribological properties of the as-prepared coatings were examined by XRD, TEM/EDS, nanoindentation, scratch and wear tests. A phase transformation from FCC to BCC, with higher nitrogen contents was observed in these coatings. A relatively high hardness value of ~17GPa was measured in the coating with the highest nitrogen content. A reduction in the adhesion strength with increasing nitrogen content was also found by the scratch test. In contrast, an improved wear resistance was achieved at higher nitrogen concentrations. It is believed the evolution of mechanical and tribological properties is related with the compositional changes and phase transformations as a function of gas flow rate. That is, the low-nitrogen content coatings exhibit FCC structures with higher ductility and toughness, whilst the high-nitrogen content coatings exhibit BCC structures but greater brittleness.

9:50-10:10(1222981)

**Experimental Investigation and Phase Diagram of CoCrMnNi–Fe System Bridging High-Entropy Alloys and High-Alloyed Steels**

*Nokeun Park, Ibrahim Onidicho, Yeungnam University, Korea; Won-Mi Choi, Byeong-Joo Lee, Pohang University of Science and Technology, Korea; Jong Bae Jeon, Korea Institute of Industrial Technology, Korea; Hamidreza R. Jafarian, Iran University of Science and Technology, Iran; Sun Ig Hong, Chungnam National University, Korea*

High-entropy alloys (HEAs) constitute a unique class of alloys that has attracted significant attention from material scientists. It has been reported that their high-configurational entropy favors the formation of solid solution phases such as face-centered cubic (fcc), body-centered cubic (bcc), and hexagonal closed-packed (hcp) crystal structures against the expected intermetallic phases according to existing physical metallurgy principles. An investigation of equiatomic and
non-equiatomic high-entropy alloys (HEAs) and medium-entropy alloys (MEAs) was carried out by performing both thermodynamic calculations and experiments. The design strategy of the alloys was based on a constant valence electron concentration (VEC) of 8 while varying the content of Fe in a $\text{Fe}_x\text{(CoCrMnNi)}_{100-x}$ where $x = 00, 20, 40, \text{and } 60$.

A phase diagram of CoCrMnNi-Fe system was presented. According to this phase diagram, increasing the Fe content reduces the melting temperature and the onset temperature of the undesirable $\gamma$ phase, with Fe50 having a single phase fcc, even at 600°C. The alloys exhibit a single-phase fcc structure after annealing at 900°C. Additionally, the probability of the formation of a bcc phase increases with the increase in the Fe content. Our experimental results confirmed that Fe20, Fe40, and Fe60 have a single-phase fcc, which is in good agreement with the results of the thermodynamic calculations.

The tensile test results revealed that both the yield strength and ultimate tensile strength decrease as the amount of Fe is increased but the uniform elongation increases. Additionally, the strain-hardening rate is significantly enhanced at higher Fe concentrations due to the activation of deformation twinning as an additional deformation mechanism. Interestingly, the critical twinning stress is significantly reduced as the Fe content is increased from Fe00 to Fe60. As a result, the deformation twins were easily activated in a specimen deformed up to a true strain of 20% for Fe60, unlike the other alloys, which exhibited no deformation twinning at the same true strain. Furthermore, it was revealed that the frequency of deformation twinning increases proportionally with increase in the Fe content.

10:30-10:45 Tea Break

10:45-11:10 Invited(1234474)

Material Wear Map for High Entropy Alloys

Nima Haghdadi, UNSW Sydney, Australia; Nima Haghdadi, Tingting Guo, Alireza Ghaderi, Peter Hodgson, Matthew Barnett, Daniel Fabijanic, Deakin University, Australia

The intrinsic scratch resistance of as-cast Al1.0CoCrFeNi (BCC) and Al0.3CoCrFeNi (FCC) in the as-cast, homogenized and recrystallized conditions was investigated using tip radii of 25µm and 0.8mm. Through analyzing the geometry of the grooves, the wear mechanism and total material loss were measured. For the FCC material in all conditions, the wear mechanism was almost the same. The wear rate increased with increasing load, and the fraction of material removed from the groove fell in the range of 0.2~0.7. A significant decrease in the wear rate was observed for the BCC material mainly due to its high hardness. The fraction of material removed from the groove for the BCC material was in the range of 0.7~0.9, which implies dominance of the cutting wear mechanism. A wear map based on 'scratch hardness' and 'scratch ductility' was constructed to enable comparison of the wear performance of materials under different loading conditions. The map was analogous to those frequently used to compare the strength and ductility of structural metals. It was found that the importance of hardness in wear is highly dependent on load. At high loads the wear performance of alloys highly depends on the scratch hardness. For low loads, however, the combination of hardness and scratch ductility dictates material total loss.

11:10-11:30(1232605)

Fabrication of Nano-Structure AlCoCrFeNi High Entropy Alloy Through Shock Consolidation and Mechanical Alloying

Ali Arab, Pengwan Chen, Beijing Institute of Technology, China

HEAs are usually fabricated using arc melting which has the disadvantages of diseconomy, and the limitations in the shape and size of final products. However, recently, quite a large number of researches have carried out to find the new fabrication techniques to fabricate HEAs with better properties such as mechanical alloying and rapid solidification. AlCoCrFeNi high entropy alloy is fabricated by different fabrication techniques. In this method, the starting powders were mixed by the mechanical alloying, and then, the shock wave was imposed to the compacted powders by explosion. The shock consolidation experiments were carried out in a set up with a cylindrical configuration, the steel tube was filled with the mixed powders which was uniaxial pressed in order to attain a 70% of theoretical density, and closed at both ends. The steel tube was surrounded by powder explosive named expanded Ammonium Nitrate with a detonation velocity of 2300m/s. The microstructure of the sample was examined by the XRD, SEM and EBSD. Body Center Cubic (BCC) and Face Center cubic (FCC) Crystal structures are identified in both milled and shock consolidated samples. The microstructure of the fabricated sample shows that the nano-size grain (average grain size of 26nm) is formed in the sample. Fabricated HEA has high hardness (550.7HV) as well as high density.
J. Amorphous and High Entropy Alloys

Symposium Organizers:

Weihua Wang, The Institute of Physics, Chinese Academy of Sciences, China; Zhaoping Lv, University of Science and Technology Beijing, China; Hidemi Kato, Tohoku University, Japan; Hojin Ryu, Korea Advanced Institute of Science and Technology (KAIST), Korea; Michael Ferry, New South Wales, Australia; Evan Ma, Johns Hopkins University, USA

August 19-21, 2019

Room: Exhibition Area (3rd Floor)

J-1: Heating Rate Effect on Soft Magnetic Properties and Crystallization of Fe-Si-B-P-Cu(-C) Amorphous Alloy System(1220525)

Yan Zhang, Tohoku University, Japan

Soft magnetic materials have been widely used for power transformers, motors, communications devices, and microelectronics, etc. Si-steel is widely used for soft magnetic material due to its low cost and high saturation magnetic flux density. However, an inescapable disadvantage of Si-steel shows much higher core loss than Fe-based amorphous/nano-crystalline materials because of the high coercivity. Among the various Fe-based amorphous/nano-crystalline alloys based on FINEMET (Fe-Si-B-Nb-Cu), NANOPERM (Fe-M-B, M=Zr, Hf, Nb) and NANOMET (Fe83.3-85-Si-B-P-Cu) with excellent soft magnetic properties, the Fe-rich Fe-Si-B-P-Cu nano-crystalline materials have been developed, which reduce production costs by eliminating expensive materials such as Nb, Zr and Hf. A high heating rate (>300K/min) is necessary to achieve a nano-crystalline alloy in NANOMET. However, the annealing process for more than 30 sheets at the same time tends to be uncontrollable at high heating rate, during which ribbon stacking density is limited in industrial application. To realize the mass industrial production of magnetic cores, two-step annealing process seems to be unavoidable. Obviously, the heat treatment process conditions need to be ameliorated and explored further. In the present work, the excellent magnetic softness is realized in Fe81.5Si0.5B4.5P11Cu0.5C2 (at.%) nano-crystalline alloy through an optimum annealing with low heating rate (10K/min). The lager the atomic size difference, the lager the elastic energy is. The thermodynamic properties of multicomponent alloy systems can be evaluated by the extrapolation from constituent binary systems. Zhang et al used a criterion with the parameter $\delta$ and parameter $\Omega$ to determine the forming ability of HEAs. Senkov et al proposed combined parameters associated with mixing enthalpy, entropy and annealing temperature. This criterion should determine the annealing temperature before prediction of composition. The mixing enthalpy of HEAs in above methods was evaluated by way proposed Takeuchi et al.

The thermodynamic properties of multicomponent alloy systems can be evaluated by the geometrical model from those of constituent binary systems by including the interaction among constituent elements. The thermodynamic-elastic energy criterion was proposed and verified by using 107 HEAs, the enthalpies of mixing have been calculated by Miedema’s theory, and the thermodynamic properties of multicomponent alloy systems can be evaluated by the extrapolation from constituent binary systems. Zhang et al used a criterion with the parameter $\delta$ and parameter $\Omega$ to determine the forming ability of HEAs. Senkov et al proposed combined parameters associated with mixing enthalpy, entropy and annealing temperature. This criterion should determine the annealing temperature before prediction of composition. The mixing enthalpy of HEAs in above methods was evaluated by way proposed Takeuchi et al.

The thermodynamic-elastic energy criterion for Composition Design of HEAs(1221728)

Lei Zhang, Guangxi College of Education, China; Hongmei Chen, Xiaoma Tao, Yifang Ouyang, Guangxi University, China

High entropy alloys (HEAs) have useful properties, such as excellent specific strength, superior mechanical performance at high temperatures, exceptional ductility and toughness at cryogenic temperatures, superparamagnetism, and superconductivity. HEAs usually intend to form BCC and/or FCC solid solution rather than intermetallic compounds. The thermodynamic properties are used to predict which phase will be formed for the HEAs. The mixing enthalpies for binary alloys can be calculated successfully by Miedema’s theory, and the thermodynamic properties of multicomponent alloy systems can be evaluated by the extrapolation from constituent binary systems. The thermodynamic-elastic energy criterion was proposed and verified by using 107 HEAs, the enthalpies of mixing have been calculated by Miedema’s theory and geometrical model. The mixing enthalpies and elastic energies of multicomponent alloys exhibit a clear relationship, that is the enthalpies of mixing should be in the range of -22 to 5kJ/mol and the elastic energy should be less than 6.06kJ/mol. The lager the atomic size difference, the lager the elastic energy is. The more negative enthalpy will be benefit to forming of the intermetallic compound. The present criterion is compared with that with the parameter $\delta$ and parameter $\Omega$, and the agreement is reasonable. It also shows good coincidence with experiment. The present criterion should be help to design the composition and new system of HEAs.

Acknowledgements

This work was financially supported by the National...
The concept of high-entropy alloys (HEAs) has been proposed since 2004. HEAs is a kind of alloys containing more than 4 principle elements, for which their configurational entropy is high. Deviating from the Gibbs’ rule, though HEAs has complex elements, they get simple phase, usually single phase, because of the phase-stabilizing contribution of high configurational entropy. HEAs usually show a good strength and ductility due to the special strengthening mechanism caused by the random atom occupation and single solid solution structure. As more special properties of HEAs, such as sluggish diffusion, anti-radiation and corrosion resistance, are discovered successively, the great applications in different condition are exploited. Refractory high-entropy alloys (RHEAs) is a family of HEAs contains at least 4 refractory elements. Except the characteristic the same as other HEAs, RHEAs have an intrinsic high melting point, probably higher than 2000℃, which endues RHEAs a great potential to substitute Ni-based superalloys. However, most of the reported RHEAs have poor plasticity at room temperature, which is the primary reason restricting the real application of RHEAs.

Fortunately, the transformation-induced plasticity (TRIP) effect, which was widely used in high-Mn steels and titanium alloys, provides a way to overcome the poor plasticity of RHEAs. The basis of TRIP effect is mechanically induced martensitic transformation, which leads to a remarkable plastic-deformation ability. And the increased phase boundary density due to transformation creates additional obstacles of dislocation slip, thereby contributing to the strain hardening. Because of this special transformation mechanism, TRIP effect can increase plasticity without decreasing the strength. Since the TRIP effect was firstly introduced in HEA at 2016, its effect on improving the plasticity of RHEAs has been demonstrated by HfZrTiTa0.5 and NbZrTiTa systems. But there is still a lot of work to do before RHEAs’ real application, because only a few reports about the high-temperature properties of RHEAs, including high-temperature creep strength, thermal structural stability and anti-oxidation capability, all of which are critical to high-temperature structural material, have been presented. Therefore, it is significant to study the service characteristics of RHEAs.

In this work, the properties including the mechanical behavior, structural stability and anti-oxidation capability at high temperature of TRIP RHEAs were measured. The mechanism behind these service characteristics of TRIP RHEAs were investigated. Above all, the potential of TRIP RHEAs as high-temperature structural material was revealed, and some improvement ways were provided. This work is helpful for the development of both HEAs and high-temperature alloys.

In recent years, the strengthening of magnesium alloys and high-entropy alloys (HEAs) have attracted more and more attentions and become hot research. Based on the idea of high-entropy alloy design, Al, Gd, Y, Zn were selected as the principal elements with obvious “solid solubility effect” with Mg according to the Hume-Rothery solid solubility theory and the existing high-entropy alloy criterion. Then Mg35Al25Gd20Y10Zn10 high-entropy alloy was designed according to non-equal molar ratio and prepared by vacuum melting. The microstructure and phase composition of the experimental alloy were determined by X-ray diffraction (XRD), scanning electron microscopy (SEM) and Energy Dispersive Spectroscopy (EDS). Meanwhile, the mechanical properties of the alloy were examined by microhardness tester and universal testing machine. The results showed that the alloys are composed of two kinds of magnesium-based solid solutions with blocky or granular second phases dispersed on it. The solid solubility (wt.%) of Gd, Zn, Y and Al in the two magnesium-based solid solutions were about 4.90, 1.60, 0.83, 0.03 and 21.10, 9.20, 4.48 and 0.93, respectively; and the microhardness was 101HV and 128HV, respectively. The atomic ratio of the main elements in the blocky or granular second phase was nearly Al:Gd:Y=6:2:1, with a small amount of solid-solved Zn. The dimension of the second phase was about 2~20μm, and the microhardness was 427HV. The engineering stress-strain curves of the alloy at room temperature compression engineering shows obvious work hardening tendency. Besides, the yield strength was 419MPa, compressive strength was 451MPa, compression rate after fracture was 17.23%, and strength-plastic product was 6850MPa %, which is much higher than that of cast magnesium alloy and deformed magnesium alloy reported at present. Magnesium-based solid solution with high solid solubility and the second phase with high hardness dispersed on it are the main reasons for the ultra-high-strength plastic product of the alloy.
J-5: Microstructural Evolution and Compressive properties of AlCuSiFe-X (X = Cr, Zn, Mn) High Entropy Alloys(1222583)

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High entropy alloys (HEAs) are currently of great research potential in materials research community. Compared to traditional binary or ternary element alloys, Multicomponent HEAs exhibit simple solid solutions in contrast to conventional alloys where a number of complex compounds form. There are various routes of metals and alloy fabrication like casting, spraying, vapor deposition techniques and chemical methods. Most of the HEAs are often produced by casting and solidification approach which are highly sensitive to casting defects, metals segregations and inclusions. Therefore, compared to popular casting methods, powder metallurgy route which consists of high energy ball milling (HEBM) and compaction steps can successfully eliminate the drawbacks of traditional metal fabrication processes. In addition, PM process is simple, safe and can be scaled to the industrial level.

In the present work, the alloying behavior of equiatomic AlCuSiFe-X (X = Cr, Zn, Mn) was investigated using X-ray diffraction, scanning electron microscopy, and transmission electron microscopy. The HEAs were prepared by HEBM and subsequent consolidation by spark plasma sintering (SPS). The results indicate that single phase FCC and BCC phases evolve after HEBM; whereas BCC/FCC phase separation, evolution of sigma (σ) phases, and fluctuations of the Al and Cu-X compositions in Al-Cu-X rich regions occur after SPS. It appears that entropy of mixing plays a key role in determining the phase formation in HEAs after SPS. Further, compressive properties of AlCuSiFeZn, AlCuSiFeCr, and AlCuSiFeMn alloys together with their hardness values were evaluated. The as-sintered bulk hardness and compressive stress values were maximum for AlCuSiFeCr followed by AlCuSiFeZn and AlCuSiFeMn. The results are discussed in terms of compositional fluctuations governed by the mixing entropy of the binary systems. It is also reported that a combination of cheaper metals like Al, Cu, Si, Fe, Zn in this alloy can reduce down the overall cost with a comparable or better structural properties in some cases compared to the popular Mn, Cr based HEAs.

J-6: In situ XRD Studies of Atomic Structure of Two Fe-Based Metallic Glasses(1222699)

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In-situ synchrotron high energy X-ray diffraction were used to study the atomic structure evolution of Fe48Cr15Mo14C15B6Gd2 and Fe48Cr15Mo14C15B6Y2 metallic glass on the process of solidification at the I15 beamline of Diamond Light Source UK. Atomic structural changes occurring in these two amorphous alloys during the process of solidification were investigated. The metallic glasses were melted with a constant heating rate, after that the temperature were held isothermally, and then the sample was cooled. The research is mainly focused on studying the atomic structure of Gd alloys in Fe-based amorphous alloys and the role played by Gd and Y element in the nanocrystallization. By combining total scattering and anomalous scattering techniques, we are able to recognize the atomic structures of multicomponent Fe-based amorphous alloys in liquid state. Real space analysis by means of the atomic pair distribution function (PDF) demonstrated that the rate and extent of the thermal expansion strongly depend on the interatomic separation. The PDF proved to be a reliable method for the description of crystallization kinetics. To clarify the role played by Gd and Y element, the difference of atomic structure and crystallization kinetics of these two Fe-based amorphous alloys were compared. This research indicated that how the local short-range ordered structure of an amorphous phase evolves into the long-range periodic structure of a crystalline phase in some Fe-based metallic glasses. It is very important in designing and developing new metallic alloys.

J-7: Porous Ceramic Composite Networks Prepared by Sintering of Metallic Glass Nanospheres (1222863)

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Porous ceramics with high specific surface area contains special physical and chemical properties, and presents potential applications in bone tissue engineering, water treatment, drug delivery systems, optical sensors, nuclear fuel materials, heat transfer and thermal energy storage. However, the fabrication of porous ceramic is still challenging. Yttrium titanate Y2Ti2O7 is an important member of the pyrochlore family because it exhibits various properties which make it suitable for potential applications in different fields, such as optical and fuel cells applications. So far, the fabrication of porous Y2Ti2O7 pyrochlores has been rarely reported. Here we report a new route to obtain porous Y2Ti2O7 pyrochlore composite networks by sintering of metallic glass nanospheres at high temperature. The metallic glass nanospheres were synthesized by selective phase etching of a two-phase amorphous alloy precursor ribbon. Then the as-obtained metallic glass nanospheres were sintered at different temperatures open to air. The changes in composition and morphology with different temperatures were detailedly analysed. The lattice parameter, electrical conductivity, X-ray analysis, Fourier Transform-Infrared Spectroscopy...
High temperature tensile deformation behavior and microstructural evolution in a non-equiatomic Fe40Mn27Ni26Co5Cr2 high entropy alloy (HEA) which has face-centered cubic (fcc) single phase was studied. The HEA was processed by severe plastic deformation, high ratio differential speed rolling (HRDSR) and post annealing. In order to investigate the high temperature tensile deformation behavior, uni-axial tensile tests were conducted at high temperatures in range of 973~1173K and at strain rate from 10^-4 to 10^-1s^-1 on ultrafine grained (~ 1.3μm), fine grained (~ 10.4μm) and coarse grained (~ 314.0μm) HEAs. To investigate the microstructural evolution, the microstructure of HEAs was observed by using optical microscopy (OM), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) techniques. In order to examine the existed phases in HEA deformed at high temperatures, X-ray diffraction (XRD) was performed. Compared with the excellent ductility and fracture toughness at room temperature, ductility and fracture toughness dramatically decreased by increasing deformation temperature albeit the HEA had recrystallized fine grains and coarse grains. In addition, dislocation climb creep (DCC) exhibited at low strain rates and at high temperatures (973~1173K) as the rate-controlling deformation mechanism in coarse grained HEA. However, grain boundary sliding (GBS) appeared at low temperature albeit the HEA had recrystallized fine grains and coarse grains. In addition, dislocation climb creep (DCC) exhibited at low strain rates and at high temperatures as the rate-controlling deformation mechanism in fine grained and ultrafine grained HEA. This GBS became obvious as the temperature increased and grain size decreased. The activation energies for plastic flow at high temperature increased and grain size decreased. The ductility and fracture toughness at high temperatures and wide strain rate. For a better understanding of tensile deformation behavior at high temperatures, the correlation between high temperature tensile deformation behavior and microstructure of HEA was also discussed.

J-10: Preparation of Metallic Glass/Crystalline Composites Using Electroless Plating Copper on Glassy Powders(1234752)

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Spherical Cu50Zr43Al7 metallic glassy powder was produced by the gas-atomized process, and a layer of crystalline copper was coated on the Cu-based
glassy powder by electroless plating to form metallic glass / crystalline Cu composite powder to improve the electrical conductivity and the ductility of the consolidated composite. The metallic glass / crystalline composite powder was densified by spark plasma sintering to obtain bulk metallic glass composite. The powder and Cu50Zr43Al7/Cu composite were characterized by X-ray diffraction and field emission scanning electron microscope. The relative density, thermal stability, mechanical and electrical properties of the specimens were tested. The effects of sintering temperature, loading pressure, holding time and particle size on the properties of samples were studied. The results show that the composite has a hardness of 320HV and a compressive strength of over 1000MPa. The strength and hardness decrease obviously with the addition of ductile crystalline copper. On the contrary, the conductivity increases continuously. Compared with amorphous materials, sintering can be carried out under lower loading pressure, and the plasticity of composites has been improved obviously. In addition, the conductivity is over $5.0 \times 10^4 (\Omega \cdot cm)^{-1}$, which is of great significance for the research of composite materials with high strength and high conductivity.

**J-11: Investigation of Mechanical Properties of CoCrFeMnNi High Entropy Alloys Fabricated by Rapid Solidification Process**

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High entropy alloys (HEAs) are very attractive materials due to their outstanding properties such as high strength, good thermal stability and high temperature strength, and exceptional corrosion resistance. High entropy alloys (HEAs) usually containing at least five principal elements by adding 5~35 at% each element unlike the conventional multi-element alloys. As a result, high mixed entropy occurs, so that an intermetallic compound is not formed and a single solid solution is formed, so that the mechanical properties are relatively higher than those of the conventional alloy. In this study, we have fabricated FCC structured single phase of CoCrFeMnNi high entropy alloys (HEAs) by the combination of two approaches, and systematically investigated and compared their mechanical properties. Initially High entropy alloys (HEAs) was fabricated by the casting plus rolling method, and characterized their properties. Secondly, High entropy alloys (HEAs) was fabricated by the new powder metallurgy process such as gas atomization, followed by spark plasma sintering (SPS) The crystal structure of the specimens from both processes was analyzed by X-ray diffraction. The fracture surfaces, and cross-sectional micrographs of the High entropy alloys (HEAs) specimens were characterized by scanning electron microscopy (SEM), and transmission electron micrograph (TEM) respectively. The mechanical properties including the compressive strength, micro vickers hardness were analyzed.

**J-12: Microstructure and Properties of Corrosion-Resistant Al-Cr-Fe-Co-Ni High Entropy Alloys**

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The AlxCrFeCoNi high entropy alloys (HEAs) with both ductile face-centered cubic (FCC) phase and tough body-centered cubic (BCC) phase have attracted extensive attentions due to their high strength and good ductility. However, pitting corrosion tends to occur at the surface of the BCC phase in Cl−-contained solutions, which may limit the applications of the AlxCrFeCoNi HEAs. In this presentation, we will report an Al-Cr-Fe-Co-Ni alloy with integration of excellent corrosion resistance, high strength and good ductility synthesized by increasing Cr content, and the influences of Cr on microstructure, corrosion behaviors and mechanical properties of the Al-Cr-Co-Ni HEAs. It was found that increasing Cr content could lead to the change in the phase structure of the alloys from single FCC to duplex FCC+BCC. For the Al-Cr-Co-Ni HEAs with duplex FCC+BCC structure, the BCC phase exhibited higher content of Cr than the FCC matrix and hence did not cause deterioration of the corrosion resistance of the alloys. The pitting corrosion resistance of the Al-Cr-Fe-Co-Ni HEAs was enhanced with increasing Cr content, and the alloys with relatively high contents of Cr exhibited no pitting corrosion in 3.5wt.% NaCl solution. Moreover, the formation of BCC phase in the Al-Cr-Co-Ni HEAs with relatively high Cr contents effectively enhanced the tensile strength, though decrease the ductility. It is notable that the Al-Cr-Co-Ni HEA with high Cr-content exhibited tensile yield strength over 600MPa and elongation of 12% besides excellent corrosion resistance.

**J-13: High-Temperature Deformation Mechanisms and Processing Maps of Equiatomic CoCrFeMnNi High-Entropy Alloy**

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The hot compressive deformation mechanism and processing maps of the equiatomic FCC CoCrFeMnNi high-entropy alloy (HEA) were studied in the temperature range between 1023 and 1323K and in the strain rate range between $10^{-3}$ and $10^{-1}$. At high strain rates above $1s^{-1}$, strain hardening was dominant even at the very high temperature of 0.84Tm, which may be attributed to the sluggish diffusion coefficient and low stacking fault
energy of the CoCrFeMnNi HEA, leading to suppression of dynamic recovery. According to the processing maps, the best condition for hot working was near $10^{-3}\text{s}^{-1}$ at 1323K. Power-law breakdown and unstable flow occurred at low temperatures and high strain rates where the strain hardening was pronounced. The activation energy for plastic flow measured in the power-law creep regime when considering the dependence of elastic modulus on temperature was 312.2kJ/mol; this value is close to the activation energy for the weighted diffusion coefficient calculated by weighting the contribution of each element in the CoCrFeMnNi HEA (284 kJ/mol). The size and fraction of the dynamically recrystallized grains increased as the strain rate decreased and the temperature increased, as in conventional metals. Both discontinuous dynamic recrystallization and continuous dynamic recrystallization (CDRX) occurred. CDRX became more distinct as the temperature increased. The deformation mechanism and behavior of the CoCrFeMnNi HEA were very similar to those of FCC pure metals in terms of the stress exponent and the effect of the stacking fault energy and diffusivity on the creep rates.
Effect of High Pressures on the Phase Transition of MoxCrFeCoNi High Entropy Alloys
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The pressure-induced face-centered cubic (fcc) to hexagonal close-packed (hcp) athermal martensitic transition in CrMnFeCoNi has drawn a great attention in high-entropy alloys (HEAs) research community, as it not only demonstrates a new paradigm to tune their structures and properties but also inspires new understanding of the intrinsic stability of the two close-packed structures. However, the key factor in determining the occurrence of this pressure-driven transition is still unclear, here, we demonstrate that the alloying of Mo with a relatively low d-band occupation into CrFeCoNi could destabilize the initial fcc structure and accelerate the pressure-induced fcc-to-hcp transition, this suggesting that the contribution of d electrons to valence states of the starting materials determines whether the transition takes place or not. Furthermore, a full recovery to the fcc phase was observed by high resolution transmission electronic microscope in Mo0.23CrFeCoNi after releasing from a high-pressure of 20GPa, at this pressure about 25\% the hcp phase was detected by synchrotron radiation X-ray diffraction. This result evidently demonstrates that the fcc structure is more stable than the hcp structure at least above 298 K at ambient pressure in Mo0.23CrFeCoNi.

Reinforcement of HEAs via Stress-Induced Phase Transformation
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High-entropy alloys (HEAs) which are composed of equiatomic or near-equatomic elements have attracted extensive attentions for their continuously revealed novel physical, chemical and structural properties. Body-center-cubic (bcc) HEAs, particularly those based on refractory elements are promising for high-temperature application but generally fail by early cracking with limited plasticity at room temperature, which limits their malleability and widespread uses. In this work, we clearly demonstrated that these brittle bcc HEAs can be successfully ductilized and toughened by exploiting the "metastability-engineering" strategy. We controlled the thermodynamically and mechanical stability of bcc phase via tuning the content of bcc stabilizer Ta in the prototype TaHfZrTi, rendering the formation of composite structure of interlaced hcp and deformation-transformable bcc phases. The destabilized HEAs exhibited pronounced ductility (from 4.0 ± 1.7\% to ~30\%) and work-hardening ability. The enhancement of comprehensive mechanical properties was attributed to collaborative transformation-induced plasticity (TRIP) and dynamic interface hardening effect. This work not only sheds new insights on development of HEAs with excellent combination of strength and ductility, but also has great implications on overcoming the long-standing strength-ductility tradeoff of metallic materials in general.