NON-FOURIER HEAT CONDUCTION AND NONLOCAL THEORY, RECENT PROGRESS AND APPLICATION IN THERMAL FRACTURE ANALYSIS

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Abstract
Non-Fourier heat conduction theories have recently been introduced to thermal stress analysis to account for the wave-like behavior of heat conduction under extreme thermal environments, such as high temperature gradient, extremely low temperature, or heat transport in heterogeneous microstructures. When considering the highly localized heating process in laser manufacturing, nonlocal heat conduction needs to be included in the heat conduction equation. Combined non-Fourier, nonlocal thermoelastic theories revealed new phenomena in thermal stress analysis of cracked structures. This presentation summarizes some recent progress in thermal fracture analysis using nonlocal, non-Fourier thermoelastic theories.

1. Introduction

High-energy pulse laser beams are widely used in additive manufacturing of metals, ceramics and other high-melting temperature materials, where the workpiece experiences sudden heating process with extremely high temperature gradient localized in the heating spot. Recent experimental and theoretical results have showed that thermal stress analysis based on the classical Fourier heat conduction and continuum mechanics will lead to a much more optimistic prediction of the thermomechanical behavior of the material than the actual situation. This overestimate in the thermomechanical response to transient, localized, high-energy heating process will eventually jeopardize the manufacturing and subsequent application of the additively manufactured products.

Non-Fourier heat conduction theories were proposed to address the transient heating process involving high temperature or temperature gradient, extremely low temperature, or heterogeneous material structures. This presentation summarizes some of our recent works on thermal stress analysis of transient heat process using non-Fourier heat conduction theories. Rationality of application of non-Fourier heat conductions and nonlocal continuum theory will be discussed first. Then two typical thermal fracture problems extracted from additive manufacturing are solved to illustrate the advantages of these theories over the classical theories.

2. Thermal fracture analysis based on combined non-Fourier, nonlocal thermoelasticity

2.1 Non-Fourier heat conduction

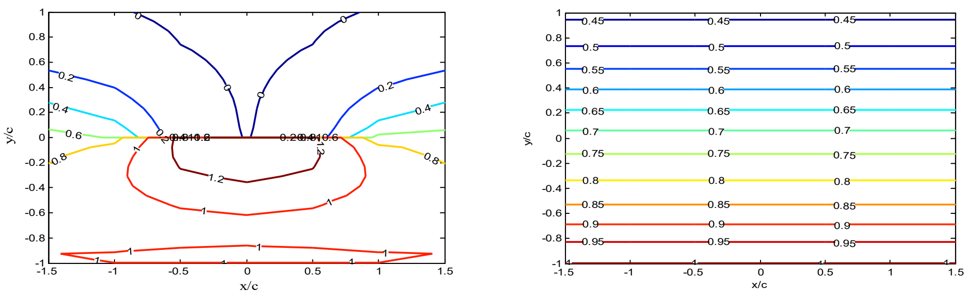
Under extreme thermal circumstances, such as high-temperature gradient, extreme low temperature close to absolute zero K, or when heat transports in a heterogeneous microstructure, heat spreads in a wave-like form, with a finite speed, instead of a diffusion form according to Fourier heat conduction, with an infinite speed. A few typical non-Fourier heat conduction theories such as the CV theory, dual phase lag theory, and memory-dependent fractional theory introduced a relaxation time to convert the heat conduction equation from diffusion equation into wave equation.

2.2 Nonlocal heat conduction and thermoelastic analysis

In laser-based additive manufacturing process, ultrafast high-energy laser beams are employed to cause localized heating in material to form various metamaterials. To reflect the localized heating process, nonlocal theory is introduced such that heat flux at one spatial point is defined as the local average over a small-influential region around it, similar as the nonlocal continuum theory. Combined with non-Fourier heat conduction, the nonlocal, non-Fourier heat conduction theories have been developed and used in various thermal fracture analysis in recent years.

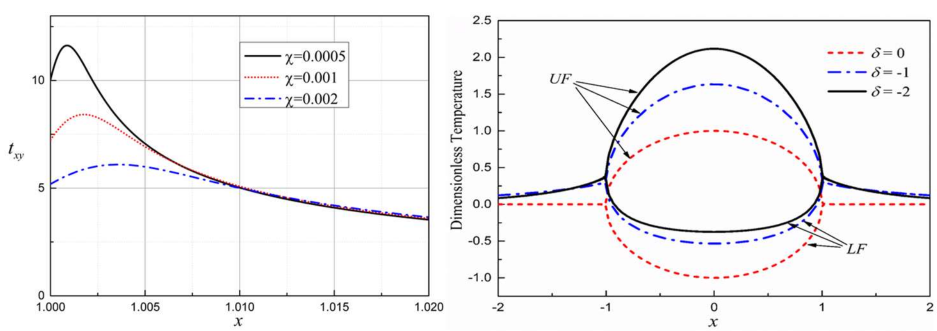
2.3 Results

Two thermal fracture problems are considered in the present work, one is a cracked half-space under thermal shock and the other is a cracked functionally graded material under heat flux from top. The latter structure mimics an actual FG thermal barrier composed of a ceramic layer on the top as a thermal shield and a metal substrate at the bottom of the structure protected from excessive heat. Figure 1 shows that under a heat shock at the bottom of the half-space, an insulating crack provides a thermal shield and heat flux jams on the lower face of the crack, whilst a conducting crack would allow heat to travel freely from the source at bottom to the top. Figure 2 shows the temperature distribution on the top and bottom surfaces of the crack and stress distribution along the extension line of the second problem using nonlocal, non-Fourier heat conduction theory. In Fig. 2, δ is the gradient parameter for thermal conductivity, χ is normalized nonlocal parameter. When the crack is assumed to be heat insulator, the upper surface is under heating while the lower surface is under cooling. In addition, when the nonlocal parameter increases, the peak stress decreases, and the location moves away from the crack tip.



(a) (b)

Fig.1 – Temperature distribution around the crack in a half-space under thermal shock from the free surface at the bottom (a) insulating crack, (b) conducting crack



(a) (b)

Fig.2 – Temperature distribution on the top and bottom faces (a) and nonlocal thermal stress in front (b) of a central crack.

3. Conclusions

Non-Fourier heat conduction leads to thermal and mechanical overshooting in comparison to Fourier heat conduction. Nonlocal, non-Fourier heat conduction theory can lead to limit thermal stress around crack tip, allowing stress-based fracture criterion to be used in thermal fracture design of advanced materials and structures under extreme thermal environments.

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