References:

1. Veeresh Tekure, and K. Venkatasubbaiah, "Effect of back-pressure ratio on the shock train structures in the isolator of SCRAMJET inlet at deferent Mach numbers", Proceedings of the 8th International and 47th National Conference on Fluid Mechanics and Fluid Power (FMFP), December 9-11, 2020, IIT Guwahati, Assam, India.
2. Veeresh Tekure, and K. Venkatasubbaiah, "Numerical investigation on the extrusive and intrusive subcavity types and their location on the primary recirculation zone for the supersonic turbulent flow through cavity-type flame holders", Thermal Science and Engineering Progress, vol. 25, pp. 100987:1-22, 2021, Elsevier publisher.
3. D. M. Bushnell, "Shock wave drag reduction," Annual Review of Fluid Mechanics, vol. 36, pp. 81–93, 2004.
4. Veeresh Tekure, Pratik Shrikant Pophali, and K. Venkatasubbaiah, "Numerical investigation of aerospike semi-cone angle and a small bump on the spike stem in reducing the aerodynamic drag and heating of spiked blunt-body: new correlations for drag and surface temperature, Physics of Fluids, vol. 33(11), pp. 116108:1-27, 2021, AIP. (Editor's pick Article)

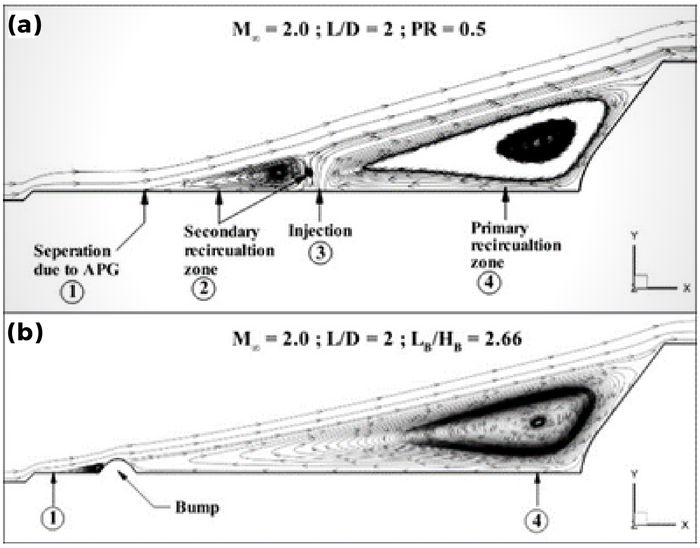


Fig. 3: Streamline contours at Mach 2: (a) spike with lateral injection, and (b) spike with a small bump on the stem

Multi-scale modeling of ductile fracture

Dr Viswanath R R S R Chinthapenta,
Associate Professor, Department of Mechanical and Aerospace Engineering

KID: 20210414

The genesis of macroscale damage in alloys lies in the microstructural inhomogeneities. The perceivable macro damage is usually initiated at much lower scales. The mechanisms leading to ductile failure are of fundamental interest in nuclear technologies, hypersonic applications, aerospace & defense sectors, sheet metal applications, ceramic matrix composites, additive manufacturing, biomedical implants, etc.

At the micro-mechanics lab, IIT Hyderabad, our group works on ductile failure mechanisms. For example, ductile failure of metal reinforcements embedded in ceramic matrix composites is one of the active areas of research. The ceramic matrix composites (CMC) are brittle in nature, particle strengthening is carried out in these materials to increase the ductility. Over several years, our team has developed and implemented advanced numerical techniques to understand the critical stages in ductile failure. The voids are the starting point for dimples commonly seen in the fractography images of the fractured ductile specimens. Hence, the stages in ductile failure can be broadly classified into void nucleation, growth, and coalescence.

A brief overview of the multi-scale model developed at our lab to understand cavitation instability is presented here. The developed model effectively captures the deformation mechanisms at different scales (macro to meso) and connects the scales using the state variables. From experimental literature, the dominant failure mechanisms observed in CMCs are ductile failure of the metal reinforcement, cracking of brittle matrix, and de-cohesion of the matrix and reinforcement. Out of these failure modes, ductile failure of the metal reinforcements is the dominant failure mechanism.

Ductile failure of the metal reinforcement, its influence on the overall mechanical properties of CMCs is quite challenging due to the complex interplay between anisotropy of the metal reinforcement, configurational defects (such as cracks), and material constraints experienced by the reinforcement. In CMCs, when the crack advances, two possible scenarios are encountered: crack circumventing the reinforcement and crack bridging the reinforcement. When the interface between the particle and matrix is weaker, de-cohesion of interface and partial matrix cracking is observed. While the interface between the particle and matrix is stronger, crack bridging phenomena are predominantly observed (see Fig. 1). All these failure mechanism results in a significant increase in fracture energy of the CMCs.

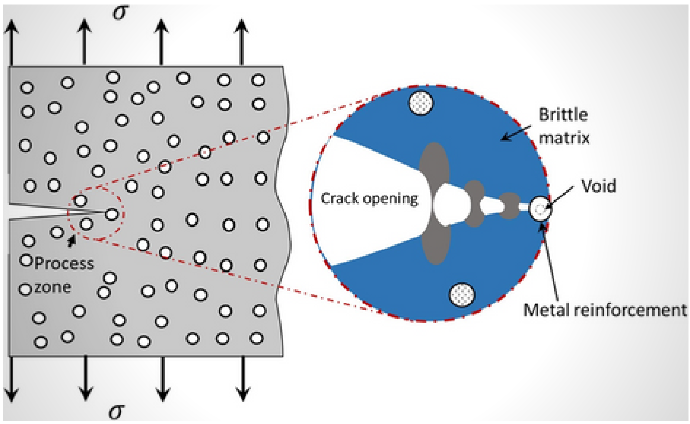


Fig. 1: A schematic of fracture in brittle matrix composite with reinforcement

In the latter scenario, fracture energy is solely due to cavitation. While in the former scenario, the observed fracture energy is partially from the cavitation, interface de-bonding, and matrix cracking. Instabilities such as exponential void expansion at certain constant remote strain are observed during cavitation. The critical stress corresponding to this cavitation instability is of interest in understanding void nucleation. Further, material anisotropy greatly influences critical stress. Earlier estimates of critical stress were based on isotropic phenomenological models. To address this, in our group, we have conducted a systematic approach to arrive at the limits of cavitation instability using mechanistic approaches based on crystal plasticity framework.

In our systematic approach, a representative material volume (RMV) was considered for a ductile reinforcement embedded with a spherical hole. For simplicity and symmetry, one eight models of RMV were considered for the simulations. Copper (Cu) single crystal properties with face cementer cubic (FCC) structure were used as reinforcement properties. The material constraint is captured through stain triaxiality. Strain triaxiality of values ranging from 1 to -0.45 was considered for loading. These loading conditions can replicate most of the loading scenarios on the reinforcement (1 representing high constrain, 0 representing uniaxial loading, -0.45 representing least constraint). The void volume fraction values were used. To understand the effect of crystallographic orientation, several orientations such as [100], [110], and [111] were considered.

Two types of failure mechanisms were observed: first, the material is failed by void growth with an increase in remote strain. In this case, the softening of the material is dominant than the material hardening. Second, the Material is failed by void growth at nearly constant remote strain (cavitation instability). While the void volume fraction is approaching zero, the cavitation instability stress is converging to constant values, called critical stress. Our work provided the procedure to estimate the critical stress values for a given orientation and reported the critical stress values for different orientations, as shown in Fig. 2. We have also reported that fracture energy and energy absorbed by metal reinforcement vary significantly with material anisotropy.

The void shape is observed to have a strong dependence on the initial crystallographic orientation. Both spheroidal and non-spheroidal voids are observed during cavitation (as shown in Fig. 3). The non-spheroidal voids are attributed to material anisotropy and void spin.

In our group, we are extending our investigation on ductile fracture to understand the complex failure mechanism such as void coalescence and void sheeting.

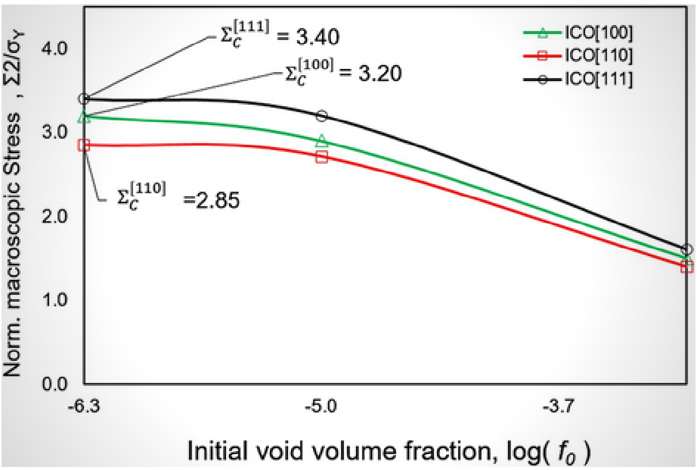
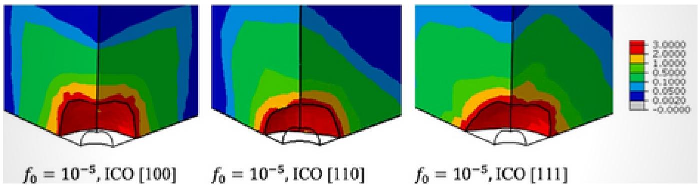


Fig. 2: Effect of material anisotropy on the cavitation limit



$f_0 = 10^{-5}$, ICO [100] $f_0 = 10^{-5}$, ICO [110] $f_0 = 10^{-5}$, ICO [111]

Fig. 3: Deformed void shape for different initial crystallographic orientation (ICO)

References:

1. MK Karanam, G Gulivindala, VR Chinthapenta, Effect of anisotropy on the ductile fracture in metal reinforcements of brittle matrix composites, Theoretical and Applied Fracture Mechanics, 112, 10293, 2021
2. MK Karanam, VR Chinthapenta, Void growth, and morphology evolution during ductile failure in an FCC single crystal, Continuum Mechanics and Thermodynamics, 33(2), 497-513, 2021

A new perspective on the law of the wall

Dr S K Zeeshan Ali,
Assistant Professor, Department of Civil Engineering
KID: 20210415

Turbulent flows are common in natural and industrial environments. A few examples include atmospheric circulation, a fast-flowing river, flow around an aircraft, and a pipeline. The law of the wall is one of the major accomplishments in turbulence research and is widely used in computational models of fluid dynamics. The law accurately predicts the flow velocity, specifically in the near-wall shear layer that accounts for the substantial fraction of the aerodynamic (or hydrodynamic) drag on the wall, e.g., aircraft surface or inner-wall of a pipe. The mean-velocity profile (MVP) can be obtained by averaging the local mean-velocity u at a wall-normal distance z over a long duration (see Fig. 1). Three distinct layers exist at an infinitely large Reynolds number Re: near-wall layer (viscous sublayer and buffer layer), overlap layer, and the wake layer.

The law of the wall stems from the imagery of turbulent eddies arising from the fluid mixing that gives rise to the turbulent shear stress. German aerodynamicist Prandtl proposed the mixing-length hypothesis, drawing an analogy between the motions of turbulent eddy and random gas molecules, in order to quantify the turbulent shear stress. Despite magnificent advances, Prandtl's classical work and recent theories fall short to find the origin of the law of the wall.

In a recent attempt, Ali and Dey found the origin of the law of the wall with the aid of a new hypothesis, called the mixing-instability hypothesis. It states:

At a large Reynolds number, the turbulent mixing at a location in a wall-bound flow produces disturbances that transmit in the form of waves, causing a continuous stretching and shrinking of turbulent eddies to produce the turbulent stress.

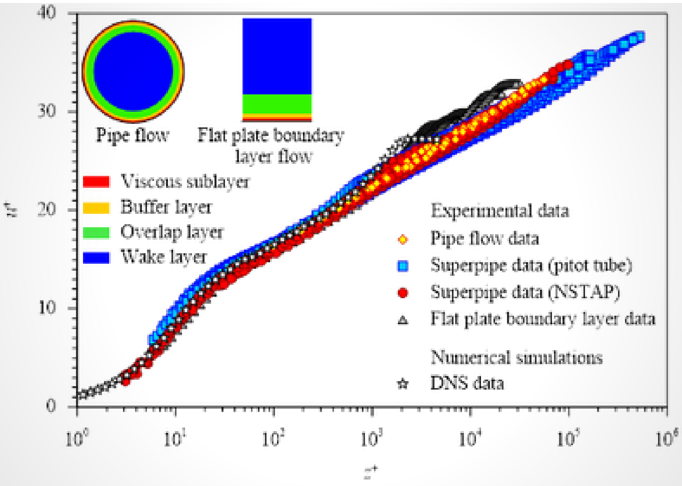


Fig. 1: MVPs comprising data of experimental observations and numerical simulations. Here, u+ = u/u*, u* is the shear velocity, z+ = zu*/n and n is the coefficient of kinematic viscosity of fluid.