Failure under complex strains and stresses: fracture and fatigue in advanced materials

Professor Filippo Berto, at the Norwegian University of Science and Technology (NTNU), has been investigating a novel method of obtaining fatigue data from advanced engineering materials. Using complex techniques which allow for examination of multiaxial loading and high temperatures, his data show promising advances in the analysis of stress testing data which will have significant impact on component design and industrial applications.

Within materials science, as is true of anything, it is important to push the limits. This is especially important when researching material fatigue. In simple terms, this focuses on understanding how much stress a material can withstand before fracturing, through repeated stress cycles under controlled levels of intensity.

THE NAME OF THE GAME

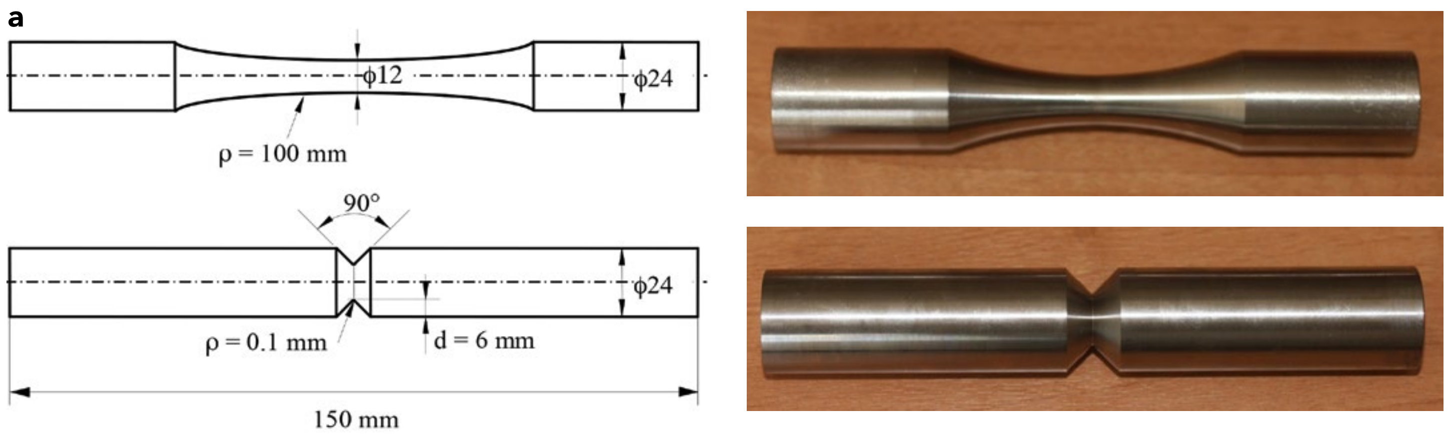
Professor Filippo Berto is an experienced researcher within the field of materials science. Having achieved the highest honour possible in his first degree from the University of Padua, Italy (one of the oldest universities in the world and consistently highly ranked), he moved to Florence to complete his PhD in mechanical design. His return to Padua was inevitable, however, as was his rapid rise from researcher to assistant professor of mechanical design and then associate professor of mechanics. Clearly a rising star in mechanical engineering, he was most recently offered the Chair of Mechanics and Materials at NTNU's Department of Engineering Design and Materials, in recognition of his academic achievements and prolific publication portfolio.

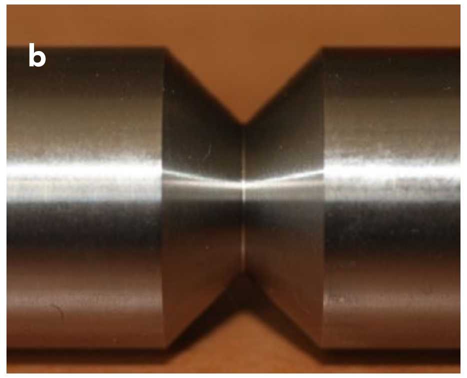
Following exhaustive searches of the literature, Prof Berto identified key areas where fatigue data was lacking for modern engineering materials. When considering high-performance materials, high strength in high-temperature conditions is of paramount importance. Most researchers studying this area have focused on creep and low-cycle fatigue (deformation of a material and relatively low number of straining events respectively). However, because of the nature of the applications, high-cycle fatigue is a more likely real-world scenario.

APPLYING THE STRESS

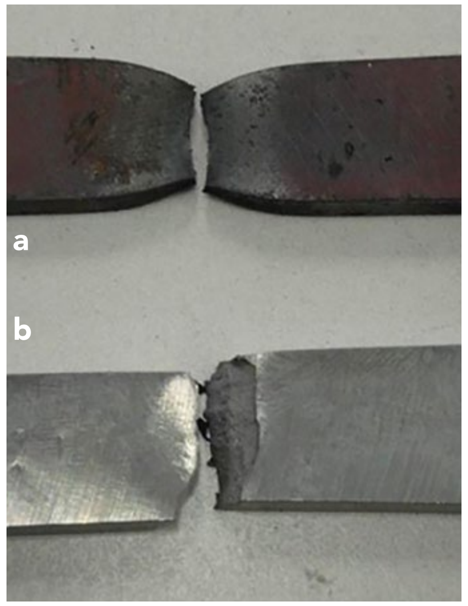
To address this dearth of data on high-cycle, high-temperature fatigue in advanced engineering materials, some researchers have suggested extrapolating current room temperature data where this is shown to be experimentally possible. This led Prof Berto to examine whether Strain Energy Density (SED), an assessment which has previously

Superalloys in turbine engines are used at 90% of their melting temperature. Therefore, being able to accurately predict how these materials behave is of paramount importance

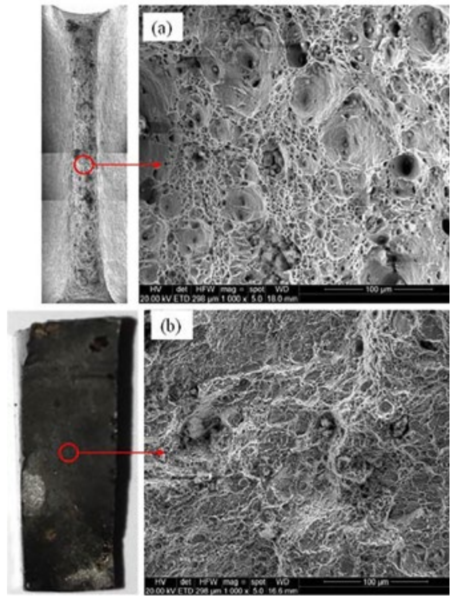




Top and Above: Geometry of un-notched and V-notched specimens (a) and details of the notch tip (b)



Above: Fracture surface of plain specimen tested at 650°C (a) (Δσ=140 MPa, N=284049), and room temperature (b) (Δσ=900, N=155000)



Above: Comparison between the fracture surface of plain specimen tested at 650°C (a) (Δσ=140 MPa, N=284049) and room temperature (b) (Δσ=900, N=155000), with the same magnification value

been shown to be applicable to room temperature data, could be extended to high temperature material fatigue.

The concept is that strain data for a material can be expressed as a function of volume to give values which hold true irrespective of the specimen's geometry. Using samples of advanced engineering materials called superalloys (such as DZ125 and Inconel 718) which are designed to be used in high temperature environments such as turbine engines, as well as high grade carbon steel and advanced titanium alloys, the team tested their fatigue at high temperature to confirm that the SED data held true. Using a combination of hourglass-shaped specimens and those which had either blunt or v-shaped notches to simulate machined components, the team subjected them to both high temperatures and cycles of increasing tensile stress to the point of failure. For the work with titanium they also included torsional stress and multiaxial loading protocols to investigate whether these resulted in diverse SED profiles.

CRACKING OPEN THE DATA

The fatigue data was analysed using standard models and specific mechanical loading equations to compare how the different samples responded to the stresses applied. This allowed for the calculation of the SED which can then be plotted against the number of load cycles. This clearly demonstrates the power of the SED approach as all data points fall within a narrow band on the scatter plot. From these data, the failure energy of each material can be calculated independently of its geometry.

It also clearly showed that the approach is extendable across the range of operating temperatures for which the material is designed. Linear relationships at room temperature can also be applied to high temperature situations, as long as certain conditions are met. Examples of these conditions include remaining within elastic (returns to original shape) or plastic (bends without breaking) deformation.

STRETCHING THE REACH

The same holds true, to some extent, for Prof Berto's work with titanium alloys. By applying different control volumes to torsional over tensile loading, the data can again be algebraically manipulated to provide comparable values for SED under conditions for torsional, tensile and multiaxial loading. This makes it possible for these varied conditions, for both notched and un-notched samples, to be simply evaluated. This synthesis of all the fatigue strength data, regardless of loading mode or specimen geometry, displays the unifying nature of the SED approach.

Q&A

What benefits, in terms of academic and collaborative opportunities, are available to you as Chair of Mechanics and Materials at NTNU?

It is like driving a Ferrari instead of driving an ordinary car. You have visibility and many contacts around the world with very good feedback on your scientific work. You have the opportunity to connect with all the most prestigious universities around the world: ETH, Harvard Berkeley, Stanford and Caltech.

What led you to investigate SED as an approach to unify stress data in advanced engineering materials?

I wanted to find a general simple method for fatigue and fracture design. Energy is the basis of all the most important physical concepts.

How can SED be most simply explained to someone unable to follow the complex algebraic equations used to describe these processes?

SED is the local energy necessary to generate damage to the material.

How do you see SED being used in 'real world' applications?

Many industries have understood the potential of SED and its versatility to solve complex problems in a simple way.

What more needs to be done to extend the field of high temperature fatigue in the high cycle regime?

New experimental tests at different temperature ranges are needed, and a greater understanding of the main phenomena related to crack propagation at high temperature.

FROM MAN TO MACHINING

It is this ability to collapse the data into a narrow band curve that makes the SED approach preferable over current methods. The more common practice of presenting the data in terms of the stress range is unable to collapse the data into such a convenient format.

For industrial applications, this is an important advance over current methodologies. As many components are continuously refined and redesigned, having a parameter for mechanical resistance which is not dependent on the geometrical shape means that testing the component every time is no longer necessary. This will save considerable time and money, and will also offer great potential within the advanced engineering materials sector.

When considering the sectors in which these materials are applied, such as the manufacture of turbine engines for aerospace and marine markets, or the further processing of metals in hot rolling and machining procedures, it is no wonder that advances such as these are required. Superalloys in turbine engines are used at 90% of their melting temperature, as the thermodynamic efficiency of these engines increases with increasing turbine inlet temperature. Therefore, being able to accurately predict how these materials will behave is of paramount importance.

As these technologies progress, the tools required to design and manufacture them also need to progress at a similar rate. Prof Berto and his team are leading the way in improving the understanding of materials science, as well as providing advantageous solutions applicable to those working within the industry.

The ability to collapse data into a narrow band curve makes the Strain Energy Density approach preferable over current methods

Detail

RESEARCH OBJECTIVES

Dr Filippo Berto's research primarily focuses on the brittle failure of different materials, the mechanical behaviour of metallic materials, the fatigue performance of notched components, and the reliability of welded, bolted and bonded joints. His recent research has looked to further assess the 'Structural Integrity' discipline, by analysing the fatigue characteristics of particular materials commonly used within engineering.

COLLABORATORS

Dr Pasquale Gallo (Kyoto University); Dr Alberto Campagnolo (University of Padua); Dr Marco Colussi, Cimolai; Dr Filippo Abbatinali, Cimolai; Dr Javad Razavi NTNU, Trondheim; Dr Alberto Lorenzon, Cimolai; Dr Marco Grotto, Officine Meccaniche Zanetti; Dr Thomas Borsato, VDP fonderie; Dr Steffen Sunde, NTNU
Industries: Cimolai; Officine Meccaniche Zanetti; Zincherie Valbrenta

BIO

Dr Filippo Berto received his degree in Management Engineering in 2003 from the University of Padua (Italy). Following this, he attended a PhD course at the University of Florence before returning to the University of Padua to work as a researcher. While there, he had many roles including both the Assistant Professor of Machine Design and the Associate Professor of Mechanics. His most recent role is one of the most prestigious available at the Norwegian University of Science and Technology, where he currently works as the internationally renowned Chair of Mechanics of Materials.

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