חוברת תקצירים-יום עיון מקוון שלמות המבנה וחקר הכשל 05.10.21

Abstract Booklet Zoom ISIG Ninth ISIG Symposium, October 5th, 2021

חקר כשלון של שני מחליפי חום

רוני שנק ואריה בוסיבא

המחלקה להנדסת חומרים

אוניברסיטת בן גוריון בנגב

בבית זיקוק לנפט הותקנו 3 מחליפי חום זהים מסוג מעטפת וצינורות. שלושתם מצננים מזוט באמצעות מים שמחוממים לכ-260°C ונמצאים בלחץ של כ-40 אטמ'. לפני כחצי שנה נמצא סדק במעטפת של אחד ממחליפי החום. לפני כחודש אירע פיצוץ במחליף חום שני.

חקר הכשלון של שני מחליפי החום כלל בדיקות ראיה, פרקטוגרפיה, מטלוגרפיה ובדיקות הרכב כימי. נמצא ששני מחליפי החום נכשלו באופן מאוד דומה, עקב התפתחות סדקים באזור המושפע מחום בגבול בין מתכת הבסיס ל**תיקון** שבוצע בריתוך. סדקים רבים נוצרו והתפתחו במנגנון שיתוך מאמצים בעקב ריתוך התיקון ובין המעברים של התיקון. התיקון בריתוך יצר מצב רגיש לשיתוך מאמצים ולכן הוא אחראי לכישלון אחרי כ-30 שנות שירות.

סדקים רבים של שיתוך המאמצים התפתחו בתהליך אקראי עד שהתמזגו לסדקים ארוכים. במחליף החום הראשון הסדק הארוך חצה את דופן המעטפת וגרם לדליפה לפני פיצוץ. במחליף החום השני הסדק היה ארוך פי ארבע וגרם לפיצוץ לפני דליפה. מה הייתה הסיבה להבדלים בהתנהגות של שני מחליפי החום ? האם ההבדל נבע מהתהליך האקראי של איתחול והתמזגות הסדקים, או שאפשר להבין את התוצאות השונות באופן החלטי וכמותי באמצעות מכניקת השבר ? בשאלה זו נדון בהרצאה.

Frictional cracks

Eran Bouchbinder, Weizmann Institute of Science

Abstract:

Frictional cracks emerge along interfaces formed by two bodies in frictional contact. They differ from their tensile (mode-I) counterparts by featuring a finite residual stress behind their propagating edges, in contrast to traction-free boundary conditions in the absence of frictional interactions. While frictional cracks share some properties with their tensile counterparts, important and intriguing differences exist. In this talk, invoking general properties of frictional contact interactions – such as their slip rate and interfacial structure dependence –, I will briefly review recent developments in understanding frictional cracks. First, I will discuss the physical origin of the finite residual stress in frictional cracks, highlighting its combined interfacial-bulk nature. Second, I will discuss the possible emergence of healing cracks, which in turn may give rise to slip pulses, a mode of rupture that does not exist in tensile fracture. Finally, I will discuss the emergence of unconventional singularities in frictional cracks, i.e. singularities that differ from that of Linear Elastic Fracture Mechanics (LEFM), and their implications for crack energy balance and scale separation. Experimental support and future research directions will be mentioned as time permits.

IMPACT RESPONSE OF THERMOREVERSIBLE METHYLCELLULOSE HYDROGELS

Daniel Rittel
Faculty of Mechanical Engineering
Technion, 32000 Haifa, Israel

Summary Thermoreversible hydrogels, among which methylcellulose (MC), are a special class of materials that solidify (reversibly) upon heating, contrary to most materials in use today. While such materials can mimic to some extent biological tissues in terms of mechanical properties, their yet unexplored behavior under shock loading has led to several new and intriguing findings, such as shock-induced gelation along with a remarkable propensity to mitigate the shock energy, which makes those gels suitable for shock protection. The work reported here was performed at Technion, as a collaboration between the Chemistry (Prof. Yoav Eichen and Dr. Galit Parvari) and Mechanical Engineering Faculties (Dr. Yonathan Rotbaum, O. Guetta and BatHen Varfman).

INTRODUCTION

Thermoreversible hydrogels are a unique kind of materials that, according to their exact composition, behave like a fluid at room temperature for instance, while solidifying at 70C. They remain solid over a range of temperatures beyond which they liquefy again [1].The phenomenon, referred to as inverse freezing, is fully reversible. Those gels, such as methylcellulose (MC) are often used in the food industry as texturing additions and are thus quite cheap. As of today, inverse freezing gels have not been integrated into engineering applications. Yet, the solidification phase transformation is specially interesting since it is endothermal, thus energy-absorbing. In a different context of shock wave and impact mitigation, one finds that the “usual” protective solutions are based on two concepts. The first one consists of defeating the incoming threat, e.g. by means of hard ceramics. The second concept relies on energy absorption, e.g. through plastic deformation. Yet, those combined concepts do not take into account the elastic precursor wave that is responsible for internal organs damage (e.g. traumatic brain injury), even if the protective device is not penetrated or damaged. In other words, there is no real protection for those cases in which the “non -damaging” elastic wave is the main component of the shock, such as sports accidents for example.

In this study, we have characterized the dynamic response and shock energy mitigation (momentum [2] and energy) capability of MC gels using a Kolsky bar setup [3] and a high-speed camera. The results of this study open the way for a new generation of shock-protecting materials with a clear orientation towards elastic energy dissipation.

EXPERIMENTAL

The investigated gel, of varying composition (5 and 10 w/o) can appear as a liquid or a solid depending on the test temperature. The quasi-static behavior is thus studied using standard equipment at "high" temperature on a solid gel [1]. For the dynamic behavior, the standard Kolsky bar setup, modified to include pressure sensitive sensors, is used in the solid state to characterize the mechanical response and rate-sensitivity of the gel. In addition, the momentum and energy mitigation characteristics are characterized in the liquid state, using an instrumented cell through which the stress wave is applied to the liquid MC gel [4]. The incident and transmitted momenta are this determined, and their ratio indicates the level of energy attenuation. All those experiments are carried out with respect to a control group consisting of water.

In this presentation we will address impact momentum and energy attenuation measurements and modelling.

CONCLUSIONS

Methylcellulose hydrogels have been investigated for the first time for their shock response. Those gels have a surprising capacity to mitigate the incoming shock momentum and energy. As such, it is believed that those materials could be suitable additions to bodily and structural protective systems with a clear orientation towards mitigation of traumatic organ injury.

References

[1] Y. Rotbaum, G. Parvari, Y. Eichen, D. Rittel, Static and Dynamic Large Strain Properties of Methyl Cellulose Hydrogels, Macromolecules. 50 (2017). doi:10.1021/acs.macromol.7b00270.

[2] O. Guetta, B.H. Varfman, D. Rittel, Shock attenuation characteristics of methylcellulose hydrogels: Phenomenological modeling, J. Mech. Phys. Solids. 146 (2020) 104220. doi:10.1016/j.jmps.2020.104220.

[3] D. Richler, D. Rittel, On the Testing of the Dynamic Mechanical Properties of Soft Gelatins, Exp. Mech. 54 (2014) 805–815. doi:10.1007/s11340-014-9848-4.

[4] Y. Rotbaum, G. Parvari, Y. Eichen, D. Rittel, Linear and Nonlinear Shock Attenuation of Aqueous Methylcellulose Solutions, Int. J. Impact Eng. 136 (2020) 103392. doi:10.1016/j.ijimpeng.2019.103392.

Stable crack propagation - a new experimental method and preliminary results

Hagit Cohen, Israel Solomon, Rami Eliasi, and **Dov Sherman**
School of Mechanical Engineering, Faculty of Engineering
Tel Aviv University, Tel-Aviv 69867, Israel
Corresponding Author: dovsherman@tauex.tau.ac.il

Abstract – We report on a new experimental method, aiming at propagating a stable crack under displacement control conditions. The method consisting of inserting a 10 mm by diameter, low-angle conic-shaped aluminum pin into a perfectly matched conic hole in thin and small precracked brittle specimen. Upon heating up the assembly on top of electrical heating stage, the thermal expansion coefficient mismatch between the aluminum pin and the brittle specimen, the crack is propagating stably. Measuring the temperature during the experiment and portraying the temporal crack length allow to evaluate the cleavage energy crystal using plane stress, linear elastic contact problem with friction by Finite Element Analysis (FEA). The method is inspired by Obreimoff's experiment and therefore we termed it OCTEM method.

Using this method, we investigated not only the cleavage energy, but also the basic phenomena associated with stable crack propagation. In long range order brittle silicon crystal, the crack is propagating in cycles of initiation, propagation, and arrest. Contrary, cleaving amorphous soda lime glass specimens show pseudo stable crack propagation with no macroscale cycles. This behavior is owing to the atomistic arrangement along the crack front. We show the importance of the gradient of the energy release rate (ERR), we term □$=dG_0/da$ and other physical properties associated with the bond breaking mechanisms.

Extracting grain boundary toughness from macroscale experiments

S. Osovski, S. Tsopanidis, Faculty of Mechanical Eng., Technion, Haifa, Israel

Probing the fracture toughness associated with microstructural features such as grain boundaries can be a challenging task, as the sampled volume and the experimental complexity limit the statistical validity of the obtained results. In this talk, I will describe a recently developed computational framework aimed at extracting the grain-boundary toughness from meso-scale experiments. The proposed framework relies on the ability of a graph neural network to perform high accuracy predictions of the micro-scale material toughness, utilizing a limited size dataset.

The merit of the proposed framework arises from the capacity to enhance its performance in different material systems with limited additional training on data obtained from experiments that do not require complex measurements. While initially developed from crack growth along grain boundaries, the proposed method can be extended to any kind of interface. The method's efficiency is demonstrated by introducing new crack growth rules with limited datasets (200-300 interfaces) and exploring the obtained prediction accuracy.

Cohesive zone modeling for unidirectional composites with fiber bridging in mode I

Hila Ben-Gur[1], Leslie Banks-Sills

The Dreszer Fracture Mechanics Laboratory, School of Mechanical Engineering, Tel Aviv University.

One of the most catastrophic failure modes of composite laminates is the separation of adjacent plies, or delamination, as a result of applied loads. It is possible to determine the delamination resistance of a laminate composite by measuring its interlaminar fracture toughness. The delamination behavior may be defined further by a cohesive zone model (CZM) which describes the cohesive behavior of the material behind the delamination tip. This model is defined as a traction-separation relationship, and it may be used in numerical analyses.

Delamination propagation within double cantilever beam (DCB) test specimens of unidirectional (UD) composite laminates under mode I deformation is usually accompanied by cross-over fiber bridging (FB). Reinforcement fibers from one face of the delamination cross-over to the other face. This causes a situation in which the cross-over fibers are simultaneously pulled from both faces of the delamination, until they reach failure by breaking or pulling out. Since these fibers bear some of the external load, they increase the apparent resistance of the material to delamination propagation, as compared to identical cases without FB. This increase may be quite significant. However, most large composite structures composed of UD plies do not generally exhibit FB. Therefore, in such cases the net fracture toughness of the composite is the property of interest for design purposes; the FB encountered in mode I testing is considered an undesired artefact that yields a fracture toughness value higher than the 'true' value. Thus, it would be helpful to have the ability to determine the portion of fracture toughness caused by FB.

The purpose of this study is to obtain a CZM of a UD composite laminate with FB, and to develop a numerical tool to predict the delamination response of the material. An additional aim is to separate the contribution of FB to the fracture toughness of the material from the rest of the dissipative mechanisms related to delamination propagation. For these purposes, mode I fracture toughness tests were carried out on four DCB specimens made of a UD carbon/epoxy composite laminate. During each test, the delamination tip position was monitored along with additional parameters to determine the fracture toughness. During the same test, the FB zone was also continuously monitored as it developed in the wake of the delamination. This enabled determination of the FB contribution to the fracture toughness. The test procedure developed to determine both these aspects of the material is rather straightforward. Furthermore, it is mostly based on standards for the determination of the quasi-static fracture toughness and requires relatively simple equipment. The fracture toughness test results of the four specimens enabled the derivation of a CZM that describes the delamination propagation behavior of the evaluated material. The CZM was implemented within a finite element program such that the numerical results duplicated the experimental ones to a good degree. A nominally identical fifth specimen was then tested and analyzed; the results validated the model.

[1] Presenting author; email address: hilabengur@mail.tau.ac.il

European Structural Integrity Society

לשכת המהנדסים
האדריכלים והאקדמאים
במקצועות הטכנולוגיים
בישראל

A Lower Bound Mixed Mode Failure Curve for an Interface Crack in Materials used for Three-Dimensional Assembled Structures

Subramanyam Reddy M* Ella Rubin* Leslie Banks-Sills*
(matti@mail.tau.ac.il) (ellarubin@tauex.tau.ac.il) (banks@tau.ac.il)

*The Dreszer Fracture Mechanics Laboratory, School of Mechanical Engineering. Tel Aviv University, 6997801 Ramat Aviv, Israel

Functional three-dimensional (3D) structures are envisioned for use in biomedical devices, metamaterials, and energy storage [1]. One of the methods for constructing these 3D structures is through controlled, compressive buckling of two-dimensional (2D) precursors which are made from stiff materials like single crystal silicon (SC-Si) [1-2]. The 2D precursor is bonded at selected locations to a highly stretchable polymer substrate like silicone rubber which may be initially pre-strained, say, up to 100%. After bonding, the substrate is released inducing buckling in the 2D precursor to produce the three-dimensional (3D) structure. The weak point of these structures is the interface between the stiff 2D precursor and the polymer substrate where an interface crack may originate and propagate.

In this presentation, details of the work carried out to determine a lower bound mixed mode failure curve for an interface crack between SC-Si and silicone rubber are presented. To this end, mixed mode fracture tests with different mode mixities were performed on Brazilian disk specimens. These tests were then numerically simulated by modeling SC-Si and silicone rubber as cubic (anisotropic) and hyperelastic (Mooney-Rivlin) materials, respectively. The virtual crack closure technique (VCCT) and displacement extrapolation (DE) methods were employed to evaluate the stress intensity factors and energy release rates. It was seen that the nonlinear behavior of the silicone rubber was relegated to a very small zone so that linear elastic fracture mechanics could be invoked outside this region. Using the energy release rate data obtained from VCCT, a mixed mode failure criterion for the interface crack was proposed. It was observed that during the fracture tests on the Brazilian disk specimens, the SC-Si failed before the interface crack could propagate. Hence, it is recommended that the failure curve obtained in this study should be considered as a lower bound of the critical energy release rate for the interface crack between SC-Si and silicone rubber [3].

References

1) Xu, S., Yan, Z., Jang, K.-I., Huang, W., Fu, H., Kim, J., Wei, Z., Flavin, M., McCracken, J., Wang, R., et al., 2015. “Assembly of Micro/Nanomaterials into Complex, Three-Dimensional Architectures by Compressive Buckling”. Sci., 347(6218), pp. 154–159.

2) Yan, Z., Zhang, F., Liu, F., Han, M., Ou, D., Liu, Y., Lin, Q., Guo, X., Fu, H., Xie, Z., et al., 2016. “Mechanical Assembly of Complex, 3D Mesostructures from Releasable Multilayers of Advanced Materials”. Sci. Adv., 2(9), p. e1601014.

Reddy, M. S., Rubin, E., Banks-Sills, L., 2020. “Determining a Lower Bound Mixed Mode Failure Curve for an Interface Crack Between Single Crystal Silicon and Silicone Rubber”. J. Appl. Mech.,

Mixed Mode Fracture Toughness in a Multi-Directional Laminate

Mor Mega1 and Leslie Banks-Sills2

1Department of Mechanical Engineering and Mechatronics, Ariel University, P.O. Box 3, Ariel 40700,

Israel, Tel.: +972-052-6381139, email: morm@ariel.ac.il

2Dreszer Fracture Mechanics Laboratory, School of Mechanical Engineering, Tel Aviv University,

6997801 Ramat Aviv, Israel

Composites, Mixed mode, Fracture toughness, Fracture resistance, Energy release rate

The objectives of this study are to determine critical initiation and resistance curves for

mixed mode, nearly mode I, and nearly II deformations in a multi-directional (MD) composite laminate manufactured by a wet-layup process. Beam type tests including the double cantilever beam (DCB), calibrated end loaded split (C-ELS), and mixed mode end loaded split (MMELS) specimens, which may provide stable delamination propagation when tested in displacement control, were tested quasi-statically in order to determine fracture resistance curves or *R*-curves.

These curves include the amount of energy required for the delamination to propagate G_R as a function of the delamination extension Δa and may be used to measure the delamination resistance to propagation. In addition, Brazilian disk (BD) specimens were tested in various mode mixities to determine the critical initiation energy release rate G_{ic} values as a function of the mode mixty. Based on the results, failure criteria of G_{ic} as a function of the mode mixity were proposed and compared. The _rst is based on the data obtained from the beam tests using the B-K failure curve [1]. The second is based on the BD test results [2]. Each of the proposed criteria may be used for prediction of failure as a function of the mode mixity for this material and interface.

The delamination studied is between a unidirectional (UD) fabric ply with _bers oriented mainly in the 0°- direction and a plain balanced woven ply with tows oriented in the $+45^{\circ}$ =?45 $^{\circ}$- directions. Five nearly mode I, six nearly mode II, and _ve mixed mode quasi-static tests were carried out using the DCB, C-ELS, and MMELS specimens shown in Figs. 1a, 1b and 1c, respectively. In addition, 27 BD specimens presented in Fig. 1d were tested in seven loading angles resulting at seven different mode mixities.

Mechanical _nite element analyses (FEAs) using Abaqus [3] were performed for each test.

The stress intensity factors K_m ($m = 1; 2; III$) were calculated by means of the three-dimensional conservative interaction energy or *M*-integral for the DCB, MMELS and BD specimens. For the C-ELS two-dimensional FEAs were carried out and the virtual crack closure technique (VCCT) was employed to obtain K_m ($m = 1; 2$). The obtained stress intensity factors were normalized using an arbitrary length scale ^*L*= 100 _ and the mixed mode phase angle which represents the in-plane mode mixity was calculated.

Based on the results, three *R*-curves and two failure criteria were generated. The failure criteria were compared. A clear difference in the G_{Ic} values obtained from the beam specimens.

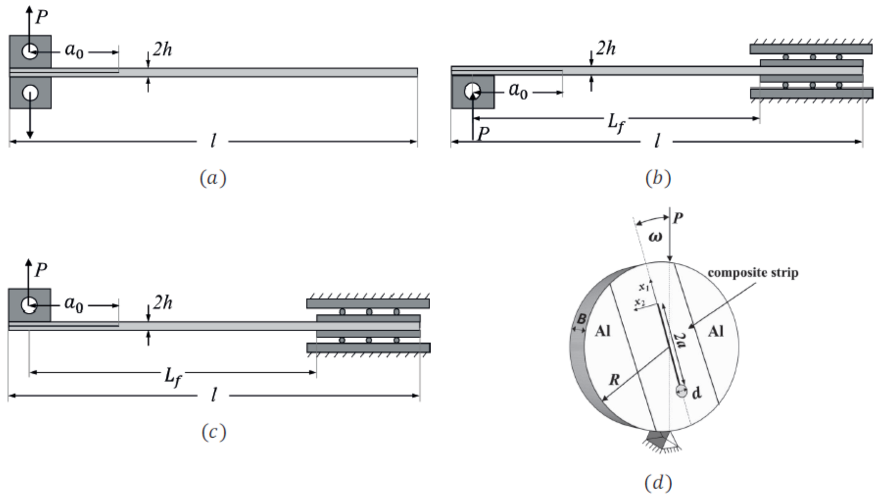


Figure 1: Specimen and test set up (a) DCB, (b) C-ELS, and (c) MMELS (d) Brazilian disk.
Versus that obtained from the BD specimens was observed for dominant mode I deformation.

As the mode mixity increased, this difference decreased. It may be concluded that the specimen thickness inuences the mode I critical energy release rate values. Whereas, for mixed mode and nearly mode II deformation the inuence is negligible.

Knowledge of the resistance curves and failure criteria for dominant mode I, dominant mode II, and mixed mode deformations provide critical properties for initiation and propagation of a delamination along the investigated interface. The results from this investigation may be used to improve the design and safety of a structure containing the interface of the considered material.

References

[1] M. L. Benzeggagh, M. Kenane, Measurement of mixed-mode delamination fracture tough-

ness of unidirectional Glass/Epoxy composites with mixed-mode bending apparatus, Com-

pos. Sci. Tech. 56 (1996) 439{449.

[2] M. Mega, O. Dolev, L. Banks-Sills, Two- and three-dimensional failure criteria for laminate

composites, J. Appl. Mech. 87 (2019) 021001: 1{11.

[3] Abaqus, Version 6.17, Dassault Syst_emes Simulia Corp., Johnston, RI, 2017.

How friction starts: Nucleation fronts initiates interface rupture

Shahar Gvirtzman & Jay Fineberg

Recent experiments have demonstrated that rapid rupture fronts, akin to earthquakes, mediate the transition to frictional motion. Moreover, once these dynamic rupture fronts are created, their singular form, dynamics and arrest are well-described by fracture mechanics. Ruptures, however, need to be created within the frictional interfaces, before they are able to propagate. According to fracture mechanics, crack propagation initiates only when a crack surpasses a critical length, the Griffith length. Below this length, the crack is stable and propagation should not occur. A critical open question is, therefore, how the nucleation of rupture fronts actually takes place, and what is the mechanism driving the creation of the initial crack. Here, we experimentally show that rupture front nucleation is prefaced by slow nucleation fronts. These nucleation fronts, which are self-similar, are not described by fracture mechanics. They emerge from initially rough frictional interfaces at a well-defined stress threshold, evolve at characteristic velocity and time scales governed by stress levels, and propagate within a frictional interface to form the initial rupture from which fracture mechanics take over. The details of the process, such as the exact threshold and the 2D shape of the front, depend on the local 'topography' of the interface at the nucleation site. These results are of fundamental importance to questions ranging from earthquake nucleation and prediction to processes governing material failure.

לשכת המהנדסים האדריכלים והאקדמאים במקצועות הטכנולוגיים בישראל

AEAI

ISIG

ESIS
European Structural Integrity Society

נושא ההרצאה	**מניעת כשל בשלב התכן**
משך ההרצאה	30 דקות
תקציר	חקר הכשל מחייב ידע ויכולות רב תחומיות, אולם האתגר המורכב יותר הוא מניעת אירוע כשל ע"י כבר בשלב התכן. בהרצאה נציג את הצורך בשילוב של ידע מעשי בחקר הכשל, בהנדסת מערכת והבטחת איכות ע"מ לקיים תהליך מניעה כבר בשלב התכן.
קהל יעד	מפתחים, מהנדסי מערכות, מומחי לחקר הכשל, מהנדסים ומנהלי פרויקטים.
מועד מבוקש	05 באוקטובר 2021
מרצה	ד"ר חנן גבאי
חברה	סי. גי. סמארטק בע"מ
אימל	Chgabay@gmail.com
נייד	05404525972
קורות חיים	מנכ"ל סי. ג'י. סמארטק – עוסק בפיתוח עסקים וחקר הכשל. מקים ושותף בחברת זוהר טכנולוגיות ירוקות שמפתחת פתרון להמרת אשפה ביתית לאנרגיה. יועץ מטעם האיחוד האירופי לחברות הזנק. בעבר סמנכ"ל פיתוח עסקים בחברת מוטורולה ישראל

European Structural Integrity Society

לשכת המהנדסים
האדריכלים והאקדמאים
במקצועות הטכנולוגיים
בישראל

Nested helicoids in biological microstructures

Israel Greenfeld, Israel Kellersztein and H. Daniel Wagner
Department of Molecular Chemistry and Materials Science, Weizmann Institute of Science, Rehovot 76100, Israel

Helicoidal composite structures in biology (Bouligands) have been the subject of active research in recent years, likely because of their unusually esthetic multiscale architecture but also because of their potential to inspire stiffer, stronger and tougher synthetic materials. In this study [1-3], the laminated structure of helicoids found in the claw of the *Scorpio Maurus Palmatus* was investigated in fine detail by means of high-resolution SEM and TEM imagery (figure 1a,b), which we believe is of unprecedented quality. Our observations and analysis depict a radically new picture compared to previous descriptions, in which laminae are twisted off-axis and are also progressively tilted out-of-plane. The helicoid is found to be neither infinite nor helically symmetric, with a highly warped shape that allows units to tightly nest in each other, providing a mechanically-interlocked structure resembling a 3D jigsaw puzzle (figure 1d). A geometric model of the Bouligand is presented (figure 1c), and its mechanical stiffness and strength are calculated using classical laminate analysis extended to laminae tilting. Structural analysis of the multilayer laminate of the claw's cuticle reveals shear enhancing mechanisms at different length scales. Synthetic implementation of the observed 3D deformed shape is challenging, but the potential scientific and engineering gains could be significant.

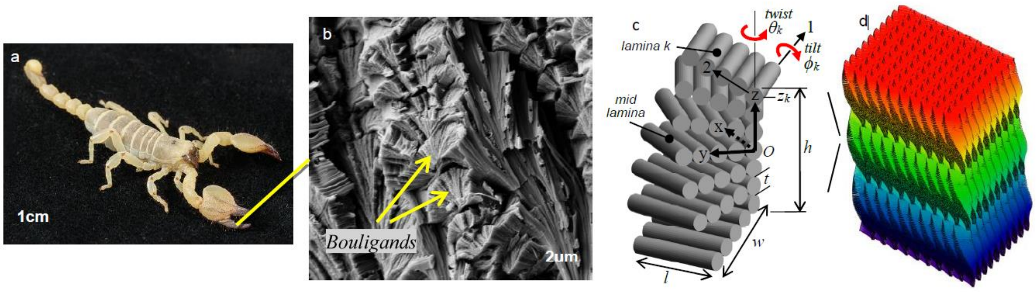


Figure 1: (a) Scorpio Maurus Palmatus. (b) Nested Bouligands. (c) Off-axis twist and tilt rotations. (d) Bouligands nesting and stacking.

[1] Kellersztein I, Cohen SR, Bar-On B, Wagner HD. The exoskeleton of scorpions' pincers: Structure and micro-mechanical properties. Acta Biomaterialia 94, 565-573 (2019).
[2] Greenfeld I, Kellersztein, I., Wagner, H.D. Nested helicoids in biological microstructures. Nature Communications 11, 1-12 (2020).
[3] Kellersztein I, Greenfeld I, Wagner HD. Structural analysis across length scales of the scorpion pincer cuticle. Bioinspiration & Biomimetics 16, (2021).

Energy balance in the propagation of step-forming cracks

Meng Wang[1*], Mokhtar Adda−Bedia[2] & Jay Fineberg[1]

1. The Racah Institute of Physics, The Hebrew University of Jerusalem, Givat Ram, Jerusalem 91904, Israel
2. Université de Lyon, Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, Université Claude Bernard, F-69342 Lyon, France
* meng.wang@mail.huji.ac.il

Griffith's energetic criterion, or `energy balance', has been known for decades as the basis of fracture mechanics. It has been pervasively used to measure material resistance to failure and describe the propagation dynamics of `simple' cracks (cracks having no secondary structure). Simple cracks can by idealized as one-dimensional cracks propagating within two-dimensional (2D) media. When cracks contain secondary structure, full crack fronts must be considered. Secondary structure within a crack front will increase energy dissipation, and it is not, a priori, clear how its presence contributes to the fracture energy. Here, we study low-speed crack propagation in hydrogels under tensile loading conditions. Such slow cracks are shown to be bistable; either simple or faceted crack states (formed by steps propagating along crack fronts) can be generated under identical loading conditions. The selection of either crack state is determined by the form of the initial `seed' crack; seed cracks generating faceted cracks contain a small local Mode III component. Once formed, simple cracks are stable. As recently demonstrated, finite mode III perturbations will trigger multiple steps that eventually coarsen. We find that this process generally leads to a single step that propagates along a crack front. As they evolve, steps locally change the instantaneous structure and motion of the crack front, breaking transverse translational invariance. In contrast to simple cracks, faceted cracks can, therefore, no longer be considered as existing in a quasi-2D system. For both simple and faceted cracks we simultaneously measure the energy flux and local fracture toughness along the crack fronts over velocities, v, spanning $0<v<0.2c_R$ (c_R is the Rayleigh wave speed). We find that the concept of energy balance must be generalized for 3D systems; faceted cracks obey energy balance, only when we account for the local dynamic dissipation at each point along the crack front. If the local structure is not properly accounted for, energy balance will appear to fail.

EUROPEAN STRUCTURAL INTEGRITY SOCIETY

לשכת המהנדסים
האדריכלים והאקדמאים
במקצועות הטכנולוגיים
בישראל

The topic: fatigue failures of jet engines

Abraham Brot* (abrot99@gmail.com)

* The author was a member of the team that studied these failures and eventually found the solution to this problem.

Abstract

Fatigue failures of aircraft can be classified as "high-cycle" and "low-cycle" failures. High-Cycle fatigue is the more common of the two.

Two examples of high-cycle fatigue failures are: the Aloha Airlines failure of a Boeing 737 aircraft at about 90,000 flights, and a Boeing 707 that crashed in Lusaka after 16,700 flights.

Two examples of low-cycle fatigue failures are: The failure of an F-111 fighter that failed at only 107 flight-hours and the two Comet aircraft that crashed at about 900 flights and 1300 flights.

This paper will concentrate on several high-cycle fatigue failures that occurred to jet-engines of civilian aircraft in 1969. The mode of failure was high-cycle fatigue due to high frequency of excitation (approximately 1300 Hertz).

This presentation describes an extended incident that occurred during 1969, which resulted in the failure of many aircraft engines, due to high-cycle fatigue.

The solution to this difficult problem is also described in this presentation.

Effects of Additive Manufacturing inherent defects on the Fatigue behavior of Ti-6AL-4V: An experimental study

Carmel Matias*(1), Alex Diskin(2), Oz Golan(3), Garkun Andrey(4) and Evgeny Strokin (4)
** E-mail:* cmatias@iai.co.il
(1) *Fatigue and Damage Tolerance Dept., Engineering & Development Center, Aviation Group, Israel Aerospace Industries (IAI)*
(2) *Head of Additive Manufacturing Center, Material Engineering & Technology Development Dept., Aviation Group, Israel Aerospace Industries (IAI)*
(3) *Senior Researcher, Center of Materials Engineering & Processes, Afeka Academic College*
(4) *The Israel Institute of Metals, Technion Research & Development Foundation*

Additive Manufacturing (AM) technology has not yet been adopted to produce airframe Principal Structural Elements (PSE per Regulation [1]), mainly due to lack of generic economic quality control methods, to detect manufacturing defects. Such items are typically susceptible to fatigue cracking.
This article presents Critical Defects features, for Ti-6AL-4V Powder Bed Fusion of Selective Laser Melting technology. The Critical Defects criteria, were based on experiment program, accompanied by Micro Computer Tomography (Micro-CT) inspections, and SEM/Fractographic failure analyses.
This study Critical Defects criteria is derived from:

- Type – Pore (Void), Lack of Fusion Surface or Inclusion (Contamination).
- Size.
- Distance from Surface.

The following tests were done:

- Quasi-Static per ASTM E8 [2]; 12mm diameter bar.
- Fatigue per ASTM E466-15 [3]; R=0.1; Round Bar, continuous radius (5mm Neck, 10mm Ends); Kt=1.0.
- Crack Growth per ASTM E647−15 [4], R=0.1, C(T), Notch=5mm, Width=30mm, Thickness=5mm.

The study used ALM EOS M290 Machine AM (Laser-Power=340W, Print-Layer-Thickness=60µm).
8 AM qualities were produced, for testing the following 8 distinct Specimen Type:

- 4 AM Printing Parameters Sets.
- 2 Thermal-Post-Processing procedures (each applied on half of the total number of Specimens produced per each of the 4 different Printing Parameters Set).

The 2 Thermal-Post-Processing procedures were:

- Heat Treatment (HT) of 800ºC for 2 hours at Argon atmosphere.
- HIP procedure per ASTM F3001.

The 4 AM Printing Parameters Sets:

- **Tray #1** – All parameters per EOS recommendation **(Reference – good quality)**.
- **Tray #2** – Parameters per EOS recommendation, except Stripe Width, which was increased to double the EOS recommendation **(best/improved quality)**.
- **Tray #3** – Parameters per EOS recommendation, except Stripe Distance, which was increased to double the EOS recommendation **(poor quality)**.
- **Tray #4** – Parameters per EOS recommendation, except Laser Power, which was decreased to half the EOS recommendation **(the worst quality)**.

The specimens were Machine processed per ASTM for each test (N6 surface roughness).

Fatigue & Crack-Growth Test Results –
Figure 1 presents the number of cycles to failure per Max. Cyclic Loading Stress, Fatigue results, via diamond-dots (8 colors per the 8 Specimen Types), in comparison to:

- (a) "AATiD" Consortium testing results [5] (brown stripes, Best-Fit: black curve, B-Value: red curve).
- (b) MMPDS Data [6] (light-blue curve).

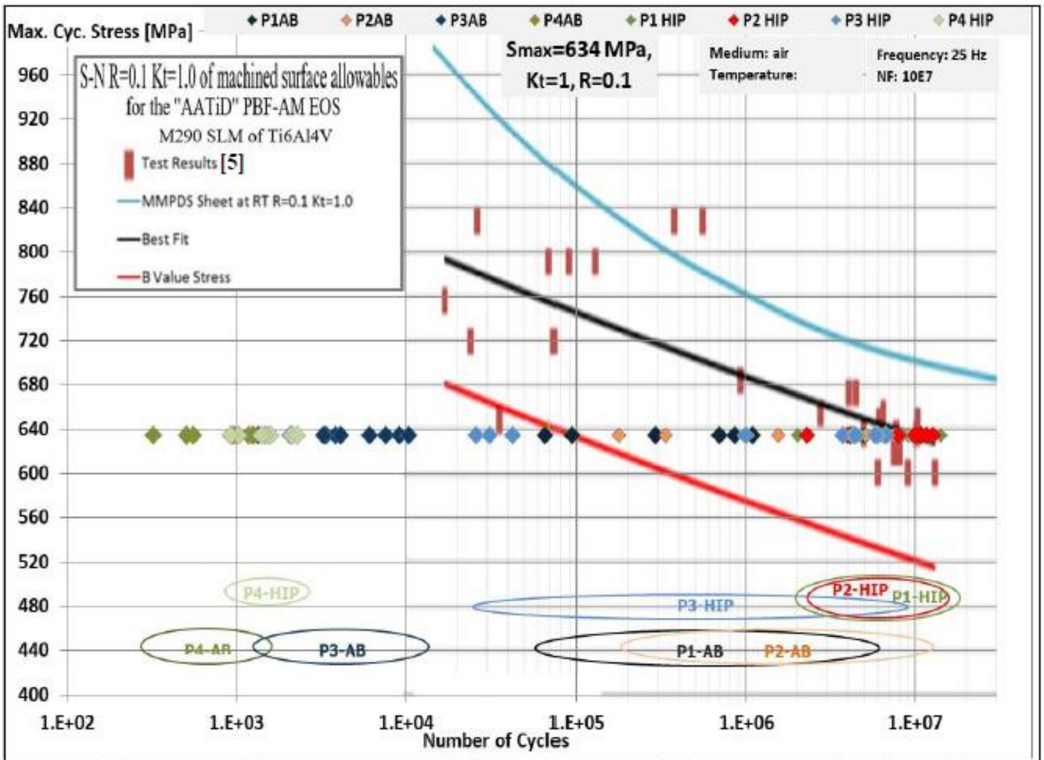
Figure 1 also presents Specimen Type Weibull Statistical results, and 8 oval shapes (per 8 Specimen Types), representing spread (variance).
Trays #1 & #2 Specimens which had Fatigue results below 3 X 10^6 cycles (required 8 X 10^6 cycles), were investigated by detailed Micro-CT inspections & Failure analysis, for Critical Defects.

Table 1 presents Fatigue tests evaluation summery for each Specimen Type.

	Characteristic-Life	Variance (spread) Level
Tray #2 Printing		
HIP –	Corresponds well to "AATiD" results	Low
NO-HIP(*) –	Corresponds well to "AATiD" results	Very High
Tray #1 Printing		
HIP –	Corresponds well to "AATiD" results	Low
NO-HIP(*) –	~ 0.5 Factor of "AATiD" results	Very High
Tray #3 Printing		
HIP –	~ 0.3 Factor of "AATiD" results	Very High
NO-HIP(*) –	Extremely low	Low
Tray #4 Printing		
HIP –	Most extremely low	Extremely Low
NO-HIP(*) –	Most extremely low	Low

(*) Stress Relieve Heat Treatment of 2 hours at 800ºC with no pressure applied.

Table 1: Specimen Type Fatigue Test Results Comparison



P1m – Printing Tray #1 The 2nd Best Quality All EOS Default

P2m– Printing Tray #2 The Best Quality EOS Default & Change Stripe Width +100%

P3m – Printing Tray #3 The 2nd Worst Quality EOS Default & Change Stripe Distance +100%

P4m – Printing Tray #4 The Worst Quality EOS Default & Change Beam Power -50%

Thermal Procedures: 2Hr. 800°C HT No Press. (AB) HIP per ASTM F3001 (HIP)

Weibull Statistical Distribution Data							
2 hours 800°C Heat Treatment with no Pressure				HIP procedure per ASTM F3001			
Tray#	Shape Parameter / Variance (n/s)		Characteristic Life	Tray#	Shape Parameter / Variance (n/s)		Characteristic Life
P1	0.787	(8/2)	5,194,789 Cycles	P1	3.067	(10/3)	10,417,260 Cycles
P2	1.485	(7/3)	9,455,652 Cycles	P2	2.502	(9/4)	12,190,150 Cycles
P3	1.630	(9/0)	6,101 Cycles	P3	0.515	(10/0)	2,610,585 Cycles
P4	2.380	(9/0)	1,014 Cycles	P4	3.448	(10/0)	1,699 Cycles

Figure 1: Fatigue (crack initiation) Test Results for all 8 Specimen Types

Crack Growth Test results, presented no practical differences among the 8 distinct Specimen Type. All Crack Growth results correlated well to the NASGRO [7] da/dn vs. ΔK data, (we assume linear-elastic, isotropic and homogeneous material, as would have been preferred for MA to replace Forges & Plates).
Quasi-Static test results showed that poor-quality AM does not meet Elasticity Modulus and Elongation ASTM Requirements. For Tray #3 AM HIP procedure did increase Elasticity & Elongation to meet Requirements, but, for Tray #4 AM, HIP did not. The good-quality AM met well the Requirements.

Critical-Defects Conclusions:
According to results gathered form: Fatigue tests, Micro-CT inspections and SEM/Fractographic failure analyses:
Surface Defects – Any type of defect and of any size, will cause early fatigue cracking, that will prevent to meet the Fatigue requirements for Airframe structures.
Internal Defects – Defects that their size is up-to 120 µm and their distance to surface is more than 10 times their size, will not cause early fatigue cracking, and will allow to meet the Fatigue requirements for Airframe structures.

Further investigation is needed to extent that criterion to more detailed criteria, such as having a function of a specific Defect size per its distance from surface.

References

[1]. Part 25 of the USA Federal Aviation Regulations (FAR), 14 CFR § 25.571 - Damage-tolerance and fatigue evaluation of structure.
[2]. ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials.
[3]. ASTM E466-15, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials.
[4]. ASTM E647-15, Standard Test Method for Measurement of Fatigue Crack Growth Rates.
[5]. AATiD CONSORTIUM – Development of Advanced Technologies for 3D Printing of Titanium Aero-structures, Rev. 2.0, Israel Innovation Authority, "The effect of process parameter modification on the final part surface roughness and porosity level", Page#270.
[6]. MMPDS Handbook - Metallic Materials Properties Development and Standardization (MMPDS): The primary source of statistically-based design allowable properties for metallic materials and fasteners used for commercially and military aerospace applications (recognized by certifying agencies within their limitations: including FAA, DoD and NASA).
[7]. NASGRO - Fracture Mechanics and Fatigue Crack Growth Analysis Software; Version 9.2 (extensively used for crack growth analyses in the Air-Frame Industry).