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The 1st International Workshop on Plasticity, Damage and Fracture of Engineering Materials

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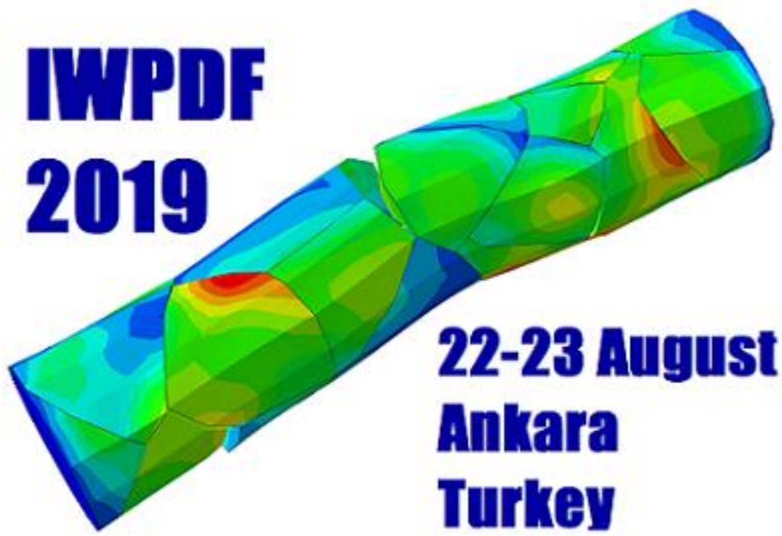

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Proceedings of IWPDF 1: The 1st International Workshop on Plasticity, Damage and Fracture of Engineering Materials 21-22 August 2019

Cihan Tekoğlu and Tuncay Yalçınkaya (editors)

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Preface

These proceedings contain the abstracts presented at the 1st International Workshop on Plasticity, Damage and Fracture of Engineering Materials, co-organized by the TOBB University of Economics and Technology and the Middle East Technical University (METU), on 22-23 August 2019 in Ankara, Turkey. The aim of the workshop is to discuss recent progress in the fields of plasticity, damage, and fracture mechanics. Both computational and experimental studies are within the scope of the workshop, which focuses on a better understanding of how the material microstructure, loading and environmental conditions affect deformation, degradation and failure of engineering materials. The workshop intends to provide an open platform for discussion on new directions in prediction and prevention of failure of engineering materials.

The organizers wish to thank all the invited lectures and the contributors for their effort in preparing their presentations, posters and abstracts in these proceedings. Selected full papers will be published in the Procedia Structural Integrity. The support from ESIS (European Structural Integrity Society), TOBB University and METU is gratefully acknowledged.

Ankara, 22 August, 2019.

Cihan Tekoğlu and Tuncay Yalçınkaya

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Damage resistance through double-transformation: Towards new generation TRIP-assisted alloys

C.C. Tasan, S.L. Wei, J. Kim

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Keywords: metastability, martensite, toughening

Abstract: Owing to their unique mechanical properties and intriguing deformation modes, high-entropy alloys (HEAs) have aroused remarkable research interest. Yet, metastability in HEAs and its corresponding effects on microstructure and property development, constitute a relatively small fraction of current literature. Earlier we designed a transformation-induced plasticity-assisted dual-phase HEA (TRIP-DP-HEA) by decreasing both the thermal and mechanical stability of the FCC phase. Here, we will present some interesting phenomena observed in this alloy, regarding damage mechanisms, mechanically-induced forward and reverse phase transformations, and thermally-induced resetting behavior, obtained using various in-situ testing and imaging techniques.

On the effective rheology of random aggregates in diffusional creep and sintering

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Keywords: Plastic flow, Mass transport, Micromechanical modelling.

Abstract: At high homologous temperature, the plastic flow of a polycrystalline material can be mediated by self-diffusion and grain boundary sliding, a deformation mode called "diffusional creep". One usually distinguishes "Nabarro-Herring" creep from "Coble" creep, depending on whether diffusion operates primarily by lattice diffusion or by grain boundary diffusion. The pioneering treatments by Herring (1950) and Coble (1963) both suggest a linearly viscous macroscopic behaviour, with shear viscosity varying as the square of grain size in Nabarro-Herring creep, and as the third power of grain size in Coble creep. These scaling relations remain widely used today to deduce the dominant diffusion mode in diffusional creep. Surface diffusion and grain boundary sliding are also operating in the presence of pores, and govern bulk and shear viscosity in sintering. Despite the vast literature on this subject, a number of questions remain open regarding the physical nature of the various mechanisms at play and their relative contributions to the effective value of the grain size exponent.

In this work, we revisit the micromechanical modelling of diffusional creep in random aggregates based on variational principles within a micromechanics framework [1]. For a dense aggregate of equiaxed grains, we show that the classical results by Herring and Coble correspond to upper bounds on the shear viscosity coefficient, and obtain new complementary lower bounds. Our results shed new light on these classical results and question the validity of the common interpretation of the dependence of viscosity on grain size. We also extend the method to address elongated grains and textured polycrystals. Results are compared to various estimates proposed in the literature. The method is further developed to investigate the effect of microstructure parameters (porosity, grain size, average coordination) on bulk and shear viscosity coefficients in sintering. The results emphasize the role of grain boundary friction coefficient both in diffusional creep and sintering. Deviation from Newtonian viscosity in sintering at high strain rate is also discussed [2-3].

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A Multiscale Approach for Cavity Initiation and Growth in Rubberlike Materials

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Keywords: cavitation, rubberlike materials, microsphere model

Abstract: The contribution presents a novel three-scale constitutive framework which considers the non-affine chain distribution at micro-scale, a porous meso-scale for existing pores in the material during manufacturing process and relevant micro-meso-macro transformations. In the first part, a *seminumerical homogenization framework* for porous hyperelastic materials that is open for any hyperelastic microresponse is presented [1]. The conventional analytical homogenization schemes do apply to a limited number of elementary hyperelastic constitutive models. Within this context, we propose a general numerical scheme based on the homogenization of a spherical cavity in an incompressible unit hyperelastic solid sphere, which is denoted as the mesoscopic representative volume element (mRVE). The approach is applicable to any hyperelastic micromechanical response. The deformation field in the sphere is approximated via nonaffine kinematics proposed by Hou and Abeyaratne (JMPS 40:571-592,1992). Symmetric displacement boundary conditions driven by the principal stretches of the deformation gradient are applied on the outer boundary of the mRVE. The macroscopic quantities, eg, stress and moduli expressions, are obtained by analytically derived pointwise geometric transformations. The macroscopic expressions are then computed numerically through quadrature rules applied in the radial and surface directions of the sphere. *A three-scale compressible microsphere model* is derived from the developed seminumerical homogenization framework where the micro-meso transition is based on the nonaffine microsphere model at every point of the mRVE. The numerical scheme developed for the derivation of macroscopic homogenized stresses and moduli terms as well as the modeling capability of the three-scale microsphere model is investigated through representative boundary value problems. In the second part, the existing spherical cavity is allowed to growth where the internal rupture under high triaxial stresses are driven by a Griffith-type crack driving force conjugate to the cavity radius [2]. The model is capable of exhibiting quasi-incompressible hyperelastic behaviour prior to cavity initiation and cavity growth under high hydrostatic tension. The performance of the proposed model and the respective algorithmic implementation is demonstrated through three-dimensional representative boundary value problems.

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Unraveling micro-plasticity and boundary mechanisms in martensite and dual-phase steel

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Keywords: micromechanics, *in-situ* testing, martensite.

Abstract: Lath martensite is the key strengthening phase in advanced high strength steels, yet unexpected ductility of lath martensite is reported in literature in both single phase and multiphase steels, although without systematic identification of the plasticity mechanisms. Here, well-defined micro-tensile tests are carried out on fully martensitic steel with a clean large substructure and a variety of substructure boundaries orientations with respect to the loading direction.[1,2] Two lath martensite deformation mechanisms were identified, namely, crystallographic slip [3] and substructure boundaries sliding,[4] that compete with each other to carry the overall plasticity. The conditions under which these two mechanisms are active depend on the difference between the highest Schmid factor of the slip systems which lie in the boundary planes and that of the slip systems which do not lie in the boundary planes.[3,4] In addition, the martensite crystallography and chemistry in dual phase and fully martensitic steel was studied in detail.[5] Subsequently, to shed light on the many contradictions in the literature regarding BCC ferrite plasticity, well-defined uniaxial micro-tensile tests [1,2] were performed on single-crystal ferrite specimens, showing highly reproducible plastic behavior in which the activation of the primary slip system always does follow the Schmid's law. With all this insight, micro-tensile tests were applied on dual phase steel specimens consisting of a ferrite and martensite grains, as an example of an important engineering steel. It was found that the boundary sliding mechanism is also of great importance for lath martensite deformation in multiphase steels, which explains earlier reports of unexpected high strains in martensite.[7]

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Towards a virtual laboratory for the design of aluminium structures: automotive applications

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Keywords: Aluminium, ductile failure, joining.

Abstract: With the emergence of electrical vehicles, the need for aluminium structures in the automotive industry is increasing. Indeed, aluminium alloys offer a very good compromise between weight, strength and ductility which makes them ideal solutions for energy absorbing structures in the crash relevant areas of a car body. To obtain an optimal solution in terms of weight and crash performance, numerical simulations are extensively used and therefore require accurate finite element models. Within the SFI-CASA (Centre for Advanced Structural Analysis, https://www.ntnu.edu/casa) and the research project FractAl (https://www.ntnu.edu/kt/fractal), a multiscale modelling framework for microstructure-based simulation of plasticity and ductile fracture of aluminium structures – or a virtual laboratory – is being developped. This framework relies on a nano-structure model [1,2], crystal plasticity [3,4], unit cell analysis [5,6] and strain localization analyses [6,7] to predict the strength, work-hardening and ductile failure of 6XXX aluminium alloys. This presentation aims at illustrating the capabilities of this virtual laboratory in the development of aluminium structures for automotive applications.

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Mixed mode fracture in brittle polymers

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Keywords: Epoxy resin, Mixed mode fracture, Nano-reinforcement, Fracture experiments

Abstract: The use of brittle and ductile polymers in different industrial applications has increased noticeably in recent decades. Among different types of polymers, epoxy resins have received much attention by researchers and engineers. However, epoxy resins are known to be susceptible to brittle fracture in particular when a crack is embedded in the epoxy component. It is common to use some reinforcement agents at different scales to enhance the load bearing capacity and toughness of epoxy resins, among which multi-walled carbon nanotube (MWCNTs) has become a popular reinforcing particle in the nanoscale. Meanwhile, it is important to investigate the mechanical behavior, including the fracture properties, of the epoxy/MWCNT composites.

The experimental results reported in the past on fracture properties of cracked epoxy-based nanocomposites are primarily confined to mode I crack problems [1-2]. However, epoxy components are very often subjected to complex loading conditions, for example when a combination of tension and shear loads (or mixed mode loads) is applied to the cracked nano-composite. The main objective of this research is to present some test results extracted from fracture experiments on epoxy/MWCNT nanocomposites under mixed mode loading. To this end, first, a new test configuration designed for mixed mode fracture tests is introduced [3]. The experimental configuration is then modeled and analyzed by finite element method in order to determine the stress intensity factors for different combinations of tensile and shear loads. To evaluate the applicability of the test configuration, first a number of experiments are performed on PMMA, as a popular and inexpensive brittle material. Afterwards, the target experiments are performed on epoxy/MWCNT nanocomposite specimens reinforced by different percent contents of MWCNT. The results obtained from the mixed mode fracture experiments are presented and discussed according to the calculated critical stress intensity factors and also the micro-mechanisms of fracture observed in the SEM pictures taken from the fracture surfaces.

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Can we use electrons to measure local stresses in polycrystalline materials?

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Keywords: High-resolution Electron Backscatter Diffraction, stress mapping, crystal deformation, EBSD.

Abstract: In material science and engineering, highly accurate local ***absolute*** stress and crystal orientation measurements are often hard to attain, while they may provide crucial information to unravel elusive mechanisms and interactions when investigating grain boundaries, phase transformations, etc. While the solution for many researchers is some form of synchrotron based (3D) X-ray diffraction, which is complex, not generally accessible and limited in spatial resolution, we explore the potential of using a new form of Electron Backscatter Diffraction (EBSD), which is commonly accessible in material science labs worldwide, to accurately measure ***absolute*** stresses and crystal orientations on the sub-microscale.

Novel in this work is to combine Integrated Digital Image Correlation (IDIC), a well-established tool in experimental mechanics for highly accurate identification of e.g. material properties [1], with High angular Resolution EBSD, a well-established tool to attain local ***relative*** stresses [2]. Through a rigorous derivation of the optimization scheme, starting from the fundamental brightness conservation between EBSD Kikuchi patterns (EBSPs), a direct one-step correlation of the maximum overlapping field-of-view (region of interest) of the EBSPs is achieved [3]. Further novelty is introduced by fully exploiting crystal symmetry and out-of-plane-stress and co-correlating the EBSD geometry, yielding simultaneous correlation of ***all*** overlapping regions of interest in multiple intergranular EBSPs [3].

As a result, highly accurate measurement of ***absolute*** stress, crystal orientation and EBSD geometry, using limited assumptions, is demonstrated on a virtual polycrystalline case-study, showing errors, respectively, below 20MPa (or 10^{-4} in strain) and 7×10^{-5} rad, ***without*** using simulated EBSPs as reference [4]. Thereby, warranting experimental validation, we present the potential of using an accessible technique to quantify the local elastic and plastic crystal deformations in challenging polycrystalline microstructures.

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Investigation of grain boundary strengthening: Experiments and CPFEM model

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Abstract: Grain boundary strengthening has been studied extensively to understand polycrystal behavior. The mechanical behavior of grain boundaries are still not accurately described with a simple model because of the complicated nature of the grain boundaries. Various different mechanisms could be present at a grain boundary such as dislocation sources, sinks, pile-ups, slip transmission from one gain to another has been noted for low angle grain boundaries, etc. In the pioneering works of Ashby and Fleck, the strengthening is explained with the difference in the strain between two neighbor grains [1]. According to more recent perspective, finite element models were used to take into account both equilibrium and compatibility to more accurately models that consider grain interactions [2]. In addition, various modeling approaches were utilized such as grain boundary dislocations [3], slip transmission [4], dislocation fluxes [5], strain gradients [6, 7]. Gurtin et al. has proposed a bi-scale model to satisfy the balance laws at micro scale [8] that was later utilized in many following references. Most of these models demand a special treatment of the finite elements near the grain boundaries, hence there is still a great need for simplified models that take into account grain interactions. In this study, an aluminum oligocrystal is studied to further understand the grain interactions. Different constitutive laws for strain hardening and flow rule are used such as; phenomenological, statistically stored dislocation density based, and geometrically necessary dislocation density based models. The effect of the three different modeling approaches on the total strain distribution is investigated to further understand and accurately model grain boundary strengthening.

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Non-linear elasticity perspective on crystal plasticity

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Keywords: Plasticity, Phase transition, Dislocation, Homogenous nucleation.

Abstract: We show that nonlinear continuum elasticity can be effective in modeling plastic flows in crystals if it is viewed as Landau theory with an infinite number of equivalent energy wells whose configuration is dictated by the symmetry group GL (3, Z). Quasi-static loading can be then handled by athermal dynamics, while lattice based discretization can play the role of regularization. As a proof of principle we study in this Letter dislocation nucleation in a homogeneously sheared 2D crystal and show that the global tensorial invariance of the elastic energy foments the development of complexity in the configuration of collectively nucleating defects. A crucial role in this process is played by the unstable higher symmetry crystallographic phases, traditionally thought to be unrelated to plastic flow in lower symmetry lattices.

Understanding Plasticity of Nanostructured Metals through Advanced Micromechanical Testing

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Keywords: nanostructured metals, mechanical behavior, structure-property relationships

Abstract: Nanostructured metals are materials with feature sizes below 100 nm. These features can take various forms such as nanograins, nanolayers and nanopores. The resulting nanocrystalline, nanolayered and nanoporous materials show outstanding strength due to Hall-Petch strengthening, which makes them very promising as structural materials of future. However, most nanostructured materials are also brittle due to the small number of dislocations available for mediating plasticity. In order to enable the use of these new generation materials in engineering applications, novel approaches that can extend their plastic limits are needed.

Recently, we have investigated the mechanical behavior of a wide range of nanomaterials under different loading conditions. The nanomaterials that we considered include nanocrystalline alloys, nanolayered metals, nanoporous metals and metallic glass-crystalline composites. We have employed different loading conditions through nanoindentation, micropillar compression and nanoscratch testing, to gain insight to the plastic behavior of these materials. Our findings indicate that one of the most promising methods to improve ductility is to combine metallic glasses and crystalline metals at the correct length scale. Nanolayered metallic glass-crystalline composites provide a simple model system to investigate this route. In these nanolaminated materials, when the layer thickness is comparable to that of shear band spacing, the crystalline layers start to effectively impede the catastrophic propagation of shear bands. The optimized amorphous-crystalline nanocomposite, as a result, provides an excellent combination of high strength and ductility. When it comes to nanoporous metals and nanocrystalline alloys, an analogous route can be taken through grain boundary engineering, which is currently the most promising approach for improving the ductility of these brittle materials.

Continuum-kinematics inspired peridynamics

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Keywords: Peridynamics, Continuum kinematics, Thermodynamic consistency.

Abstract: The main objective of this presentation is to develop a novel continuum-kinematics-inspired approach for peridynamics (PD), and to revisit PD's thermodynamic foundations. We distinguish between three types of interactions, namely, one-neighbour interactions, two-neighbour interactions and three-neighbour interactions. While one-neighbour interactions are equivalent to the bond-based interactions of the original PD formalism, two- and three-neighbour interactions are fundamentally different to state-based interactions in that the basic elements of continuum kinematics are preserved exactly.

In addition, we propose that an externally prescribed traction on the boundary of the continuum body emerges naturally and need not vanish. This is in contrast to, but does not necessarily violate, standard PD.

We investigate the consequences of the angular momentum balance and provide a set of appropriate arguments for the interactions accordingly. Furthermore, we elaborate on thermodynamic restrictions on the interaction energies and derive thermodynamically-consistent constitutive laws through a Coleman--Noll-like procedure. Notably, we show that various choices for temperature or coldness satisfy the dissipation inequality and provide meaningful temperature or coldness evolution equations together with Fourier-like conduction equations. See our recent contributions [1,2] for further details.

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A State-Based Peridynamic Truss Element for Progressive Failure Analysis of Composites

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Keywords: Peridynamics, Truss Element, Composites, Cracking

Abstract: Composite materials have been widely used in military, automobile, and aircraft industries due to their strength-to-weight ratio, corrosion resistance, hardness, and toughness. Stiffness of composite materials depends on fiber directions and type of fibers and resins. Their failure involves a progressive series of events with discrete failure modes such as matrix cracking, fiber-matrix shear, and fiber breakage.

The prediction of the material behavior and failure modes of the composite structures is a challenge for the classical computational methods such as finite element method (FEM) because their governing equations involve spatial derivatives which are not defined at discontinuities such as cracks. Therefore, the mathematical structure of the formulation breaks down if there is any crack in a body. In order to eliminate the shortcomings of the classical methods, a state-based peridynamic (PD) truss element was introduced by Madenci et al. [1]. This PD element is extremely suitable for failure analysis of structures since its stiffness matrix is expressed in terms of the nonlocal form of the spatial derivatives. This feature allows crack nucleation and propagation at multiple sites with arbitrary paths in the structure. Also, this PD element provides computational efficiency because of the ability to have non-uniform discretization in the analysis of deformation and cracking within a finite element framework.

This study investigates the progressive failure analysis of composite structures by using a state-based PD truss element. Its capability is demonstrated by considering a composite lamina having different fiber orientations with and without a defect in the form of a crack under tensile loads. Crack nucleation and growth are based on the maximum principal stress and visibility criteria. The solution is achieved by employing an implicit algorithm until crack initiation or growth, and then continuing with an explicit algorithm.

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Unified Mechanics Theory

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Keywords: Damage Mechanics, Thermodynamics, Fatigue

Abstract: The field of classical mechanics is based on Sir Isaac Newton's work in "The Principia," published in 1687. In this work, Newton introduced the world to three universal laws of motion, which describe the relationships of any object, the forces acting upon it and the object's resulting motion. It is these three laws that make up the foundation for classical mechanics, and all subsequent theories of mechanics are derived from them. But Newtonian mechanics still cannot account for the past, present or future of any aspect of a physical body or its governing equations.

Around 1850, Rudolf Clausius and William Thomson (Kelvin) formulated both the First and Second Laws of Thermodynamics. Because the field of thermodynamics governs the past, present and future of all physical bodies, the aging process and life span of any physical system can be modeled in accordance with the thermodynamics laws. Still, thermodynamics alone cannot convey the response of a physical body under an external force at any given moment – something classical mechanics equations are able to achieve.

Over the last 150 years, many unsuccessful attempts were made to unify the fields of classical mechanics and thermodynamics, in order to create a generalized and consistent theory of evolution of life-span, degradation, fatigue and fracture of inorganic and organic systems. All past attempts to unify Newtonian Mechanics and Thermodynamics were based solely on the use of curve fitting to physical experiments, and empirical models. Unified Mechanics Theory unifies laws of Newton and Thermodynamics using entropy generation rate with following equations,

$$F=(1-\Phi) \ and \ F=k \ u \ (1-\Phi)$$

Where Φ is a Thermodynamics State Index (TSI) can have values between zero and one. TSI is directly calculated from the physical entropy generation mechanisms in the material/system without curve fitting modeling and or testing.

Unified Mechanics Theory can predict the degradation, fatigue and fracture of any physical system based purely on mathematical calculations and without the need for testing or curve fitting phenomenological models. In this presentation, recent advances in Unified Mechanics Theory will be presented.

Fracture predictions of U-notched samples: A discrete energy approach

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Keywords: Fracture criterion, Crack onset, Failure predictions, U-notches

Abstract: Kodsi [1] proposed a crack initiation criterion based on the notion that nucleation is a sudden and discrete phenomenon for isotropic, linear elastic media in a brittle state. In this theory, Griffith's criterion [2] is cast into a finite difference form and nucleation occurs only when the total potential energy is equal to the energy spent on a finite-length crack. The length is obtained from Pugno and Ruoff's [3] energy-based equivalent to the non-local stress criterion [4,5] with a bounding stress argument. Asymptotic analysis provides a closed-form expression for the change in total potential energy due to a perturbation in the domain representing the finite-length crack. Fracture toughness and material strength are the only parameters required to operate the criterion. A distinct advantage of the criterion is applicability to both sharp and blunt notches, as well as ease of automation in a post-processing framework of a structural analysis software [6].

This work provides the formulation specific to blunt notches, summarises the theory and investigates further the capability of the criterion. Crack propagation from numerous PMMA samples weakened by U-notches that were subject to mixed-mode fracture are studied. Comparison to experimental results are made and good agreement is demonstrated, lending further support to the theory.

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Fractographic Features of Long Term Operated Gas Pipeline Steels Fracture under Impact Loading

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Keywords: gas pipelines, impact toughness, delaminations.

Abstract: Main gas pipelines are strategic objects on which a country's energy security is significantly dependent. Therefore, a very important task is to ensure the safe operation of gas mains during their long term service. One of the main characteristics for assessment of pipeline steels state is impact toughness which is commonly used for evaluation of the metal suitability for gas-transportation systems. Reduction in impact toughness of structural steels clearly indicates their embrittlement, caused by long term operation under a combined action of working stresses and other adverse service conditions, i.e. aggressive environments action, hence, a risk of brittle fracture rises.

It is known that pipelines are commonly made of rolled low-alloyed steel with ferritic-pearlite microstructure. Due to the production process peculiarities, the structure of these steels reveals texture. Narrow, discontinuous strips of perlite grains are separated by wide bands of ferrite grains aggregations. Besides, ferrite grain size gradient is observed in both (transverse and longitudinal) pipes sections. This promotes an anisotropy of steels' mechanical properties. Namely, an essential difference has been evaluated between values of impact toughness determined by Charpy testing for specimens cut in mutually perpendicular directions. The values of KCV are higher for longitudinal (relative to the rolling direction) specimens as compared with transverse ones for all tested steels regardless of their strength and operation time. It could be explained by the difference in a length of perlite grains strips separated by ferrite grains in specimens of different orientation. In the case of longitudinal specimens testing, the fracture plane intersects almost uninterrupted strips of pearlite and ferrite grains that leads to a higher resistance to brittle fracture in this direction. In contrast, fracture of transverse specimens realizes by detachment along structural elements of the texture (delamination). Since the continuous pearlite strips in this plane are considerably shorter (for 17H1S steel their length is ~150 μm against ~2 mm in the longitudinal direction), hence, a path with the lowest brittle fracture resistance could be chosen easier.

The main fracture peculiarity revealed by the fractography for the operated steels comparing to the steels in the initial state is the appearance of delaminations on the fracture surfaces, which are oriented in the rolling direction. The tendency to rising the delaminations amount on the fracture surfaces of the operated steels with their service time is noticed, besides, the maximum delaminations amount is found on fracture surfaces of transverse specimens. This is in a good agreement with the results of the Charpy testing, namely, the lower impact toughness, the more delaminations on the fracture surfaces. Therefore, a conclusion is made that impact toughness drop caused by long term operation of pipeline steels is definitely concerned with the delaminations amount on the fracture surfaces.

Microstructural factor for the difference of brittle crack propagation resistance by the direction in thick steel plate with texture

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Keywords: Brittle crack propagation, Arrest, TMCP, Misorientation, Twist Angle

Abstract: In recent years, steel plates used for large structures such as container ships tend to be extremely thick, and their strength is increasing. Since the risk of brittle fracture increases as the thickness of the steel plate becomes thicker, it is important for ensuring security to arresting property of the brittle crack. In large container ships, there are two scenarios for appropriately arresting the propagation of brittle cracks just in case of the occurrence of brittle fracture. Scenario 1 is postulated to crack initiation in hatch side coaming and propagation into the deck, and scenario 2 is from the deck to hatch side coaming. Although the experimental fact that the required brittle crack arrest toughness *K*ca for arrest is lower in scenario 1 than scenario 2 is known, its mechanisms are not clear [1]. Thus, the authors decided to carry out an experiment to isolate the cause.

The first experiment is a three-surfaces slatted Charpy test which was developed in order to evaluate propagation resistance only and contrast to V-notch Charpy test which largely includes initiation property [2]. A steel plate in which a strong texture exists and a steel plate subjected to heat treatment above Ac3 to eliminate such texture were prepared. For each steel plate, two types of test specimens were prepared: one in which a crack is propagated in the thickness direction (corresponding to Scenario1), and one in which a crack is propagated in the width direction (corresponding to Scenario2). In order to understand further mechanism for the difference, EBSD analysis was performed for each steel type, the twist angles [3] in neighbor grains were analyzed, and the correlation with the absorbed energy was considered. It is finally concluded that average twist angle in crack path becomes a good parameter for a resistance to brittle crack propagation.

The second experiment is the DWTT test. Using the steel plate used in the Charpy test and specially processed DWTT specimens, attention was focused on the propagation phenomenon of brittle cracks. The brittle crack propagation arrest length was measured, and the relationship with parameters such as surface roughness was considered.

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Fracture Prediction of Additively Manufactured ALSi10Mg Materials

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Keywords: Fracture, Porosity, Additive manufacturing.

Abstract: In the scope of the study, the plasticity and ductile fracture behavior of additively manufactured AlSi10Mg tensile specimens were investigated at quasi-static strain rate experimentally and numerically. Small uniaxial tensile, notched and shear test specimens were produced in three different scanning directions, i.e.0°, 45° and 90°, by Selective Laser Melting (SLM) method according to the contributions [1, 2]. Digital image correlation software (Aramis software, GOM GmbH) was used to record digital images during deformation with a camera and local equivalent strains on the deformed specimens were determined by digital image correlation analysis. Simulation studies were carried out in commercial software LS-Dyna. Cazacu-Barlat orthotropic yield criterion, which can describe both the anisotropy of a material and the yielding asymmetry between tension and compression, were determined to describe the orientation-dependency of the yield response [3]. In order to predict the deformation behavior of the additively manufactured specimens, *MAT_CAZACU_BARLAT (*MAT_233) was selected [4]. The flow curve was extrapolated with Hockett-Sherby hardening law on the basis of ductile fracture experiments. The stress triaxiality is highly significant factor that controls the initiation of ductile fracture. However, unpredicted fractures are attributed to the evolution of pores in the material. The porosity distribution in the material was affected highly by production parameters in AM method. Heterogeneously distributed pores caused unexpected damage on the surface where the supported structure was produced showed unstable behavior. Therefore, the initial failure started at the supported structure for the notched specimens. In order to interpret the damage evolution caused by pores, SEM (Scanning Electron Microscope) images were obtained at fractured surface and non-damaged surface. The results showed that the pores in structures were highly big and intense to be neglected. For this reason, numerical specimens including randomly distributed pores were created and investigated to observe the effect of pores simultaneously. The numerical results showed that the existence of randomly distributed pores in the model showed more realistic description of the material behavior, especially in plasticity and fracture.

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Variation of Stress Triaxiality Sheet Metal Shear Compression (SMSC) Specimen

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Keywords: Sheet metal shear compression, Stresstriaxiality.

Abstract: Stress state parameter such as stress triaxiality becoming essential in structural damage assessment. In this work, a newly designed fixture for large plastic strain testing of sheet metal is numerically examined. In the proposed design, a representative volume of sheet metal is constrained with two rigid bodies (top and bottom), which transform axial compressive load to constrain-free gage section. This configuration was numerically analyzed for three hypothetical bilinear hardening materials. The numerical results showed that the global prescribed displacement can be recovered at the gage section; also, stress (strain) state is three-dimensional, stress and strain at the gage section is uniform. The stress triaxiality vary with the slot angle and material. Where for slot angle are (25˚, 35˚, 45˚) the stress triaxiality varies in the range of (-0.18 to -0.33). However, the variation of stress triaxiality with materials is not significant. This study confirms the potential of this configuration for large strain testing as well as the variation of stress triaxiality in the compression region for sheet metal.

Application of XFEM with Degraded Properties for Fracture Evaluation

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Keywords: Damage Criteria, Extended Finite Element Method, Fracture Mechanics.

Abstract: During the last four decades, lots of researches were conducted to examine damage and fracture with different stress triaxialities. To resolve the transferability issue, several local approaches reflecting micro-mechanical features have been employed for estimation of constraint effects. For instance, fracture resistance (J-R) curves of low alloy and high Cr steels were successfully characterized by small punch testing and subsequent finite element analyses with GTN and Rousselier models [1]. However, application of this kind of approach requires time consuming calibration of a couple of damage parameters.

In this study, extended finite element method (XFEM) was adopted due to relative simplicity in numerical modelling and calibration processes. Particularly, two user subroutines based on either strain rate or stress ratio changes were developed and incorporated into XFEM analyses, respectively. Thereby, fracture behaviors of nuclear pipes [2] and penetration nozzles [3] as well as compact tension specimens [4] were estimated in conjunction with age-related degradation mechanisms such as primary water stress corrosion cracking and thermal aging embrittlement.

XFEM analyses results were compared to a reference crack growth curve of nickel-based alloy, and existing fracture mechanics solutions of typical weld metal of austenitic stainless steel with residual stress distribution and base metal of cast austenitic stainless steel. These methods will be expanded to assess other materials, degradation mechanisms and components, if specific damage criteria are properly defined as well as further verification is available, without complex environmental facilities or relevant experimental efforts. The XFEM application experiences and plan are also discussed.

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Fracture Toughness (Mode-II) of Nanostitched Composites

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Keywords: Nanoprepreg, nanostitching, fracture toughness (Mode II).

Abstract: Laminated composites demonstrated low delamination strength[1-3]. For this reasons, z–axis reinforced fiber architectures were designed by three dimensional (3D) weaving[4] braiding[5] stitching technologies[1, 4] including z-pin anchoring and flocking. Since beginning of the 1990s, nano particles as a form of sphere and single wall or multiwall tubes as well as nanofibers were employed in fibrous composites by adding the nano in the matrix to enhance the delmanination resitance of composite[6-7]. The mode–II interlaminar fracture toughness properties following the end notched flexure method (ENF) of nanostitched carbon/epoxy nanoprepreg composites were studied. The fracture toughness (GIIC) of the nanostitched composites showed 3.4 fold increase compared to the pristine sample. Thus, the nanostitching improved the mode–II toughness of all the carbon/epoxy composites considering to the nano, and pristine composites. It was obtained that the type of stitch fiber as well as fabric pattern, in particular prepreg carbon stitching fiber and satin prepreg woven fabric was effective. The basic mechanism for the enhancement of the GIIC toughness in the nanostitched composite was the interlaminar resin layer failure especially as a form of shear hackle marks in where nanostitching arrested the delamination in stitching zone during crack propagations. MWCNTs in the matrix and filament also mitigated the stress concentration probably as a form of debonding/pull-out/stick-slip/friction. Therefore, nanostitched carbon/epoxy woven composite exhibited improved damage tolerance performance considering to the pristine composite.

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Phase-field approach to model fracture in human aorta

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Keywords: crack phase-field model, human aorta, aortic dissection.

Abstract: Over the last decades the supra-physiological and pathological aspects of arterial tissues have become a prominent research topic in computational biomechanics in terms of constitutive modeling considering damage and fracture [1].

The current study presents a variational approach to the fracture of human arterial walls, featuring a thermodynamically consistent, gradient-type, diffusive crack phase-field approach. A power balance renders the Euler-Lagrange equations of the multi-field problem, i.e. the deformation and the phase-field. The respective constitutive model is essentially anisotropic and in accordance with the tissue morphology. A novel anisotropic phase-field model accounts for not only the altered crack patterns with respect to the orientation collagen fibers, but also the distinct strain-energy contributions due to isotropic and anisotropic parts [2, 3, 4].

The prediction of the crack pattern are studied via single edge-notched tests to ascertain anisotropic features of the model. Aside from that, a novel simple concept of design, i.e. an idealized cylindrical model of the multi-layered thoracic aortic wall with a notch representing the initial tear provides insights regarding the nascent crack growth associated with aortic dissection. In particular, the analysis indicates crack onset and progression around the initial tear while aligning with the direction of the first fiber family, capturing the helical pattern of the aortic dissection in the aorta [4]. The results also lay bare the need for a systematic experimental characterization of the human aorta for an inclusive parameter identification.

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Experimental Investigation of Crack Propagation Mechanisms in Commercially Pure Aluminum Plates

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Keywords: Ductile fracture, plate tearing, crack propagation.

Abstract: The crack surface morphology in tearing of ductile metal plates depends on the mechanical properties, chemical composition and the microstructure of the plate material as well as on the loading conditions and the specimen geometry; see e.g. [1]. This study assesses the crack surface morphologies observed in commercially pure aluminium plates (Al 1050 H14). Mode I tearing was performed in both single and double edge notched tensile test setups with specimens cut from five different plates with different thickness t, viz. $t \in \{0.5, 1, 3, 4, 5 \text{ mm}\}$. In each combination, the long axis of the notch was either parallel (0°) or perpendicular (90°) to the rolling direction. Fractographs showed that, for specimen thicknesses smaller than 5 mm, the crack had a cup-cup morphology almost throughout its entire length for 0° specimens, while slanted crack propagation was visible in some regions of 90° specimens. For t = 5 mm, on the other hand, the dominant crack morphology was slanted for both directions, the extent of the cup-cup regions being larger for 0° specimens. The crack morphologies were repeatable for each direction-thickness combination, while also being consistent for both test setups having different loading conditions. The differences in the mechanical properties and chemical compositions of the plates with different thicknesses were measured to be relatively small. This suggests that damage–related microstructural parameters (such as the volume fraction, size, shape and spatial distribution of second phase particles, which act as void nucleation sites; see e.g. [2]) have the largest relative effect on the crack surface morphology for the plates tested in this study.

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The importance of 'Dynamics' in the design and performance testing criteria for railway track components

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Keywords: Dynamic properties, Dynamic load actions, Response spectra, Performance-based Design.

Abstract: It is unquestionable that track dynamics have caused various problems in railway operations and maintenance. Broken sleepers due to impacts at rail joints, switches and crossings, transition zones, bridge ends, and so on can result in failure of fastening systems and later lead to detrimental train derailments. Excessive ballast settlement and dilation from dynamic load conditions can weaken track lateral resistance and eventually track misalignment under extreme climate. These are a couple of clear evidences that railway industry faces daily. However, most railway practitioners still ignore the dynamics aspects when designing, testing, and manufacturing railway track components. The importance of 'dynamics' in the design, performance testing and manufacturing of track components have been highlighted with evidences in this paper. The thorough review of track load conditions is discussed. The proposed change from static or quasi-static design to a more rationale dynamic design has been discussed. This implies the change from "*quasi-static load > static analysis and design > static and cyclic tests > quasi-static behaviors > individual component performance*" to "*realistic dynamic load > dynamic analysis > dynamic design and behavior > individual component performance > track performance*". Fundamental issues of dynamic testing of materials and structural components have been described to aid the understanding of inexperienced practitioners. The essential need to determine dynamic properties of materials and components, for dynamic design considerations will be highlighted. It is crucially important that such the dynamics aspects are highlighted so that the dynamic resistance of the components and railway tracks can be established for better public safety and operational reliability.

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Mechanical characterization of metals by small sampling size

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Keywords: plasticity; metals; sampling size.

Abstract: Classical plasticity models permit to simulate accurately the macroscopic response of several metals. Thus, the output of even complex experiments can be correctly interpreted with the support of numerical simulations [1]. This combined approach fosters the development of indirect material characterization methodologies based on non-destructive testing, potentially applied on site for fast integrity assessment of structural components [2].
In this context, reducing the sampling size improves the maneuverability of the portable equipment and mitigates the invasiveness of the tools employed for residual strength evaluation [3]. However, the representativeness of the collected information may become an issue.
This contribution focuses on the equivalence of the material properties that can be inferred from metal sampling of typical dimensions of hundreds or dozens microns, corresponding to indentation tests carried out at maximum load differing by one order of magnitude. This topic is addressed herein by the comparison of the results gathered from experimental and numerical analyses of pipeline steel.

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Improvement of the Mechanical Properties of Magnesium Alloy AZ31 Using Non-linear Twist Extrusion (NTE)

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Keywords: Non-linear twist extrusion; Ultrafine grain; Severe plastic deformation.

Abstract: Mg and its alloys have recently drawn huge attractiveness for several structural applications since they possess low density, and high specific strength. However, the complex form of structural components requires high formability; unfortunately, Mg and its alloys have poor ductility. Studies have shown that this low formability could be caused by the HCP crystal structure with limited slip system [1]. Such low formability has led to limited application for structural components. Several studies attempt to improve their mechanical properties and formability [1,2]. This paper focuses reports on improving the mechanical properties of AZ31 using severe plastic deformation (SPD).

Nonlinear twist extrusion (NTE) was applied to deform wrought AZ31 alloy. NTE is a modified twist extrusion, and the advantage of NTE is the absence of strain reversal and more homogeneous strain distribution. The detail of NTE is described in the reference [3]. The billets were subjected to 1 pass at temperatures of 473K and 523K. The grain refinement mechanism of AZ31 alloy differs from that of FCC metals under simple shear deformation where the large grains are subdivided by boundaries having low misorientation angles. Elevated temperatures conditions were considered to avoid premature fracture by activating another slip system in addition to basal slip. At room temperature, only basal slip systems are activated [3]. The microstructure and mechanical properties were examined before and after 1 pass. The mechanical properties were investigated by Vickers's hardness test and tensile test.

Grain refinement is achieved after 1 pass with improved homogenous structure. Twins were evident at 473K and a bimodal structure was realized at an elevated temperature of 523K. The initial hardness of 57 Hv as received material significantly changed after 1 pass, with 51% and 19% rise to 86Hv and 68Hv after 473K and 523K respectively. The yield strength and ultimate tensile stress improved from 177 MPa and 363 MPa to 234 MPa and 382MPa after 1 pass. Both hardness and tensile properties were improved by1 pass at 473K, and this is attributed to grain size reduction and strain hardening. Results obtained at 523K are partly influenced by texture based on Taylors relation. Agree with Taylor relation. High However, the ductility of the material deteriorated in the successive 1 pass. The study in progress aims at comparing other SPD with equivalent plastic strains at successive passes.

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Computational generation of subsequent yield surfaces in porous, ductile Solids

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Keywords: subsequent yield surface, porous ductile solid.

Abstract: Typical ductile fracture involves void nucleation followed by void growth and coalescence. Evaluation of subsequent yield surfaces for porous ductile solids is essential for understanding various practical problems like forming, fatigue and problems involving abrupt changes in strain path. Various parameters like loading path, magnitude of pre strain/stress and the definition of yield influence the subsequent yield locus that may expand, translate, distort, or rotate. Following Schmidt [1], a special four-noded user element is developed in ABAQUS, that is tied to a RVE having periodic boundary condition, restrained rigid body rotation and subjected to either macroscopic deformation gradient or Cauchy stress. The algorithm gives the freedom to control all stress component independently, making it easier to unload and reload the RVE macroscopically along proportional or non-proportional stress paths. The macroscopic stress state of the RVE in the six-dimensional stress space can be traced, making the algorithm particularly favorable for tracing out subsequent yield surfaces. Khan et al. [2] have shown experimentally that the subsequent yield loci strongly depend on the yield definition. They have used offset method (offset from the linearity) to probe the yield point. For the low offset values, a 'nose' develops in the pre-strain direction and flattening occurs at the opposite direction. But for higher offset values uniform expansion of the yield surface is reported.

In this work, we computationally generate subsequent yield surfaces for voided ductile solids. A spherical void has been considered inside the cuboidal RVE. The matrix material is made up of elastic-plastic material that follows the von Mises yield criteria. Simulations have been performed in the macroscopic stress space, and attainment of critical rate of plastic energy dissipation density marks yield. To ensure that the yield loci are convex, normality has been checked. For the low plastic rate dissipation, the 'nose' in the prestressing direction and flat region in the opposite direction has been reproduced. On the other hand, for the higher plastic rate dissipation, subsequent yield surface is seen to expand almost uniformly, which is similar to results presented in the literature.

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Physical Mesomechanics and Spectrum of Materials Surface Layer at Friction Process

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Keywords: physical mesomechanics, scale level, fatigue, surface layer effect, thermo-mechanical theory of wear.

Abstract: The paper reviews the physical mesomechanics of structurally inhomogeneous media, developed on the verge of continuum mechanics (macro level) and physics of plasticity and strength of deformable solids (micro level). According to the concept of the structural level of deformation, at friction the surface layer of deformable solids is an independent leading functional subsystem. It is shown that with an increase of the deformation level of material, it develops autonomous processes (plasticity waves) inside, which have a significant impact on the staginess of plasticity flow localization and the destruction of contacting bodies, at the meso level the deformation has a transitional-rotational character.

In the sliding contact zone, the friction surface structure have tribological characteristics that are significantly different from the initial data. The proposed theoretical model for the mechanism of failure as a result of the thermo-mechanical loading in friction validates our assumption on the formation of the surface layers of low density in the pre-surface layer of dislocation and intense cracking. These results are consistent with the experimental data and the radiography of structural changes in the thin surface layers of metal in friction.

The studied model suggests the similarity between processes of the mechanical interaction occurring in the surface layers of material in friction, and the impact interaction. Therefore, based on this model the concept of surface layer formation as result of the thermo-mechanical effect does not contradict the experimental data as for the established normal friction regime as for the critical friction described by grasping.

Role of residual stresses to crack initiation and propagation under impact loading

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Keywords: Residual stress; impact loading; crack initiation; crack propagation.

Abstract: Considering fatigue failures, cracks initiate as a result of increase in dislocation density due to forward and reverse loading leading to dislocation motion, i.e. slip. As more loading cycles are applied, more dislocations accumulate at slip planes along slip directions leading to strain localization, formation of intrusions and extrusions and finally fatigue cracks to initiate. To increase fatigue performance of metallic materials, mechanical surface treatments including shot peening and laser peening are applied to induce beneficial compressive residual stresses introduced as a result of inhomogeneous plastic deformation [1]. Compressive residual stresses superimpose with applied tensile loads leading to increase in number of cycles to have crack initiation. On the crack propagation side, compressive residual stresses act as crack zone shielding, leading to decrease in Ktip, stress intensity factor at crack tip, so that crack growth rate can be slowed down. Considering both fatigue crack initiation and propagation mechanisms, required steps are time-dependent. On the other hand, for impact loading where strain rates are very high, time is very limited for crack initiation and propagation. Therefore, failure mechanism can be expected to be different compared to fatigue failures. In this study, tungsten cube projectiles with a speed of 400 - 600 m/s were sent to 10 mm-thick Al6061-T651 aluminium plates to investigate the role of residual stresses under impact loading. Since, fracture of any metallic material can be associated with nucleation and growth of micro-cracks [2], the possibility of residual stresses to delay crack initiation and propagation under very high strain rates was explored. Shot peening was applied to aluminum plates and up to −300 MPa compressive residual stresses were achieved. As observed from the impact experiments, plugging fracture mode was observed due to very hard and blunt projectile and softer aluminium plates used in the set-up. The experimental results suggested that compressive residual stresses were unable to improve the performance (measured as ballistic limit) under impact loading. Therefore, it was concluded that residual stresses have no significant effect on crack initiation and propagation under impact loading, i.e. very high strain rates for the set-up used in this study.

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Applications on Three-Dimensional Fatigue Crack Propagation Using Fracture and Crack Propagation Analysis System (FCPAS)

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Keywords: Finite element method; three-dimensional mixed mode; fatigue crack propagation

Abstract: In this study, results from two applications on three-dimensional fatigue crack propagation using the in-house developed "Fracture and Crack Propagation Analysis System (FCPAS)" are presented. These applications are an inclined penny shaped crack in a large body under tensile load [1] and multiple semi-elliptical surface cracks in a dog bone shaped specimen under tensile load [2]. FCPAS uses finite element models to calculate three-dimensional mixed mode stress intensity factors and other sub-modules to predict shapes of the incrementally growing crack fronts and the resulting fatigue crack propagation lives. The evolving crack surfaces are generated by successively adding the incremental growth surfaces and re-meshing and re-solving the finite element model using the standalone program FRAC3D, a finite element-based standalone program employing three-dimensional enriched finite elements. The results show that the fracture surfaces evolve into a mode-I type three-dimensional crack as expected. Very agreements are obtained between the results of the current studies and those of [1] and [2] in terms of both evolving crack surfaces and crack propagation lives. Therefore, it is concluded that the applied method is capable of accurately predicting linear elastic three-dimensional fatigue crack propagation problems.

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Interlaminar tensile strength of different angle-ply CFRP and GFRP composites

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Keywords: Interlaminar Tensile Strength, Curved Beam Strength, Delamination

Abstract: Due to high specific strength and modulus requirements, demand for the use of polymer-based composites in structural applications have been increasing more than ever. On the other hand, their interlaminar properties are known to be relatively weak. Such structures are prone to interlaminar failures including delaminations under static or impact loads. Interlaminar tensile strength (ILTS) is one of interlaminar properties which gives an indication of delamination onset in through the thickness loading for composite structures, while fracture toughness is another property which gives information about propagation of delamination. Conventionally ILTS value which is experimentally obtained specifically for 0˚//0˚ interface according to ASTM D6415 [1] is used in design and analysis even for interfaces with different ply orientation. In this paper our objective is to investigate the effect of ply orientation on the ILTS for CFRP and GFRP laminates. For this purpose, curved beam strength (CBS) experiments are conducted on CFRP and GFRP 0˚//0˚, 25˚//-25˚, 45˚//-45˚ and 65˚//-65˚ interfaces. It is found that for CFRP laminates 0˚//0˚ ILTS is significantly higher than the other orientations whereas no such difference is observed in the ILTS values for GFRP laminates. Furthermore, except for the 65˚//-65˚ interfaces, all failures occurred only as delamination in both CFRP and GFRP laminates, whereas in 65˚//-65˚ laminates matrix cracks are found to precede delamination.

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Investigation of Fretting Fatigue Failure Mechanism of Lug-Bush Connection Members

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Keywords: Fretting fatigue, Stick-slip zones, Tribolayer.

Abstract: Lug-bush connection members are widely used in aerospace industry, specifically in the connection of rotors to helicopter main body. Small amplitude cyclic loadings cause fretting on the mating surfaces of these connection members when the tangential force acting on the mating surfaces is less than the force required to create a bulk motion [1]. Under these loading conditions, only a fraction of the contact area experiences relative motion therefore, stick and slip zones are formed in accordance with the existence of relative motion between mating surfaces [2]. In this study, failure mechanism of a titanium lug and a steel bush combination subjected to high cycle tensile fatigue loading is investigated. The contact surfaces are inspected using a digital microscope and a scanning electron microscope (SEM). Different surface conditions are observed through the mating surfaces which are proved to be stick and slip zones. Black residues are observed at the slip zones, which are caused by the relative motion of the contacting lug and bush surfaces. Elemental compositions of the stick and slip zones are obtained with energy dispersive spectroscopy (EDS) analysis in SEM. The results showed that rubbing of lug-bush surfaces created wear debris at the slip zone which was then corroded and formed a tribolayer containing fine metal particles and oxides. The crack is observed to initiate from this tribolayer.

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Formulation and implementation of a new porous plasticity model

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Keywords: porous plasticity, softening, damage

Abstract: A new rate independent porous plasticity framework is proposed in order to model the ductile damage behavior of metallic materials. The plasticity behavior is governed by a simple yield function that could also be written in a potential form. It includes porosity functions affecting both deviatoric and hydrostatic stress evolution. The model has been motivated from the creep models based on the void growth mechanisms suggested by Cocks (see [1]). The porosity functions are based on the evolution of spherical RVEs and has a similar representation to the yield function proposed by Yalçınkaya and Cocks (see [2]), which is derived from the growth of cylindrical voids. The current version of the model predicts damage solely due to void growth and it is going to be extended to include the void initiation and coalescence criteria. The numerical examples address the performance of the developed model for the evolution of porosity through unit cell calculations and for the necking of a uniaxial tensile bar. The preliminary void growth calculations in the unit cell study is acceptable at triaxiality values below 1.

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Development of a micromechanics based cohesive zone model and application for ductile fracture

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Keywords: cohesive zone model; ductile fracture; porous plasticity.

Abstract: It is a well-known fact that the underlying physical mechanism for the initiation and propagation of cracks in metallic materials is the nucleation, growth and coalescence of micro-voids. Cohesive zone modelling has been one of the most popular approaches for modelling this type of degradation process, yet it is mostly based on phenomenological relations and do not consider the physics at the fracture process zone. The idea here is to bridge the information obtained from the physical fracture mechanism due to void growth to a traction-separation law in order to obtain a physically motivated relation to be implemented in crack propagation simulations. In this paper, the derivation and implementation of a micromechanically motivated traction separation law in the context of ductile fracture is discussed. The formulation of traction-separation law is based on the growth of pores in an array of representative volume elements where pores are idealized as cylinders. Traction-separation laws are derived under normal and shear loading for mode-I and mixed-mode respectively. Upper bound theorem is applied and different laws are obtained with different assumptions [1][2]. The obtained traction-separation laws are used as the constitutive model for cohesive elements. Numerical simulations are conducted for a compact tension specimen to illustrate the performance of the model under mode I loading where the effect of size and shape of pores are illustrated explicitly. It was observed that increasing initial pore fraction or decreasing initial pore height has a detrimental effect on the material, decreasing strength and toughness as expected. Moreover, as a second example the intergranular cracking of polycrystalline aggregates is studied using the obtained micromechanics based mixed mode relations where the bulk response is obtained through strain gradient crystal plasticity approach.

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A Micromechanics Based Numerical Investigation of Dual Phase Steels

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Keywords: Dual-phase steel; Representative Volume Element; Crystal Plasticity

Abstract: The aim of this paper is to investigate the effects of microstructural parameters such as the volume fraction, morphology and spatial distribution of the martensite phase and the grain size of the ferrite phase on the plasticity and localized deformation of dual-phase (DP) steels. For this purpose, Voronoi based representative volume elements (RVEs) are subjected to proportional loading with constant stress triaxility. Two alternative approaches are employed in a comparative way to model the plastic response of the ferrite phase, namely, micromechanically motivated crystal plasticity and phenomenological J2 flow theory. The plastic response of the martensite phase, however, is modeled by the J2 flow theory in all the calculations. The predictions of both approaches closely agree with each other in terms of the overall macroscopic response of the DP steels, while clear differences are observed in the localized deformation patterns. The results of the present study are also compared with experimental and computational findings from the literature.

Fracture analysis of round-tip V-notched components made of rubber-like materials using averaged strain energy density criterion

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Keywords: Rubber components, Round-tip V-shape notch, Averaged strain energy density criterion

Abstract: Nowadays, hyperelastic materials such as rubbers and elastomers have become increasingly important in research and industry. A network-like structure, consisting of polymeric chains, has led to unique properties such as high and purely elastic deformations in rubber-like materials [1]. However, similar to brittle materials, the existence of any geometric discontinuities like a crack or notch will affect the behavior of rubbers. Thus, the prediction of rupture condition in these materials is of paramount importance.

One of the energy-based criteria, which has attracted many attentions due to its convenience in use and high precision, is the averaged energy density (ASED) criterion. Based on this criterion, a limited amount of energy in a specified volume around the stress concentration region controls the fracture of components [2]. This criterion, which was already utilized extensively for brittle materials, has been recently extended for being used in cracked components having non-linear behavior like rubbers [3, 4].

On the other hand, by examining the previous studies, it can be concluded that despite the importance of rounded V-shaped notch, no research has been carried out in the presence of this type of stress concentration in hyperelastic materials. As a consequence, this study is devoted to investigate the rupture of rubbers containing a round-tip V-shape notch using the ASED criterion. To this end, first, some experiments are performed for rounded-tip V-notched rubber samples. Afterwards and in order to utilize the ASED criterion for predicting the rupture loads of tested samples, some finite element modeling considering both geometric and material non-linearities are performed. The comparison between the estimations of the ASED criterion and the corresponding experimental data reveals the high efficacy of this criterion in hyperelastic materials weakened by round-tip V-shape notches.

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Finite Element Modelling of TBC Failure Mechanisms by Using XFEM and CZM

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Keywords: Extended Finite Element Method (XFEM), Cohesive Zone Method (CZM), Thermal Barrier Coatings (TBC).

Abstract: Thermal Barrier Coatings have been widely used in modern turbine engines to protect the nickel based metal substrate from the very high temperature service conditions. In this study, some of the failure mechanisms of typical Air Plasma Sprayed TBCs consisting of three major layers: Inconel 718 substrate, NiCrAlY based metallic bond coat (BC) and Yttria Stabilized Zirconia (YSZ) based ceramic top coat (TC) are investigated. Understanding of the cracking mechanism of TBC in terms of design and performance is very important, because the behavior of TBCs on ductile metallic substrates is brittle. To this end, four-point bending experiments conducted in Kütükoğlu [1] are analyzed by using XFEM and CZM. XFEM is used both for the initiation and the propagation of cracks in ceramic top coat. The method is based on the partition of unity concept and uses enrichment functions to enhance the degrees of freedom of in the vicinity of cracks. The main advantage of the method is that it does not require the mesh to match the geometry of discontinuities. For the modelling of delamination between top coat and bond coat CZM is used by embedding the cohesive zone into the model using a cohesive interface. CZM describes material separation with a traction-separation law which is the basis for computing the delamination crack initiation, propagation, and opening at the interface [2]. Three different four-point bending tests with varying top coat and bond coat thicknesses are studied by using the finite element method. Finite element analyses are conducted with the commercial finite element software ABAQUS which allows to use both techniques in same finite element model. It is observed that multiple vertical cracks are initiated in the TC. Cracks initiate at the free surface of YSZ, propagate through the whole TC and reach the TC/BC interface. At the TC/BC interface cracks propagate between two layers along TC/BC interface in the form of delamination. It is observed that the average crack spacing increases with the increasing thickness of the TC similar the experiments. Furthermore, failure behavior obtained in simulations are found to be consistent with the experimental results.

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A phase-field approach to viscoelastic fracture in rubbery polymers

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Keywords: crack phase-field model, rubbery polymers, viscoelasticity

Abstract: Rubbery polymers are widely used in, e.g., the automotive, the aeronautical and space industry. Rubbery polymers consist of network of long polymer chains responsible for the elastic response and a secondary free chains superimposed to the elastic network in terms of entanglements leading to the rate-dependent viscoelastic response. The fracture toughness of rubbery polymers is a rate-dependent phenomenon which manifests itself in the sense of monotonically increasing fracture toughness with rising crack velocity under tearing tests [1]. In order to communicate the above-mentioned phenomena, the ground state elasticity, in the current study, is accounted by the eight-chain model of Arruda & Boyce [2], whereas the superimposed viscous effects are incorporated into the model in terms of a number of Maxwell elements [3]. For the evolution of the viscous deformations, a new relaxation kinetics is introduced without the multiplicative split of the deformation gradient, thereby capturing the shear and volumetric creep deformations. As a novel aspect, local phase field approach similar to damage mechanics formulation governs the failure of the superimposed chains, while the degradation of the elastic network is governed by a rate-dependent phasefield approach [4,5]. The model parameters are fitted to extant experimental data from the literature. We, afterwards, demonstrate qualitative results of the proposed model by means of representative numerical examples.

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Implementation and Verification of Dirlik's Damage Method for the Random Vibration Fatigue of Notched Beams

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Keywords: Random Vibration Fatigue, Dirlik's damage method, Notched beam

Abstract: Random vibration fatigue analysis utilizes various damage counting methods such as Narrow Band, Steinberg, Tunna, Dirlik and Hancock etc., [1]. Among the methods, Dirlik's empirical formula for the cycle counting is the most superior in terms of accuracy and it is the most widely used frequency domain stress cycle counting method in vibration fatigue analysis [2]. Dirlik has derived an empirical closed form expression, for the determination of the probability density function of the cycle counting of stress ranges, which was obtained using extensive computer simulations to model the signals using the Monte Carlo technique, [3]. Dirlik's cumulative damage (D) is then calculated after the cycle counting process. After the determination of damages for each frequency of interest by the Dirlik's method, one can then use the Palmgren-Miner linear cumulative damage rule to calculate the total fatigue damage (D) or fatigue life (1/D), [4]. The failure occurs when the cumulative damage (D) reaches to value of 1. In this study, in order to verify the Dirlik's method, random vibration fatigue analyses are conducted using the Dirlik's method and analysis results are verified by the random vibration fatigue tests of aluminum and steel notched beams. The finite element analysis is conducted by MSC Patran-Nastran and fatigue analysis is conducted by the nCode program via using the Dirlik's method. Fatigue analysis and test results show that the Dirlik's method stays in the safe side in the analysis. In other words, analysis results give shorter fatigue lifes than the tests, but they are in acceptable ranges and this is preferable in the fatigue discipline. In conclusion, the results of the fatigue analysis and tests show that the Dirlik's method works well in the random vibration fatigue analysis.

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Materials Selection for Aircraft Skin Panels by Integrating Multiple Constraints Design with Computational Evaluations

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Keywords: Materials selection, structural components, finite element analysis

Abstract: Among the principal load-carrying parts of an aircraft, the center wing box yields the main mechanical load-carrying area and is composed of many structural components and elements such as upper and lower skin panels, internal rods, ribs, stringers, front and rear spars [1]. For the structural analysis of such real complex systems, simplified representations of the same sections would be used alternatively to determine whether components could withstand loadings without experiencing failure, thus stay in the margin of safety [2]. Nevertheless, these components should contribute to weight efficiency while carrying in-plane loads and distribute out-of-plane loads to in-plane members safely. Materials selection plays a crucial role for the determination of such candidate materials along with their material properties in specific structural applications. It is usually performed by considering proper objectives, constraints and free variables with respect to functions of the components of a system. Since Composite Material Handbook (CMH-17), Metallic Materials Properties Development and Standardization (MMPDS), and Preliminary Material Properties Handbook (PMP-HDBK) databases are embedded in materials selection software [3], best candidate materials would be easily identified by using coupling constant(s) such as in multiple-constraints designs [4, 5]. In this study, Ashby's methodology was applied to determine best candidate materials for constructing skin panels in a center wing box of an aircraft. According to materials selection approach, continuous fiber reinforced epoxy composites was stipulated as one of the best candidate materials. Computational failure analysis was then carried out by referring the proper material properties from materials selection software.

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Damage Evolution in Dual Phase Steels at Different Strain Rates and Temperatures

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Keywords: damage, DP, void

Abstract: Damage formation in dual phase steels is a complex process due to the two-phased, incompatible microstructure of these materials. This makes the damage evolution sensitive to the conditions of industrial deformation processes such as higher temperatures and strain rates. Therefore, in our study, the damage parameter is measured and compared under the industrial forming conditions (temperatures between 25 - 300 ºC and strain rates between 10-3-10/s) for DP590 and DP800 steels having different ferrite/martensite ratios. In addition, scanning electron microscopy, resonance frequency and damping analyzer, and ultrasonic sound velocity measurement techniques are utilized for the measurements to compare the effectiveness of each technique. Initial results yield consistent damage parameter values from all the measurement techniques. At a given strain rate, damage increases with temperature and in the steel having higher ferrite content, DP590, highlighting the importance of forming conditions and microstructure in damage evolution. The reasons for increased damage are explained by possible microstructural and deformation mechanisms operating in DP steels.

Computational Investigation of Dynamic Fracture in Curved Laminates

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Keywords: Delamination, Cohesive Zone Modelling, Cohesive Zone Modelling.

Abstract: Most of the primary and secondary structures include curved shape parts in the aircraft and wind turbine structures. Due to the presence of curved regions at which significant interlaminar stresses have developed, delamination followed by a reduced load carrying capability of the component may cause catastrophic failure of all structure. Therefore, it is substantial to know the origins of delamination in laminated composites. For this purpose, dynamic delamination in unidirectional and fabric curved laminates are investigated numerically in this study.

The analyses are based on the experimental studies conducted by Tasdemir [1]. Two and three dimensional finite element analysis of the specimen under quasi-static loading is performed using ABAQUS/Explicit [2] in conjunction with cohesive zone modelling [3-5]. A major delamination is observed approximately at 35% of the thickness in the experiments and 40% of the thickness in simulations for both unidirectional and fabric curved laminates. In three dimensional finite element model results, it is observed that delamination initiates at the center of the width for unidirectional laminate and initiates from free-edge for fabric laminates due to stress singularities at that region which originates from mismatch between different ply orientations. Both two and three dimensional finite element analysis are consistent with experiments in terms of main delamination location, failure load and stiffness values of the specimen before failure.

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Investigating Energy Absorption Accessible by Plastic Deformation of a Novel Seismic Damper using Artificial Neural Network

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Keywords: Energy absorption capacity; multi-stage damper; plastic deformation.

Abstract: According to today's need in improving the safety of high-rise structures, damping of the dynamic energy imposed by earthquakes is top on the agenda. To dissipate the kinetic energy some novel dampers have recently been introduced, where the plastic deformation is the main mechanism. Maleki and Mahjoubi [1] studied a new design of dual-pipe dampers to improve the amount of absorbed energy using plastic deformation and similarly, two other studies were performed utilizing tubes inside dampers by which the energy absorption capacity improves measurably [2,3]. Present study is about a new hybrid damper which enhances the energy absorption capacity of the structure, by expanding load-displacement hysteresis curves, compared to other common dampers of the same dimensions. In this study, the validated numerical results expanded by artificial neural network technique were utilized to investigate the dimensional effects of the introduced damper on the amount of the energy absorbed through plastic deformation while loading the damper under protocol SAC 97.

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Development of a regression model for the life assessment of open-hole specimens with double through cracks utilizing stress intensity factor calculations via XFEM

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Keywords: Fatigue Life Assessment, Regression Model, XFEM

Abstract: Crack growth due to fatigue loading is one of the most reported chronic problems in aerospace structures, specifically in riveted panels in airplane fuselages. Crack nucleation usually occurs in spots with high stress concentration such as fastener holes. Regular inspections are conducted to spot cracks and for life prediction. Many analytical solutions have been developed for specific fracture problems such as conformal mapping [1][2] and beta functions for stress intensity factor corrections [3]. In this study, a regression analysis model has been developed to calculate fatigue life of open-hole specimens with double through cracks without significantly compromising on the accuracy. In the first phase of the study, experimental fatigue life data for open hole 2024-T3 aluminum specimens with double through the thickness cracks is extracted from the report of Crews [4]. Life assesment model corresponding to the experimental data is generated using the Forman equation [5] to fit the da/dN vs delta K crack growth data, and material constants and plane stress intensity factor of 2024-T3 alloy in the Forman equuation are obtained. XFEM method has then been employed to model the same open-hole specimen geometry with double through the cracks to check the accuracy of the XFEM and AFGROW results with the experimental fatigue life data. Extended finite element simulation for the crack growth and determination of the stress intensity factor during the crack propagation has been performed using a code developed in ANSYS Parametric Design Language (APDL). Following the convergence analysis, the optimal mesh size and the enrichment characteristics needed for XFEM analysis have been ascertained. Good agreement has been obtained between the delta K values calculated by XFEM and the analytical results calculated by the empirical curve fit using finite element results developed by Harter [3][5], with less than 5%variation.

In the second phase of the study, a design field for significant variables is defined and the experiments are designed according to the faced central composite method for the response surface method. Then, all cases of the designed faced central composite experiments are investigated utilizing the XFEM method to extract SIFs using the Kmax failure criterion. Moreover, obtained SIFs are utilized to assess the life prediction using a code developed in MATLAB by emloying the FORMAN equation and experimental material constants obtained beforehand, via Vroman integration. Afterward, in order to identify the main and interaction effects , the significance level of crucial crack parameters (such as applied stress, crack length, hole radius etc.), and to generate the regression model, analysis of variance (ANOVA) is conducted for the designed experiments using the statistical analysis package Minitab. In conclusion, fatigue life results obtained by XFEM methodand by the, regression analysis of the RS experiments resulted in a regression model capable of acceptable life prediction.

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Numerical Investigation of Drop Test of Combi Boiler Structure

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Keywords: drop test, combi boiler, ls-dyna

Abstract: The combi boiler is a heating appliance that is used for providing a heat power for central and domestic hot water lines. These type of devices are exposed to loads such as drop, vibration, temperature, and stack that may cause damage starting from production to end user. Drop is more pronounced when considering other damage factors in terms of the effect of damage and probability of occurrence [1]. Therefore, the numerical tools are widely used for dimensioning of parts and system design in the product development [2]. The main intension is to determine loads, acceleration and strain levels due to impact loading caused by drop during the transportation of appliances. The 3D finite element code of ANSYS LS-DYNA was selected as a numerical tool. The CAD models of analyzed parts were exported from NX and mesh was generated with hexahedral elements by using LS-PrePost. Initial velocity was generated which is coming from standardized drop conditions such as drop height and orientation. Additionally, rigid wall was generated in order to simulate crashing base. For the material model, MAT_098 Simplified Johnson-Cook was used and the dynamic mechanical characterization tests were carried out in order to obtain material model parameters [3,4]. As a result of modelling studies, the stress wave propagation through the panels, maximum stress regions and failure initiation sites were determined. The side panels was slightly distorted and the weak points were observed at the contact regions. In addition to these, absorbed impact energy by structural parts of boiler, caused by drop, without protective packaging material was calculated. Consequently, with the help of developed numerical methodology, the behavior and reliability of structural elements of combi boiler were predicted and design was oriented in advance of experimental drop tests.

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Morphology and Orientation Dependent Localization and Necking in Dual Phase steels

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Keywords: Dual Phase (DP) steel, Crystal Plasticity, Microstructure.

Abstract: The current study addresses the plastic deformation, localization and the necking behavior of polycrystalline dual phase steels having different martensite volume fractions through crystal plasticity finite element method. The full size micron-scale polycrystalline samples are built through Voronoi tesselation and deformed under uniaxial loading condition. For the modelling of martensite phase J2 plasticity with isotropic hardening is employed while in randomly oriented ferrite grains the crystal plasticity theory works. The material parameters are identified with respect to the experimental data from the literature (see [1]). The attention is focused on the effect of the microstructural morphology and the orientation distribution on the formation of the shear bands and necking of the samples. An outlook is also presented for the modelling of crack initiation and crack propagation in the analyzed samples.

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An Investigation on Mechanical Behaviour of Horizontal Axis Wind Turbine (HWAT) Blade With Various Wind Speed

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Keywords: Horizontal Axis Wind Turbine, Blade, Mechanical Behaviour

Abstract: Wind energy being one of the most important renewable energy sources, is used to meet the growing energy demand of the world and wind turbines are used to utilize this energy source [1,2]. Due to the fact that the kinetic energy of the wind is taken by the blade and transmitted to the generator through mechanical elements, The first ring of the energy production chain is the blade in wind turbines. Nowadays, Research & Development (R&D) activities are focused on the growth of the turbine and blade sizes. As a result of the increasing blade dimensions, the weight of the blade and the loads acting on the blade would be increased. Thus, the mechanical design and mechanical behavior of the blade have become much more important [3-5]. In this study, the mechanical behavior of a blade (deformation, stresses and failure analysis) belonging to three-bladed wind turbines with horizontal axis, being widely used today, has been evaluated for different wind speeds (5 m/s, 10m/s and 15 m/s). For this purpose, Fluid Structure Interface (FSI) analysis of ANSYS Workbench software has been used to analyze the mechanical behavior of the blade exposed to the fluid originated loading conditions. In the present work, the deformation of the blade at the wind speeds of 5 m/s, 10 m/s and 15 m/s has been determined as 3.0687 m, 1.7234 m, 1.1663 m, respectively. It can be deduced that these values do not exceed the recommended values as shown by the recent studies [6]. In addition to these, it is planned to evaluate the normal and shear stresses in the blade and to analyse the failure of blade according to the theories namely Tsai Hill, Tsai-Wu and Hashin theories at different wind speeds.

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Comparison of residual stress fields of as-forged and heat-treated fasteners by the contour method

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Keywords: Residual stress; contour method; cold forging; heat treatment

Abstract: One of the most-widely preferred metal forming process, cold forging is based on severe plastic deformation of metallic materials introduced by dies and tools. Due to non-homogenous plastic deformation, significant amount of residual stresses are inherently introduced. As known from the structural integrity point of view, residual stresses can increase or decrease the service performance of engineering parts depending on being tensile or compressive [1]. Considering cold forged parts, heat treatment (quenching and tempering) is generally applied not only to increase the mechanical properties in terms of plastic deformation limit and hardness but also to have homogenous microstructure and residual stress-relief. In this study, the contour method, one of the experimental residual stress measurement techniques, was employed to obtain residual stress fields of as-forged and heat-treated samples. The contour method is based on elastic stress relaxation upon material removal and Bueckner's superposition principle. The samples to be investigated were cut by Electrical Discharge Machining (wire-EDM) and residual stresses to be obtained were elastically relaxed leading the surface displacements. The surface contours were obtained by Coordinate Measuring Machine (CMM) and fed into the FE model of the cold forged parts as a boundary condition after a data analysis to eliminate noise and artefacts arising from cutting or contour measurement steps. Finally, 2D residual stress maps of as-forged and heat-treated samples were obtained. Near-edge residual stress results were observed to be affected from cutting artefacts, as also declared in the literature [2]. As inner regions are more crucial in order to evaluate the residual stresses after heat treatment, the comparison of as-forged and heat-treated samples were carried out. Based on the residual stress results, it was shown that residual stresses were completely relieved after heat treatment, as expected. Therefore, it was concluded that the heat treatment parameters were appropriate in terms of residual stress relaxation.

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Evaluation of Different Crack Growth Retardation Models under Single Overloads Using Al-7075 Material

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Keywords: Crack growth; overload; retardation

Abstract: In this study, validities of different crack growth retardation models existing in the literature are evaluated by performing fatigue crack growth experiments. Compact tension specimens made from rolled Al-7075 plates with L-T crack orientation are used. In the experimental analyses, by keeping the minimum alternating load at a constant value, the magnitudes of the overloads are changed systematically and the crack growth behavior is monitored for each test. For the same conditions, crack growth predictions with retardation effects are made by employing the existing retardation models in the literature and they are compared with the experimental measurements. The results show that the higher the magnitude of the overload, the higher the retardation effect. It is also observed that except two models, all retardation models predict the retarded crack growth behavior with a reasonable closeness to experimental measurements.

Three-Dimensional Mixed Mode Stress Intensity Factors for Inclined Elliptical Surface Cracks in Plates under Uniform Tensile Load

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Keywords: Finite element method; three-dimensional; stress intensity factor

Abstract: In this study, main results from parametric analyses of three-dimensional inclined elliptical surface cracks using FRAC3D are presented in terms of normalized mixed mode stress intensity factors (SIFs) along crack fronts. FRAC3D is the solver of in-house developed "Fracture and Crack Propagation Analysis System (FCPAS)" and is a finite element-based standalone program employing three-dimensional enriched finite elements. In the analyses, values of the main parameters affecting the problem, which are normalized crack depth with respect to plate thickness (a/t=0.2, 0.4, 0.6, 0.8), crack aspect ratio (a/c=0.25, 0.50, 1.0, 2.0, 4.0) and crack inclination angle (β =0^o, 15^o, 30^o, 45^o, 60^o, 75^o), are changed systematically in their realistic ranges to obtain a wide library of solutions representing the general problem and to develop empirical SIF equations that are valid for all values of the main parameters in their pre-determined ranges. This resulted in a total of 120 three-dimensional fracture analyses. The results show that as the inclination angle of the surface crack increases, mode-I SIF decreases along the crack front, while mode-II and mode-III SIFs increase up to β=45^o, which contains the plane with maximum in-plane shear stress. For higher values of β, mode-II and mode-III SIFs start decreasing as expected. As the normalized crack depth increases, the normalized SIFs also increase. When the depth point and the free-surface point are compared with each other, it is seen that the crack aspect ratio also has big effect on the relative values of the normalized SIFs.

Modelling strength and failure of the bolted joints of a fiber reinforced epoxy composite using rate dependent Mat_162 composite model

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Keywords: Bearing, composite, damage.

Abstract: Bolted joints are commonly found and in some cases non-avoidable in structural parts including aviation and space industry. The fiber reinforced composite bolted-joints are particularly important since several different intricate failure modes depending on the geometrical parameters and loading types may occur sequentially or simultaneously. On the other side, well-defined testing methods are available in the ASTM D5961 Standard entitled "Test Method for Bearing Response of Polymer Matrix Composite Laminates" [1] and extensively used in the experimentation of the composite bolted joints, examples of which are found in refs [2, 3]. In general, three types of experimental macro failure modes so-called the net-tension, shear-out and bearing are observed in the bearing tests. Modelling efforts on the bearing response of composite joints have been so far on the constant loading rate with no strain rate sensitivity of the composite fracture strength and modulus [2, 3]. It is well known that the composite strength and modulus are strain rate dependent and the variations in strain rate may alter the stress distribution and associated damage and failure modes. In this study, the axial loading of a composite plate (0/90) with a bolted-joint was numerically investigated for its load-time behavior and damage formation in response to increasing loading rates. A material model based on MAT_COMPOSITE_MSC_DMG (MAT_162) in Ls-Dyna was used to simulate the composite plate. The MAT_162 combines the composite failure developed by Hashin [4] with the damage by Matzenmiller et al. [5] and the strain softening after failure. The material parameters were first confirmed with experimentation and then changed in the simulations in order to determine the effect of loading rate on the load and damage behavior. The results have shown that the strain rate sensitivity of the composite changed the load-time profile and the failure modes of the composite, signifying the effect of loading rate and its variation during loading.

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Delamination Analysis of Tapered Composite Laminates Using 3D Cohesive Elements

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Keywords: Tapered Composite, Delamination, Cohesive Element.

Abstract: In some applications, a variation in thickness of composite laminates is required to achieve a predefined geometry or property. It may be accomplished by dropping off some plies within a layup which leads to a tapered laminate [1]. Ply drops form discontinuities and in turn high localized stresses. On the other hand, the load carried in the dropped ply is transferred into the adjacent plies, resulting in more complex inter-laminar and intra-laminar stresses and makes the in-plane and out of plane damage analyses more complicated [2]. Cohesive Zone Modelling has been increasingly used for the analyses of the delamination behavior in composite laminates [3]. In spite of widespread use of cohesive zone modelling in delamination studies of laminated composites, there are very few studies using cohesive zone modelling in tapered composites which are limited to very simplified models or applying unrealistic assumptions such as using void in resin pocket area. In this study, the initiation and propagation of delamination in tapered composite laminates are investigated using two and three dimensional finite element modelling with cohesive zone elements. The structural model with several drop-offs is assumed to be under tension. For this purpose, UD plies of 0-degree and 45-degree orientations are used for each sub-laminate. For a single step drop off, the results show that the delamination failure starts at the interface between ply drop-off and resin pocket. The next delamination generally starts either from the belt / resin pocket interface or the resin pocket / core sub-laminate interface. Depending on the parameters involved, it may propagate toward thin section and sometime thick section. The preliminary results show the progression of delaminations within various interfaces which are compatible with literature.

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Bending Behavior of Laminated Composite Plates with Embedded Cracks by Using Refined Zigzag Theory

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Keywords: Refined Zigzag Theory, Composite Plates, Peridynamic Differential Operator

Abstract: A wide variety of modern civilian and military aircraft use fiber-reinforced laminates and sandwich panels for primary load-bearing structures. A laminated composite is composed of stiff fiber-rich and soft resin-rich layers through the thickness. Depending on the nature of the loading, failure can occur within the strong fiber-rich layers or the weak resin-rich layers in the form of a fiber breakage, matrix cracking, and delamination. Understanding the behavior of such structures can result in weight and cost savings by designing against unnecessary conservatism, and minimizes the number of component level structural testing which is prohibitively expensive and time consuming.

The initiation and propagation of cracks should be accounted for as early as possible in the design process. At this stage, detailed, yet computationally expensive, three-dimensional finite element (3-D FE) solutions are prohibitive for rapid design. In this respect, higher-order theories such as the Refined Zigzag Theory (RZT) offer a potential compromise. These theories can provide highly accurate through-thickness stresses, which are the crucial drivers in a delamination event, and because they are based on fewer degrees of freedom, large-scale structural analyses can be performed more efficiently.

This study investigates the bending behavior of laminated composite plates with/without cracks using Refined Zigzag Plate Theory recently developed by Barut et al. [1]. The element employs anisoparametric shape functions so that it does not suffer from geometric locking. Also, the element is free of shear correction factor because each layer has a constant shear strain variation. Peridynamic Differential Operator [2] was implemented to obtain accurate through-thickness transverse stress distributions.

The comparisons against the analytical solutions [3] obtained for a simply supported laminated composite plate under a sinusoidal distributed loading prove the validity and accuracy of the present approach for the stress analysis of composite plates with/without delaminations.

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Simulation of Drop-Weight Impact Test on Composite Laminates using Finite Element Method

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Keywords: Drop-weight impact, Finite element analysis, Composite damage

Abstract: Use of fiber-reinforced plastics (FRP) in engineering applications is favorable because they offer numerous advantages such as light weight, high stiffness and strength. However, laminated FRP composites are susceptible to delamination damage which leads to considerable losses in the residual strength. In the design phase, damage tolerance analysis consisting of sequential transverse impact and compression after impact (CAI) analyses are conducted with certified methods. Since testing alone is highly expensive due to the manufacturing and testing of large number of coupons required to verify every geometry, loading, environment and failure mode, development of virtual test setups which accurately predicts impact damage and CAI strength is of great interest [1]. In this study, a virtual drop-weight impact test setup is developed to simulate standard large mass - low velocity impact tests [2]. 3D finite element model is generated in ABAQUS/Explicit. Spherical impactor and specimen fixture are modeled as rigid bodies. 3D solid elements are used in modeling of composite laminates. Constitutive material model accounting for both interlaminar and intralaminar failure modes is implemented via a user-written VUMAT subroutine. In order to assess the accuracy of the simulations, comparisons with real experimental results are performed.

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Micromechanical Aspects of Amorphous Plasticity through a Strain Gradient Crystal Plasticity Framework

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Keywords: Randomly ordered microstructures, strain gradient plasticity, amorphous plasticity

Abstract: Plasticity of amorphous materials is a topic of current interest for both meso- and microscale modelling frameworks due to the superior mechanical properties of such materials. Understanding the deformation behavior in materials with structural disorder is still a goal that has not yet been fully accomplished. One approach, which deals with this disorder, is based on random variations of local yield stresses [1]. There, it turned out that ideal J2 plasticity of the simulation specimen having a randomly selected yield stress in its each element results in formation of shear bands. In the current work, we extend this study by employing a rate-dependent strain gradient plasticity framework (see e.g. [2]) combined with the previously used structural disorder approach. The advantage is that the gradient approach remedies the localization of shear bands into single finite elements. Results are critically compared with the model from [1]. Furthermore, the length scale parameter for the gradient term will be linked to thermodynamic properties of realistic shear bands.

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Effect of Repair Processes on the Mechanical Properties of Composites used in Aerospace Applications

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Keywords: carbon fiber reinforced polymers, repair of aerospace components, mechanical testing

Abstract: Composites have been gaining increasingly wide acceptance in aerospace industry in recent years. Development of repair techniques that can recover the pristine material characteristics is an important aspect for the reliable use of repaired components. Among different repair techniques, bonded scarf repairs are commonly used when high strength recovery is desired, and surface flushness is a must from an aerodynamic point of view. [1]

Under ideal repair conditions, using the same material and processes of the original parts, scarf-repaired composites are assumed to recover 80% – 100% of the original laminate strength [2]. Most studies in the literature have focused on the strength recovery of the laminates repaired under these "ideal conditions" [3]. However, assembled or in-service parts also need repairs, and in this case the repair conditions are far from ideal, potentially resulting in lower strength.

In this study, we investigated the strength of scarf-repaired carbon fiber reinforced polymer laminates under uniaxial tension, through of experimental and finite element modeling approaches. Effects of various repair parameters on the mechanical behavior of the composite are quantified. The results indicate that the repair parameters and conditions have a big impact on the strength of the repaired component. The findings provide important reference data that can be used to develop new design guidelines and structural repair manuals that can improve the reliability of repaired components in aircrafts.

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Finite Element Analysis of Interfacial Shear Strength Measurements Performed on Nanolayered Metals

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Keywords: nanolayered materials, micropillar compression, finite element analysis

Abstract: Nanolayered metals are composed of alternating layers of metals with layer thicknesses below 100 nm. Nanolayered metals are promising materials due to their outstanding mechanical properties, thermal stability, and radiation resistance. For incoherent nanolayers such as those composed of FCC and BCC metals, the interfacial shear strength between the layers is low. This low shear strength traps the glide dislocations at the interface, and determines the upper limit for the yield strength of the composite. Therefore, it is important to quantify the shear strength of various metal-metal interfaces in order to gain insight to the mechanical behavior of nanolayered metals.

Recent developments in nanomanufacturing and nanomechanical testing have made such interfacial strength measurements possible through micropillar compression experiments. However, the deformation within the layers make the interpretation of the data challenging. Furthermore, micropillar specimens tend to have taper which results in a complicated stress state, and the physical vapor deposition-based manufacturing of the layers cause rough and wavy interfaces.

In this study, we investigated the effect of several experimental artifacts on the shear strength measurements through finite element analysis. Comparison of the simulation results with experimental data shows that the compressive strength of the layers relative to the interfacial shear strength is the most critical parameter for obtaining reliable measurements. In addition, the correct calculation of the shearing area becomes important for tapered pillars. Overall, the findings of this study provide guidelines for performing accurate interfacial shear measurements using micropillar compression technique.

On the Fracture Surface Morphology under Ductile Plate Tearing at Steady State

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Keywords: Ductile failure, Gurson model, finite element method.

Abstract: Ductile fracture occurs through nucleation, growth and coalescence of voids. The two main mechanisms of void nucleation in metals and metal alloys are the brittle cracking of second phase particles and the decohesion of the interface between the particles and the surrounding matrix. The ease of void nucleation, which is detrimental for ductility, is therefore closely related to the size, shape, spatial distribution and volume fraction of second phase particles as well as the strength of the particle-matrix interphase. It is, for example, well established that void nucleation becomes more and more difficult with decreasing particle size; see e.g. [1]. A direct link between the properties of the particles and the tearing mode (cup-cup, cup-cone, slanted or mixture of the three) of a crack propagating in a ductile metal is, however, missing in the current literature. In order to shed light on this issue, the authors of the present abstract have recently investigated the effects of the volume fraction, size and spatial distribution of spherical particles on the crack morphology in a finite element (FE) framework; see [2]. In the two-dimensional (plane strain) FE framework developed in reference [2], the presence of particles are modeled by embedding porous plastic "void nucleation sites" in an otherwise homogeneous, non-porous matrix. The results showed that a low volume fraction of small particles leads to cup-cup morphology, while a large volume fraction of large particles forces the crack to slant. The present study extends the work in reference [2] by allowing the void nucleation sites to assume elliptical shapes, and focuses on the effects of the aspect ratio and the orientation of (the long axis of the) nucleation sites with respect to the main loading direction. The preliminary results show that the fracture surface has a cup-cup (respectively, slanted) morphology if the nucleation sites are aligned parallel (respectively, perpendicular) to the main loading direction.

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