Cavitation studies in Materials: New insights from modern techniques in 2D/3D/4D characterisation

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Special Issue Guest Editorial Article :

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Cavitation is ubiquitously associated with the final stages of failure in structural materials. As this view pervades the approach to component design, the emphasis in the development of modern structural materials has been to strengthen the microstructure without concern for properties that inure them against the degrading influences of cavitation. Thus, materials development via microstructural design has been the paradigm in vogue. As a result the research into origins, proliferation and mechanisms of cavitation in materials has been inadequate to provide a robust theoretical framework for failure of materials exposed to degradation phenomena. The inadequacy to understand the behaviour of cavitation in materials has been perhaps most acutely felt in the development of ferritic – martensitic heat resistant steels for elevated temperature application. This is because in order to extend the temperature range of application of these steels to 600°C and beyond, the knowledge of the factors responsible for cavitation led embrittlement, that is present right from incipient strains accumulated during creep failure at low stresses would be indispensible. The importance of this aspect has been well known to the scientific community, for example the inaugural issue of "*Materials Science and Technology*" in 1967 (then published as "*Metal Science*") dwelled on the theme concerning the physical origins of cavitation at grain boundary precipitates[1]. However until recently the tools to investigate damage phenomena in materials to develop and confirm a robust theoretical framework was lacking which contributed to the present state of poor knowledgebase on cavitation in materials. In the last decade rapid development in the technique of micro-tomography has led to an explosive growth in its application to understand the mechanisms of damage and failure of a diverse class of materials. One of the highlights of this growth is application of the tomographic technique to dense structural materials such as steels at large synchrotron sources (eg. SPring-8, ESRF and APS) and, the development of an array of complementary destructive techniques, that are capable of volumetric characterization of microstructure of materials. This has contributed to the rise of the 3D/4D paradigm that provides a new approach to complement the traditional structure – property correlation method to understand the mechanical behaviour of materials. This approach is now being increasingly applied to understand the cavitation behaviour in materials by interrogating the bulk in multi-dimensional and multi-modal manner. The present special issue highlights the application of these 3D/4D techniques to provide new insights on the cavitation behaviour of structural materials, through a set of 12 invited peer reviewed papers.

The issue of creep naturally finds prominence in the several papers in this special issue. The type IV failure is a pernicious problem during creep of weldments[2] in 9-12%Cr steels and efforts to arrive at suitable micro-structural design[3] to mitigate this problem have led to the development of an experimental grade MARBN steel on the basis of an understanding that a reduction of a zone of fine grain structure in HAZ would enhance resistance against this form of embrittlement. Although on a macro-scale this microstructure was achieved, the synchrotron studies combined with EBSD studies by Schlacher et. al.[4] provided the insight that individual fine grain at the local scale can act as sites for intense cavitation promoting the failures at stresses below 100 MPa. This typically illustrates the need to investigate damage contained in the microstructure in a multi-scale and multi-modal manner. The task of obtaining a 3D characterisation of micro-structure in multi -scalar and -modal terms, is highly challenging and set of techniques/protocols need to be developed to commit such a volumetric information. One such example that appears in the special issue is the newly developed technique of Correlative Tomography applied by Burnett et al[5] along with complementary SANS studies by Jazaeri et. al[6] on a AGR power station steam header (1C1/1, cast 55919) of austenitic stainless steel (316H) removed from service (after 65000 hours, exposed to 16 MPa internal pressure at 525°C) near a region at the opening mouth of a large reheat crack. While the application of SANS established that the crack mouth region rather than its tip contains extensive cavities up to about 350 nm in size, through the application of the Correlative Tomography the association of these cavities with the second phases ($M_{23}C_6$, sigma and G phase) and chemical composition of stringers were established. On the basis of multi-scale information on cavitation and second phases an insightful discussion on the possible roles of the latter, along with the influences of grain boundaries and residual stress on the development of creep voids has been provided. A factor in such an analysis that is missing relates to the information of the grain mis-orientation obtained from EBSD characterisation. Two papers in the special issue concern this aspect, one from Abbasi et. al.[7] and the other from Yardely et. al.[8] . The work being reported by the former is of significance as it provides an unique example of combining the power of serial sectioning over a *large volume* with information from EBSD to reveal the classification of grain boundaries in copper in terms of their propensity for creep cavitation. In contrast to the 3D approach Yardely et. al. provides a detailed exposition of a new automated method to map the creep damage in 2D to crystallographic hierarchy quantified by EBSD of the tempered martensitic microstructure of heat resistant steels. These destructive techniques capable of volumetric characterisation of damage are principally in the micro-meter length scale. In order to capture the nature of damage in materials in the sub-micrometer length scale, FIB serial sectioning has emerged as an appropriate tool to characterise creep cavities in 3D from incipient stages close to their nucleation. It is believed that at low stresses damage in tempered martensitic steels begins at early stages of creep and hence tool such as FIB-serial sectioning would be useful to know the point of explosion of cavitation. With these principal aims Yadav et. al.[9] applied FIB serial sectioning in coupons extracted from interrupted creep of P91 steel at 60 MPa and 650°C for 9000 hours. Small cavities of about 600 nm size could be distinguished to be present in the microstructure of the sample possibly undergoing viscous creep. Significantly the sample also contained pre-existing cavities prior to creep that rapidly increased in size, number and volume fraction as compared with the newly developed small cavities formed in the microstructure. Of late an interesthas been created on the role of entrained defects in structural materials on subsequent cavitation behaviour during service.[10] The influence of the presence of prior damage generated in materials due to melting, casting etc. on the propensity to cause cavitation led failures has been reviewed in this special issue by Campbell[11] that emphasized the role of bi-films.

The tomographic technique, apart from its non-destructive nature to characterise bulk in 3D, is also unique in terms of its capability to provide 4D information that can reveal the kinetics of damage proliferation in material. Metal matrix composites of light metals such as Aluminium, are one of the extensively investigated materials using micro-tomography, especially using in-situ experiments. The imaging the bulk of these advanced structural materials typically contain damage from the conditions such as heating and cooling during processing or temperature excursions during service that may not be revealed at the surface. Accordingly Chapman et. al.[12] investigated the damage that developed due to thermal cycling of SiC reinforced Al 2080 metal matrix composite using micro-tomography scans that detected and quantified the growth of the cavitation developed at the particle matrix interface due to difference in their expansion coefficients as a function of thermal cycling. These weak interface properties of the Al based metal matrix composites have been improved using metallic glass reinforcements rather than using alumina or SiC particulates. The paper by Ferre et. al.[13] appearing in the special issue explores the damage caused by these superior class of reinforcements in a Al+Al5083 matrix containing Zr based bulk metallic glass particles in two processing variants to fabricate the MMC. The carbon fibre reinforced polymers are yet another popular class of new generation structural materials and little is known about their failure mechanisms. Sket et. al.[14] have attempted to provide a new insight on their deformation and damage mechanisms by in-situ tests.

The role of cavitation to be beneficial rather than an un-desirable phenomenon, the latter being the abounding theme of the special issue thus far, is perhaps best illustrated by its functional necessity in bone implants. While the research themes appearing in the special issue focuses on the undesirability of the presence of cavities as a detriment to the structural performance, porous super-elastic metals such as NiTi for bone implant applications combine the functional and structural requirements by their specific architecture of its interconnected cavities. The paper by Gupta et. al.[15] in the special issue provides a quantitative assessment of the interconnected porosity using a new connectivity – tortuosity index in a porous NiTi fabricated by SHS evaluated from tomographic scans. The concluding paper in the special issue by Gupta et. al.[16] seeks to critically examine the potential of the various 3D techniques, principally based on tomography, for life assessment of heat resistant steels exposed to creep phenomenon with reduced empiricisms. The directions of future research to realise the potential of tomography for residual life assessment are outlined.

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Guest Editors

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