P. Dynamic Behaviour of Materials:I

Symposium Organizers :

Marc Andre Meyers, University of California, USA; Na Yan, Northwestern Polytechnical University, China

Tuesday AM Room: Room VIP (1st Floor)
August 20, 2019 Symposium: P

Chairs:
Lanhong Dai, Institute of Mechanics, China
Na Yan, Northwestern Polytechnical University, China

8:30-9:00 Keynote (1222706)

Superior Dynamic Response of CrCoNi-Based High-Entropy Alloys

Marc Andre Meyers, University of California, San Diego, United States

High impact resistance of the CrCoNi-based high-entropy alloys (HEAs) is expected from their excellent high-strain-rate plasticity. The high strain-hardening ability of the Al0.3CoFeCrNi and CrMnFeCoNi high-entropy alloys, enabled by solid-solution hardening, forest dislocation hardening, and mechanical twinning, marked strain-rate sensitivity and modest thermal softening, result in an excellent resistance to shear localization. The resistance to shear localization was studied by dynamically-loading hat-shaped specimens to induce forced shear localization. However, no adiabatic shear band could be observed for Al0.3CoCrFeNi high-entropy alloy. For the CrMnFeCoNi high-entropy alloy, a shear strain of ~7 has been found to be required for shear-band propagation (using a hat-shaped specimen that enables one single shear band to initiate and grow). This compares very favorably to a shear strain of ~1 for a Ti-6Al-4V alloy, ~3 for 1006 steel and ~5.5 for copper. The superior resistance to shear localization is originated from twinning due to its low stacking-fault energy. We build the slip-twinning relationship for CrMnFeCoNi high-entropy alloy. Dislocation prefers to slip at low strain-rates and high temperature. In comparison, twinning happens at high strain-rates and low temperatures. In addition, twinning often happens at a larger strain when dislocation slip gets difficult. Recrystallized ultrafine-grained grains (diameters of 100~300nm) are revealed inside the shear band. Their formation is explained by the classical rotational dynamic recrystallization mechanism. A high density of recrystallization twins was formed in the CrMnFeCoNi high-entropy alloy during the dynamic recrystallization process inside the shear band. The "pop-out" mechanism does not require concurrent grain-boundary movement for the formation of recrystallization (or annealing) twins and is therefore a possible mechanism, enabled by the lower stacking-fault energy. Results on shock hardening (front surface) and spalling (rear surface) of the CrMnFeCoNi high-entropy alloy employing laser ablation shock compression have also been revealed. The remarkable high-strain-rate plasticity is significant for ballistic applications.

9:00-9:25 Invited (1261622)

Bioinspired Ceramic/Polymer Segmented Armour

Pedro Miranda, University of Extremadura, Spain

Here we report on the development of multi-segmented ceramic/polymer armour elements inspired in the armadillo and boxfish carapaces, which consist of rigid hexagonal segments connected by collagen fibres. This ingenious armour design, created by nature through billions of years of evolution, ensures protection as well as flexibility. First, finite element modelling (FEM) is used to analyse the effect of scale geometry and other impact parameters on the ballistic protection provided by a segmented ceramic armour. The impact of cylindrical fragment simulating projectiles (FSPs) onto alumina-epoxy scaled plates is simulated, while scale geometrical parameters (size, thickness and shape) and impact conditions (FSP diameter, speed, location) are varied. The amount of damage produced in the ceramic tiles and the final residual velocity of the FSP after the impact are evaluated. Segmentation drastically reduces the size of the damaged area without significantly reducing the ballistic protection in centred impact, provided the tile size is kept over a critical value. Such critical tile size (~20mm for impacts at 650m/s) is independent of the scale thickness, but decreases with projectile speed, although never below the diameter of the projectile. Off-centred impacts reduce the ballistic protection and increase the damaged area, but an appropriate tile shape can minimize this effect. Hexagonal scales, like those found in the natural dermal armours of the boxfish and armadillo, are found to be optimal, with ballistic protection varying by less than 12% with impact location. Preliminary results on the fabrication and characterization of the proposed ceramic/polymer segmented armours are also presented; and design guidelines for the fabrication of segmented protection systems are discussed.

9:25-9:50 Invited (1222566)

The Effect of Texture on the Evolution of Adiabatic Shear Band: Experiment and Simulation

Tao Suo, Northwestern Polytechnical University, China

The dynamic (or high strain rate) responses of nanostructured face-centered-cubic alloys with different stacking fault energies after severe plastic deformation (ECAP, equal channel angular pressing) were investigated under uniaxial compression. It is found that adiabatic shear bands were easier to appear in those alloys with lower stacking fault energy, even though under quasi-static loading more obvious hardening behavior was observed with decreasing stacking fault energy. To understand the formation mechanism of adiabatic shear bands, firstly thermal softening during dynamic loading was considered. Dynamic tests within a wide range of temperature and interrupted loading revealed that adiabatic temperature rise prior to plastic instability has only minor effect on the onset of shear localization. Unlike medium/high stacking fault energy materials, strong textures have always been reported after severe plastic deformation in the metals with low stacking fault energy. Hence, influence of texture on the propensity to adiabatic shear bands was taken into account. The dynamic anisotropic behaviors show that the pre-existing texture formed during severe plastic deformation is responsible for the initiation of localized deformation, and the adiabatic temperature rise in the localized region promotes the formation of adiabatic shear bands. For understanding the mechanism for adibatic shear l;ocalization int this unuausal naostructured face centered cubic (FCC) metal, the crystal plasticity mehod was emplyed. To verify the effect of texture on the formation of adiabatic shear bands we have incorporated preferred orientation of grains into finite element modeling based on crystal plasticity. An elastic-viscoplastic continuum slip constitutive relation was adopted to describe the mechanical response of materials, in which the dependence of slip systems' resistance on the temperature evolution was also considered. The simulation results are in good accordance with the experimental results. As such a more comprehensive picture of the formation of adiabatic shear bands in such materials has been uncovered along with the underlying mechanism.

9:50-10:10 (1372602)

Effect of Microstructural Aspects in the Heat-Affected Zone (HAZ) of High Strength Pipeline Steels on the Stress Corrosion Cracking (SCC) Mechanism : in Simulated Acidic Soil Solution

Xueda Li, China University of Petroleum (East), China

Three types of microstructure, which consist of bainite/ferrite matrix and varied distribution of martensite-austenite (M-A) constituent, in the heat-affected zone (HAZ) of high strength pipeline steel were simulated using Gleeble simulation. Effect of microstructural aspects on the stress corrosion cracking (SCC) behavior was studied through slow strain rate tensile (SSRT) test in simulated acid soil solution at open circuit potential. The results showed that three types of microstructure exhibited significant difference in the SCC sensitivity. Analysis on the SCC mechanism showed that the distribution of martensite-austenite (M-A) constituent had large effect on the initiation of SCC microcracks. Galvanic effect and stress concentration between M-A and matrix, as well as hydrogen involvement are attributed to assist the formation of microholes at M-A/matrix interface, and SCC microcracks could readily nucleate through coalescence of these microvoids, especially when the M-A constituent are in continuously distributed along the prior austenite grain boundaries. Consequently, distribution of M-A constituent had large effect on the SCC sensitivity. When the M-A constituent was in dispersive state, the SCC sensitivity was low. As to the propagation, SCC microcracks preferred to propagate along the interface between elongated M-A constituent and upper bainite laths, whereas acicular ferrite and quasi-polygonal ferrite could inhibit the crack propagation. The present work revealed the SCC mechanism from the perspective of initiation and propagation process of SCC cracks, which can give contribution to the welding design and microstructure control in the HAZ.

10:10-10:30 (1222579)

Microstructure and Mechanical Properties of Ti-6Al-4V Titanium Alloy under Laser Processing

Chen Zhen, Central South University, China

Ti-6Al-4V titanium alloy is a typical α-β two-phase titanium alloy containing 6% α stable element Al and 4% β stable element V and widely used in aerospace medical fields. Laser welding is a solid-state connection process that can melt a material in a very short time and cooling rapidly. Microstructure and mechanical properties of the Ti-6Al-4V titanium alloy under laser welding was investigated by optical microscope (OM), electron probe microanalysis (EPMA), transmission electron microscope(TEM) and nanoindentation, respectively. Results show that the structure of the hardened phase in melting is very tiny, and the microstructure of the titanium alloy consist of crossed β-phase lath crystals and nanosized equiaxial grains. On the one hand, the martensite nucleates at the edge of β-phase lath crystals, and the other lattice remodeling through shear phase transformation forms a more staggered martensite structure. On the other hand, nanograins appear at the intersection of the crossed β-phase laths. The heat-affected zone near the welding core is composed of residual α phase and the lath acicular structure. In terms of mechanical properties, the tensile strength of the welded joint is higher than the matrix and the microhardness values of the titanium alloy increases from the matrix to the welding zone. The nanoindentation tests show that during the loading stage, the applied load in the ultrafine grains in the weld zone is larger than that for the heat-affected zone grain and matrix grains under the same displacement. The displacement of the weld zone is approximately 200nm, which is consistent with the width of the martensite observed in the TEM. During the holding time, the creep displacement value of the melt zone is the smallest, indicating that the creep resistance of the melt zone is better than matrix. Formation of the microstructure of titanium alloy under the laser processing is discussed at the final section.

10:30-10:45 Tea Break

10:45-11:15 Keynote (1234210)

Dynamic Fracture of Metallic Glasses under Shock Loadings

Lanhong Dai, Chinese Academy of Sciences, China

Bulk metallic glass (BMGs), due to lack of long-range order and the absence of tranditional defects such as dislocations and grain boundaries, have a series of intrinsic mechanical properties. Although considerable works on fracture behavior of BMGs have been made during past decades, how BMGs fail at impact loadings is relatively unclear. In this talk, we will demonstrate the physical picture of dynamic microdamage nucleation and evolution of BMGs under shock loadings and reveal the underlying mechanism via couple of examples, including spallation, cavitation instability, dynamic fracture surface pattern evolution etc. For study of spallation behavior of BMGs, we develop a multi-stress pulse technique via the specially designed double flyers based upon single-stage light gas gun. This technique leads the samples to be subjected to dynamic tensile loadings of identical amplitude but with different durations. By using this technique, spallation fracture is revealed clearly to be originated from microvoid. Furthermore, theoretical model was estabilished and the explicit expressions for the void nucleation rate as well as the critical pressure for cavitation instabilities were obtained. It is found that a dimensionless inertial number controls dynamic void growth, where the inertial effects can suppress the void growth while the viscous effects will suppress vibrating growth. d growth, where the inertial effects can suppress the void growth while the viscous effects will suppress vibrating growth.

11:15-11:40 Invited (1368546)

Rate-Dependent Plastic Instability Mechanisms of Aluminum Alloy with the Effect of Interface Behaviors

Pengfei Wang, Hebin Jiang, Songlin Xu, University of Science and Technology of China, China

In this work, the rate-dependent behaviors of 2A12 aluminum alloy with hollowed cylinder geometry were designed for analyzing the dynamic adiabatic shear instability mechanisms. The stress drop was observed in the stress strain curves as the strain rate increases to $3600s^{-1}$. Metallographic images of recovery specimens showed obvious localized deformation band under dynamic loading. The plastic deformation behavior with the lubricated interface state shows a prominent shear instability property, the numerical results reveal the shear band runs through the two surfaces with different interface friction coefficients. The high speed camera and digital image correlation (DIC) methods were used to analysis the instability deformation process. The initial surface state of ring-shaped specimen not only influences the onset strain and the yield strength, but also controls the duration of plastic instability stage. The formation mechanism of localized deformation bands and the constitutive equation of the stress drop stage were then theoretically analyzed.

11:40-12:05 Invited (1222156)

Microstructure and Mechanical Properties of a FeCoNiCrMn High Entropy Alloy at High Velocity Loading

Bingfeng Wang, Central South University, China

The equiatomic CoCrFeMnNi high-entropy alloy owning a single-phase solid solution with the face-centered-cubic structure is one of the extensively investigated high entropy alloys. Powder metallurgy is an promising way to prepare the high-strength CoCrFeMnNi high-entropy alloy with homogeneous compositions and microstructures. The deformation behavior of the high-entropy alloy deformed under quasi-static conditions has been widely studied. However, the study of high-entropy alloys under high strain rates (beyond $1\times10^3s^{-1}$) was rarely reported. As we know, the application of the high-entropy alloy often requires the study of its mechanical performance and microstructural evolution in dynamic deformation processes, such as penetration, impact cyclic loading, and shock loading. The CoCrFeMnNi high-entropy alloy prepared by powder metallurgy has homogenous microstructure and little segregations. The deformation behavior of the CoCrFeMnNi high-entropy alloy at strain rates ($1\times10^3s^{-1}$ to $4\times10^5s^{-1}$) was investigated, including the serration behavior and the shear localization of the alloy under dynamic conditions. Results indicate that the CoCrFeMnNi high-entropy alloy has only small serrations on the stress-strain curves even deformed at high strain rates ($>1000s^{-1}$), and the value of the yield strength of the powder-metallurgy high-entropy alloy CoCrFeMnNi is larger than that of the as-casting high-entropy alloy CoCrFeMnNi and the other steels. Shear band is an important deformation mechanism for the CoCrFeMnNi high entropy alloy at dynamic loading. Microstructure and mechanical properties in a shear band are investigated by the transmission electron microscope (TEM) and the nanoindentation technique. Core of the shear band is composed of ultrafine grains. It can be revealed that the ultrafine grained materials in the shear band have much higher hardness and a small strain rate sensitivity. Combined the mechanical properties obtained via the nanoindentation and the microstructure, the formation of a shear band in a CoCrFeMnNi high entropy alloy is caused by a rotational dynamic recrystallization mechanism.

12:05-12:25 (1453321)

Quasi-Static and Dynamic Compression Properties of Modified TC4 Titanium Alloys

Rui Liu, GRIMAT Engineering Institute Co., China

This paper aimed to study the quasi-static and dynamic properties of modifed TC4 titanium alloys. The ingots in weight of 20kg, with nominal compositions of commercial Ti-6Al-4V, Ti-6Al-3V-0.3O, and Ti-6Al-4V-0.3O-0.1B were melted, and then multi-forged into bars with 50mm in diameter. The bars were heat treated at temperatures of 30~60˚C above their β-transus temperature in purpose of obtaining homogeneous Widmannstatten microstructure. The quasi-static tensile properties were tested by MTSTM testing system at strain rate of $10^{-3}s^{-1}$. The dynamic compression properties were tested by Split Hopkinson Pressure Bar system at strain rate of $2000\sim4000s^{-1}$. The results show that the quasi-static properties of Ti-6Al-3V-0.3O alloy are comparable to commercial Ti-6Al-4V alloy, while Ti-6Al-4V-0.3O-0.1B alloy shows a better strength. Among the three alloys, Ti-6Al-4V-0.3O-0.1B alloy exhibits the best bearing capacity under dynamic compression loading. Visible damages can be observed in commercial Ti-6Al-4V and Ti-6Al-3V-0.3O specimens at strain rate of $2200\sim2500s^{-1}$, while in Ti-6Al-4V-0.3O-0.1B alloy at strain rate of $3200\sim3500s^{-1}$. The average dynamic flow stress of Ti-6Al-3V-0.3O alloy is comparable to commercial Ti-6Al-4V, over 200MPa lower than that of Ti-6Al-4V-0.3O-0.1B alloy. The value of maximum strain during homogeneous dynamic plastic deformation of Ti-6Al-4V-0.3O-0.1B alloy is approximately 0.24, 50% ~ 60% higher than that of Ti-6Al-3V-0.3O and commercial Ti-6Al-4V alloy.

12:25-12:45 (1222666)

Experimental Study on 2D-C/SiC Subjected to the Unpenetrated Impact and Post-Impact Mechanical Behavior

Wei Hu, Northwestern Polytechnical University, China

In this paper, the impact behavior of 2D-C/SiC at different velocities was investigated by experimental method. The specimens were impacted at the speed of 50m/s, 70m/s, 90m/s and 110m/s respectively by a steel sphere with the diameter of 4mm. It can be seen from the picture of high-speed camera, the debris cloud size from the back of the specimen increases with the impact velocity before 90m/s. The debris cloud size was larger at 110m/s than the one at 90m/s, which indicates that the damage mode was different than before. There was double-zone damage mode on the surface of the impact area, including compression-based damage in the internal part and the tension-based damage in the annular part. At the lower velocities of 50m/s, there was no visible damage on the surface of the back side. When it comes to the speed of 70m/s, the corner fracture could be found on the edge of the specimen. The reason is that the compressive wave propagates to two related free surfaces, then the two unloading tensile waves interacted with each other. The spallation occurred at the velocity of 90m/s and 110m/s, coupled by one-fracture mode and three-fracture mode respectively. When the specimen was impacted at 110m/s, the back surface initially fractured at the center of the impact zone, followed by the two fractures near the center. The difference between the two modes can be attributed to the different interfacial strength and fiber strength. If the compressive wave is not strong enough, the unloading wave is more dissipated in the delamination instead of in the breakage of higher-strength fibers. Moreover, the DIC method was adopted to measure the strain of the impact area to understand the post-impact tensile behavior of 2D-C/SiC. As the impact velocity increases, the residual strength of the material decreases slowly initially, and then it drops sharply.

P. Dynamic Behaviour of Materials: II

Symposium Organizers :

Marc Andre Meyers, University of California, USA; Na Yan, Northwestern Polytechnical University, China

Tuesday PM
August 20, 2019

Room: Room VIP (1st Floor)
Symposium: P

Chairs:
Bingfeng Wang, Central South University, China
Pengfei Wang, University of Science and Technology of China, China

13:30-14:00 Keynote (1299361)

Impact Resistant Natural Polymer Composites: Hooves and Horns

Wei Huang, Nicholas A. Yaraghi, David Kisailus, University of California, San Diego, USA; Alireza Zaheri, Horacio Espinosa, University of California, Riverside, USA; Wen Yang, Jae-Young Jung, Joanna McKittrick, Northwestern University, USA; Zezhou Li, Robert O. Ritchie, University of California, Berkeley, USA; Susan M. Stover, University of California, Davis, USA

Keratin is one of the most common natural structural biopolymers with remarkable mechanical properties that generate different functionalities in natural materials, such as in offensive weapons in sheep horns, defensive armor in pangolin scales and turtle shells, protective and energy absorptive layers in animal hooves and as environmental barriers in bird feathers and animal hairs. Energy absorption is one of the most important properties of keratin in tissues under extreme loadings. Although solely composed of polymer constitutes, keratin is one of the toughest natural materials. The toughness of keratin is greater than bone and wood, which are considered structural biological materials with desirable mechanical efficiencies. Bighorn sheep fight with each other, reaching speeds of ~9m/s with a deceleration of ~450g, which creates large amounts of impact energy. An unshod horse trotting at ~4m/s on an asphalt surface has a deceleration ~56g. Although sustaining less impact than horns, the high frequency of the contact with the surfaces also requires excellent energy absorption properties. Here we report on the structure and compressive static and dynamic mechanical properties of sheep horns and equine hooves samples oriented in different directions. High-resolution synchrotron x-ray micro-computed tomography and transmission electron microscopy, coupled optical and scanning electron microscopy were used to characterize the pristine and deformed samples. The major microstructural elements are tubules and cell lamellae. The lamellae consist of keratin cells, with a disc-shaped morphology, with an average thickness of ~2μm and diameter of ~20~30μm. The cells contain macrofibrils (~200nm diameter) composed of intermediate filaments (~12nm diameter), parallel to the cell surface. Samples subjected to high strain rate Hopkinson bar experiments showed energy-absorption mechanisms such as shear banding, lamellae buckling and delamination. We believe that our findings will provide inspiration for bioinspired designs of energy-absorbent synthetic structures and materials. This work is funded by a Multi-University Research Initiative through the Air Force Office of Scientific Research (AFOSR-FA9550-15-1-0009) and a National Science Foundation Biomaterials Grant (1507978).

14:00-14:25 Invited (1222158)

Shear Localization and Microstructural Evolution in Dynamic Deformation Process

Na Yan, Northwestern Polytechnical University, China

Shear localization is a general failure mechanism of structural materials when subjected to dynamic loading. It occurs when thermal softening suppresses the strain-hardening and strain-rate hardening effect. The microstructure of the shear bands is modified significantly due to drastic thermal excursion and severe plastic deformation. Due to the excellent strain hardening of FCC alloys, special attention is paid to the dynamic behaviour of fcc Al0.3CoCrFeNi and CrMnFeCoNi high-entropy alloys (HEAs). These two kinds of single phase high-entropy alloys were subjected to dynamic impact to examine their dynamic properties, such as strength, and deformation mechanisms, especially focusing on shear localization.The dynamic behavior of single phase HEAs was investigated using a combination of Hopkinson bar experiments and hat-shaped specimens. The strain-hardening rate of FCC Al0.3CrFeCoNi HEA is significantly higher (above 1000MPa) than a coarse-grained pure Al and is retained in the dynamic regime. The combination of multiple strengthening mechanisms such as solid-solution hardening, forest dislocation hardening, as well as mechanical twinning leads to an excellent work-hardening rate in this alloy, which is significantly larger than that for pure aluminum. The resistance to shear localization of this alloy was studied by dynamically-loading hat-shaped specimens to induce forced shear localization. However, no adiabatic shear band could be observed at a shear strain ~1.1. The formation of profuse mechanical twins near the inserted tip in the hat-shaped specimen indicates twinning-induced continuous strain-hardening, which suppresses shear localization in competition with the thermal softening effect. For CrMnFeCoNi HEA, only the specimen with a high shear strain of ~7 develops a shear band. The temperature inside the shear band can rise to the recrystallization temperature (~0.4 Tmelting), ~1550K. The formation of a narrow shear band is found with a width only about 10 μm and nanostructured grains (100~300nm) inside the shear band. The elongated ultrafine-grained grains are proposed to be the first stage of severe shear deformation. Then, they break up into small ultrafine-grained grains and rotate to the equiaxed configuration according to the classical rotational dynamic recrystallization mechanism.

14:25-14:50 Invited (1222355)

Investigation on the Adiabatic Shear Behavior of Heat-Treated Ti-6Al-4V Alloy under Different Strain Rates

Chunhuan Guo, Harbin Engineering University, China

Recently, the metal-intermetallic laminate (MIL) composite Ti/Al3Ti consisting of ductile metal (Ti-6Al-4V) and brittle intermetallic (Al_3Ti) is considered as a potential candidate in aerospace engineering and lightweight structural armor plating and has been widely researched and applied in recent years because of their low density, high strength, high stiffness and high modulus. As a new structural material, the mechanical response, fracture behavior, damage evolution, etc. have been investigated until now. However, many investigations are focused on the entirely deformed behavior except the unit of MIL composite, for example the behavior of ductile metal (Ti-6Al-4V). In order to understand the mechanical behavior of Ti/Al3Ti MIL composite and to supply essential material model used in finite element method, it is very significant to obtain the mechanical properties of ductile and brittle phases in MIL composite. Therefore, it is necessary to test the mechanical properties of each phase (Al_3Ti and Ti-6Al-4V). In this way, we test the mechanical behavior of Ti-6Al-V alloy under different loading condition using Instron testing machine and Hopkinson bar, which have the same heat treatment as the preparation process for MIL composite. The experimental results show that the occurrence of the serrated deformations is accompanied by the generation of adiabatic shear bands. The adiabatic shear effective became obviously with increasing strain rate. When the strain rate was higher than 1100/s, the compressive specimen was fractured along with 45 degree direction. For the fractured specimen, the adiabatic shear can be observed using the fracture. According to the SEM observation, the width of the adiabatic shear band has a linear relationship with the strain rate in a certain range. Based on the above results, the constitutive equation of heated Ti-6Al-4V alloy is obtained by the Johnson-Cook model, which can be used in the numerical simulations of MIL composite. The results attained in this work can help us to understand the deformation behavior and mechanism of MIL composite.

14:50-15:10 (1222571)

Elastoplasticity Properties of Alpha Keratin Bovine Hooves

Bingqian Zhou, Central South University, China

School of Materials Science and Engineering， Central South University, Changsha Bovine hoof with alpha keratin structure, as a biological structural material, has high toughness among the natural biological materials. As the interface between the ground and the skeleton, bovine hooves play an important role in preventing bony skeleton from impact and destroy, accounting for its structure and composition that can disperse pressure and reorient the crack propagation. Although, when comparing to metallic material, its physical properties such as stiffness, toughness and strength may not be outstanding, the low density and light weigh allow them to obtain some high specific applications. In order to find a way to understand the essence of bovine hooves and except to use feasible method and materials to achieve bionics, we choose bovine hooves to research mechanical properties and micro-structure evolution under the fracture experiments. We use an engineering fracture mechanical method to research the fracture toughness of bovine hoof, and apply the J-integral and Wei-bull distribution analysis methods to evaluate the fracture toughness, and also investigate microstructure of the bovine hoof by transmitted electron microscope and nanoindentation. Results show that it always reaches the peak values at 17wt% moisture content, and the mean Intergalactic of longitude orientation along the growth lines are higher than transverse orientation normal to the growth lines, and the longitude specimens are trended to crack redirect. On a more micro scale, the toughness of bovine hoof depends on many parameters, such as the volume fraction and orientation of the intermediate filaments (IFs), and the interface structures between inter-tubular materials and tubules are also thought to be of paramount importance. The IFs arrangement vary from about 0° to 90° against to tubule axis but not uniform distribution. This results in the different fracture characteristics of different layers of bovine hoof wall form inner toward to outer. Furtherly, we put forward a hypothetical mode to explain the structure of the alpha keratin bovine hoof. The fracture induced laminated keratinous structure could form extensive strain-transition interfaces and tubules play an important role in re-orientating cracks propagation, which could absorb crack energy and make crack blunt.

15:10-15:30 (1222651)

Effects of Strain Rate on Mechanical Properties of FeCoNiCrAl0.1 High Entropy Alloy

Kun Jiang, Northwestern Polytechnical University, China

Unlike traditional alloys, which contain one and rarely two base elements, high-entropy alloys HEAs composed by multiple principal elements, generally contain more than four major elements in similar concentrations, ranging from 5 to 35at% for each element. In this work, the effects of strain rate on mechanical deformation of FeCoNiCrAl0.1 HEA with face-centered cubic (FCC) structure were investigated. Standard quasi-static and dynamic tensile/compression testing were performed at strain rate of $10^{-3}s^{-1}$ and $10^{3}s^{-1}$ using a universal testing machine (Instron5848, USA) and Split-Hopkinson Tension / Pressure Bar (SHT/PB) respectively to study the effect of strain rate on the properties of FeCoNiCrAl0.1 HEA, and dynamic compression testing was performed at both room temperature (298K) and liquid nitrogen (77K). Both pre- and post-deformation microstructures were studied using electron microscopes. The results show that this kind of HEA has excellent work-hardening rate and high strain-rate sensitivity of yield strength, as the strain rate increases from $10^{-3}s^{-1}$ to $2600s^{-1}$, the true tensile yield stress increases from 200MPa to 480MPa and its ductility is not reduced, these results may due to its low stacking fault energy and the existence of short-range order. SEM image show that the fracture modes of HEA are obviously different under quasi-static and dynamic conditions, a large number of dimples were found upon the appearance of fracture under dynamic conditions, which are not found under quasi-static conditions. Due to the different deformation mechanism under the quasi-static condition that compression deformed material show profuse mechanical twinning while the tensile deformed material did not exhibit any mechanical twinning. FeCoNiCrAl0.1 HEA exhibited significant tension/compression asymmetry in its work hardening rate and ductility. In addition, the dynamic mechanical properties of the FeCoNiCrAl0.1 HEA under low temperature was explored in this work. Low temperature environment can significantly improve the mechanical properties of HEA. Under the condition of dynamic compression, the true yield strength of FeCoNiCrAl0.1 HEA increased from 400MPa to 560MPa when the temperature decrease from room temperature to liquid nitrogen temperature under the strain rate about $4000s^{-1}$.

15:30-16:00 Tea Break

16:00-16:25 Invited (1234620)

Temperature Rise Associated with Adiabatic Shear Band: Causation or Consequence

Yazhou Guo, Qichao Ruan, Shenxin Zhu, Haosen Chen, Yulong Li, Daining Fang, Northwestern Polytechnical University, China

One of the most important issues related to dynamic shear localization is the correlation among the stress collapse, temperature elevation and adiabatic shear band (ASB) formation. In this work, the adiabatic shear failure process of pure titanium was investigated by dynamic shear-compression tests synchronically combined with high-speed photography and infrared temperature measurement. The time sequence of stress collapse, ASB initiation, temperature rise and crack formation was recorded. The key characteristics of ASB, such as temperature, critical strain, propagation speed and cooling rate were systematically studied. The fraction of mechanical work converting into heat, i.e., the Taylor-Quinney factor, was derived to be 0.25 to 0.55 and it is also positively dependent on the loading rate. This experiment result indicates the commonly used values of 0.9~1.0 should be re-evaluated. The measured temperature rise at the maximum stress (or before ASB initiation) is in the range of 50~90°C, which by itself is not enough to outplay other strengthening mechanisms (such as strain rate hardening). Micro damage induced by the large shear strain should also be responsible for the stress drop. The measured temperature within the ASB is about 350~650°C, whereas the material close to the ASB is also heated. About 37μs after the stress collapse, the temperature reaches its maximum, which is due to the continuous development of the shear band until macro crack formation. The observed fact that temperature rise is quite behind ASB initiation suggests that it could not be the trigger for ASB formation. Therefore, the analytical and numerical analyses of ASB initiation based on temperature perturbation or thermal softening lose their foundation

16:25-16:50 Invited (1222704)

Dynamic Behavior of Ultrafine-Grained and Noncrystalline Titanium at Cryogenic Temperature

Zezhou Li, University of California, San Diego, United States.

The mechanical behavior of ultrafine-grained (500nm) and nanocrystallline (100nm) titanium was examined in the high strain-rate regimes. The stress of ultrafine-grained and nanocrystalline titanium increases significantly compared with coarse grained titanium due to the Hall-Petch effect. In compared with coarese-grained titanium, the strain-hardening rate of the ultrafine-grained and nanocrystalline titanium is significantly lower due to the reduced dislocation activation volume. The strain-rate sensitivity of ultrafine-grained and nanocrysalline titanium does not change too much at both room and low temperature, in comparison with coarse-grained titanium, indicating no significant change of deformation mechanisms. The combinarion effect of low strain harndieng rate, general strain rate sensitivity and increased thermal softening effect made ultrafine-grained and naocrystalline titanium more prone to the shear localization. Dynamic deformation and failure mechanisms of ultrafine-grained and nanocrystalline titanium were studied by using a specimen geometry in which the forced shear was imposed into a narrow region at room and crogenic temperatures. The lower temperature can lead to the formation of narrower shear band under same strain and the strain-rate conditions. The combination effect of the decrease of the thermal conductivity, the decrease of the specific heat capacity and the increase of the thermal softening parameter can lead to the very narrow band of ultrafine-grained and nanocrystalline titanium at cryogenic temperature. The microstructure inside the adiabatic shear band consists of a mixture of elongated grains and equiaxed nanograins that are smaller than initial grains. Formation of equiaxed recrystallized grains inside the shear band was still caused by the classical rotational dynamic recrystallization mechanism in both titaniums. The dislocation density at grain boundaries decreases in a very short time during the cooling process of the well develpoed shear band, which results in the sharp boundary configurations as observed by the trasmission electron microscopy.The adiabatic shear bands were then subjected to the combined brittle and ductile failure.

16:50-17:10 (1222573)

Shear Localization in Near Beta Titanium Alloy

Xu Ding, Central South University, China

Near β Ti-5Al-5Mo-5V-1Cr-1Fe (Ti-55511) titanium alloy has high strength to weight ratios and very attractive combinations of toughness, corrosion resistance and superior fatigue resistance, and is widely applied in aerospace, biomedical and marine industries. Shear localization, also called adiabatic shear band, is a narrow zone in the specimen deformed under high strain rate loading conditions, and is a signal that the material has already lost deformation resistance. Shear localization is the main failure mechanism of the Ti-5Al-5Mo-5V-1Cr-1Fe titanium alloy deformed at a high strain rate. In the present work, an adiabatic shear band is generated in a hat-shaped Ti-55511 titanium alloy after dynamic deformation at cryogenic temperature 173K and room temperature 293K in Split Hopkinson Pressure Bar system. Double peaks appear on the curves of the strain and the stress during the shear localization process when the phase transformation occurs. Widths of the shear bands are affected by the nominal strain of the specimens and the treatment temperature. Microstructure and mechanical properties of a shear band are investigated by optical microscope, high resolution electron microscopy and nanoindentation, respectively. Results show that grains in the boundary of the shear band are highly elongated along the shear direction, and the core of the shear band consists of ultrafine equiaxed grains with sizes 0.1~0.5 microns and with low density of dislocations; and sizes of the grains in the shear band obtained at the cryogenic temperature are smaller than those in the shear band obtained at the room temperature. Strain rate sensitivity of ultrafine grains in the shear band is independent to deformation temperature and grain size, and strain rate sensitivity exponents are dependent on the loading strain rate and positive proportion with increasing the loading strain rate. Finally we find rotational dynamic recrystallization mechanism and phase transformation can take effect on the generation of the new ultrafine equiaxed grains in shear band by results analysis of experimental found and molecular dynamics simulation.

17:10-17:30 (1222634)

Effect of Loading Rate on Mode I Fracture Toughness of Carbon Nanotubes Reinforced Carbon Fibers / Epoxy Composites

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Compared with traditional materials such as aluminum alloy and steel, carbon fiber reinforced resin-based materials have high specific strength, specific stiffness, and good fatigue resistance, so it is used more and more in the fields of aviation, weapons, electronics. However, fiber reinforced resin matrix composites have the disadvantages of low interlayer toughness and insufficient impact damage resistance, and need to improve interlayer toughness through some interlaminar toughening methods. Carbon nanotubes (CNTs) are ideal materials for strengthening and toughening of composite materials due to their large aspect ratio, high specific surface area, and excellent mechanical and electrical properties. In this study, the CNT films produced by the floating catalyst chemical vapor deposition method is interleaved between the layers of the carbon fiber resin-based composite material to improve the interlaminar fracture toughness of composite laminates. Carbon nanotube film was found to be porous by analyzing the SEM micrography, which is beneficial to resin infiltration. After hand-laying the preform, we use vacuum assisted resin transfer molding method to mold the composite laminates. We determined the Mode I interlaminar fracture toughness under different loading rate of the composites with different area densities CNT films. Double cantilever beam (DCB) test geometry was employed for both quasi-static and dynamic fracture tests. The quasi-static test was performed on Instron 5848 tester, and the test method is accorded to ASTM 5528. The dynamic test was performed on a novel dual electro magnetic Hopkinson bar[5], which can achieve symmetric dynamic loading. The range of loading velocities is 10~30m/s. To determine the frature toughness, we use a hybrid experimental-numerical method. By analysis the test results, we can found that the interlayer of carbon nanotube film can enhance the interlaminar fracture toughness significantly compared with the neat composites. And there is a loading rate sensitivity can be found in the test.

17:30-17:50 (1222631)

Remarkable Strength Properties and Shear Fracture of (Al0.5CoCrFeNi)0.92(MoC)0.08 High Entropy Alloy under High Velocity Loading

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High entropy alloys (HEAs) contain at least five elements in an equiatomic or near-equiatomic ratios and have excellent properties such as superb hardness, high heat resistance and strong corrosion resistance. As a broad category of high entropy alloy, AlxCoCrFeNi HEAs have aroused huge interests of researchers since the appearance of high entropy alloy. And they found that the Al0.5CoCrFeNi HEA has a face-centered cubic (FCC) plus body-centered cubic (BCC) solid solution structure and an excellent properties due to the strengthen of BCC structure on the well plastic FCC structure. Powder metallurgy is admitted as a cost effective preparation method and can produce uniform fine grain. Powder extrusion is one preparation method of powder metallurgy which includes the gas atomization and the following hot extrusion of pre-alloyed powder. We studied the mechanical properties of the (Al0.5CoCrFeNi)0.92(MoC)0.08 HEA prepared by hot extrusion under split Hopkinson pressure bar. Microstructure and mechanical behavior of the (Al0.5CoCrFeNi)0.92(MoC)0.08 HEA were investigated using optical microscope (OM), X-ray diffraction (XRD), electron probe microanalyzer (EPMA), and scanning electron microscope (SEM). Results show that the (Al0.5CoCrFeNi)0.92(MoC)0.08 HEA has a uniform FCC+BCC solid solution structure and an optimized grains about 0.5 μm, and the yield strength is sensitive with the strain rate and the values increasing with the strain rates. The Johnson-Cook plastic model is obtained to describe the dynamic flow behavior. The hat-shaped specimens were used to investigate forced shear localization. However, the shear band does not be founded at the designed shear zone, and the cracks even propagate on the both sides of the shear zone. The failure of forming shear band can contribute to the high strain hardening rate, which makes the current HEA an excellent candidate for penetration protection application such as armors.

P. Dynamic Behaviour of Materials

Symposium Organizers :

Marc Andre Meyers, University of California, USA; Na Yan, Northwestern Polytechnical University, China

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Room: Exhibition Area (3rd Floor)

P-1: Experimental and Numerical Study on Impact Resistance of Composite Ice-Resistant Plate （1222679）

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The ice-resistant plate of a turbo-prop airplane is a layer of attached skin, which usually is symmetrically outside the fuselage and corresponding area of the propeller plane. In order to prevent the fuselage from being damaged by the ice block throwed from the propeller. Therefore, the Impact resistance design of the ice-resistant plate is particularly important.In the present work, by using the gas gun, The experiment of the ice block impacting the different ice-resistant plates was made. In the meantime, a three-dimensional digital image correlation (3D-DIC) method was employed to measure the deformation field of the ice-resistant plate under ice block impact. By comparing the Strain-time curve and displacement-time curve between the glass fiber reinforced composite ice-resistant plates and aluminum alloy ice-resistant plates, The results indicated that glass fiber reinforced composites ice-resistant plate can reduce the weight on the premise of ensuring its impact resistance. In the numerical model, the VUMAT subroutine of ABAQUS was used to define the mechanical properties and damage parameters of the composite ice-resistant plate and the Smooth Particle Hydrodynamic (SPH) method was used to build the ice block model to simulate the complex impact process of ice block on the ice-resistant plate. The finite element model was found to be in excellent agreement with experimental data. The simulation results indicated that the closer the ice block was to the vertical impact, the higher deformation of the fuselage would be; If the initial angle of impact changed within 10 degrees, the influence on the experiment result can be ignored; Under the condition of a fixed layer thickness, changing the composite layup can influence the impact resistance of the ice-resistant plate, the glass-fiber reinforced composite with layup shows excellent impact resistance.

P-2: Effect of Cr and W Contents on Charpy Impact Properties of Fe-Cr-W Oxide Dispersion Strengthened Steels (1235326)

Daehyun Kwon, Gunhee Lee, Jonghee Baik, Jung Gu Lee, Univeristy of Ulsan, Korea; Sanghoon Noh, Korea Atomic Energy Research Institute (KAERI), Korea

Oxide dispersion strengthened (ODS) ferritic/martensitic (F/M) steels are considered to be the most promising structural materials for several types of advanced nuclear systems, in which they would most likely compose the materials in the cladding tube for fast reactors and the blanket for fusion reactors. The homogeneous distribution of nanosize yttrium oxide particles in the ODS steels improves high-temperature strength and creep properties, and it also benefits irradiation resistance because of the effective sink of interface between oxide particles and matrix for irradiation-induced point defects and helium atoms. By means of powder metallurgical routes, mechanical alloying offers an economical and appropriate method of synthesizing complex ODS alloys by high energy ball milling at room temperature. However, it is well known that ODS F/M steels produced by mechanical alloying exhibit relatively weak Charpy impact properties and low fracture toughness with respect to conventional F/M steels. Such brittle features generally depends on multiple factors, which not only include the oxide morphology and distribution, but also microstructural factors, such as effective grain size, plastic anisotropy, and microtexture. In this study, the effects of Cr and W contents on the microstructure and Charpy impact properties of Fe-Cr-W ODS steels were investigated. ODS steels was fabricated by mechanical alloying and hot isostactic pressing, followed by hot rolling. The Charpy impact was tested at -40˚c in longitudinal-transverse (LT) and longitudinal-short transverse (LS) orientations. The high contents of Cr and W induced strong <110> texture in the elongated F/M matrix, which is associated with the deformation mechanism during hot rolling. This microstructural anisotropy resulted in splitting of crack-divider type in LT specimens during impact testing, while crack-arrester type was observed in LS specimens. On the other hand, when the contents of Cr and W were relatively low, the equiaxed grains were produced with the segregation of coarse oxide particles along the grain boundaries. With this microstructure, the similar impact fracture behaviors were observed irrespective of the specimen orientation. In addition, the total absorbed energy during impact testing was separated into the energies for crack initiation and propagation, and the relative portion of each energy was interpreted by correlating it with the corresponding microstructure.