

Anisotropy investigation of a single crystal superalloy using laser-spot infrared thermography

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Abstract

Thermal property investigation of anisotropic materials such as single crystal superalloys are still in interest of practical and fundamental reasons but remains challenging using conventional testing methods. In this study, a single crystal superalloy is tested using laser-spot thermography, and its thermal anisotropy is investigated. Determining anisotropic thermal conductivity at microscopic scales is challenging, as it appears isotropic at the macroscopic scale. Infrared thermography is one of the best-known techniques for measuring material heat transfer properties and facilitating visualization of temperature distribution through the specimen. The proposed study uses the active thermography method of laser-spot infrared thermography, in which a laser spot is focused onto the sample surface and the thermal response is captured from the surface of the specimen with an infrared camera. A detailed analysis of temperature gradients and heat diffusion patterns aids in the measurement of thermal conductivity values along the sample's different crystallographic directions. The directional bonding characteristics and inherent crystallographic structure of the alloy account for the in-plane thermal conductivities calculated from experimental thermal measurements. The laser-spot thermography method has proven to be an effective tool for mapping the material's thermal conductivity anisotropy with high sensitivity and high spatial and temporal resolution. The investigation into the anisotropy of the material provides an insight into heat flow in the structure and helps in optimizing the design and overall performance of the material system.

1. Introduction

Single crystal superalloys are advanced materials known for superior thermal stability and mechanical capabilities and are used in high-temperature applications such as power generation turbines and gas turbine engines. A highly organized crystalline structure and the absence of grain boundaries facilitate the distinctive microstructural properties of single crystal superalloys [1-3]. The anisotropic material properties, such as thermal conductivity, play a major role in determining the overall performance of single crystal superalloys. The anisotropic thermal conductivity of a material is defined as the ability to transfer heat in varying crystallographic directions [4-5]. To make a single crystal superalloy more efficient and useful in high-stress situations, it is important to measure its anisotropic thermal conductivity in each direction.

Conventional testing methods for studying anisotropic thermal conductivity are complex and time-consuming experimental setups that lack temporal and spatial resolutions [6-7]. On the contrary, infrared thermography is a non-destructive testing method that facilitates the inspection of specimens with high accuracy and studies the temperature distribution and heat transfer through the specimen [8-10]. An extensive study on thermal property measurements using the flash thermography method on homogenous and isotropic materials is being done [11-14]. In this proposed study, laser-spot infrared thermography is applied to the surface of the specimen to analyze the anisotropy in the thermal conductivity. Laser-spot thermography helps in the concentrated heat application in small regions and studies the rapid thermal responses and material behavior more locally [15]. Extensive studies are done on composite materials and metals for thermal property evaluation using laser-spot thermography, which shows its potential for detailed investigation of anisotropy [16-17]. The proposed study focuses mainly on two objectives; firstly, to establish an efficient laser-spot thermography experiment, and secondly, to quantify the anisotropic thermal conductivity of a single crystal superalloy. The proposed study is an initial step towards measuring the material properties of anisotropic materials using thermal imaging methods.

2. Methodology

2.1 Laser-spot infrared thermography experiment

The laser-spot thermography tests are carried out on the surface (front side) of the sample to determine the anisotropy. The specimen investigated in this study is a single crystal nickel-based superalloy, and the sample was prepared by cutting the superalloy into an octagonal prism piece. Figure 1(a) shows the experiment setup of the laser-spot infrared thermography on the prism specimen. The laser-spot thermography experiment consists of a continuous-wave laser source as input heat source, a mid-wavelength infrared (MWIR) camera, and a thermal data acquisition system. The sample is excited with a laser spot of 1.14 mm diameter and a pulse duration of up to 1 s, and the temperature development



is recorded with a MWIR infrared camera at a recording speed of 3 kHz in the partial image. Figure 2(a) shows the schematic image of the specimen applied with concentrated laser-spot heating in the center, and Figure 2(b) shows the temperature gradient profile measured using the IR camera. The concentrated laser heat source is applied at the center of the sample, and heat diffusion is measured using an IR camera with a high spatial resolution of $33.5 \mu\text{m}/\text{pixel}$ and a temporal resolution of 0.33 ms. The complete heating and cooling are shown in the temperature gradient profile, which show the sample is gradually heated during the excitation using the laser source and cools down abruptly when the heat source is switched off. This 1D temperature profile shows only the heat conduction through the thickness of the specimen. Unlike in an isotropic medium, heat conduction in an anisotropic medium is complicated and varies with the directions.

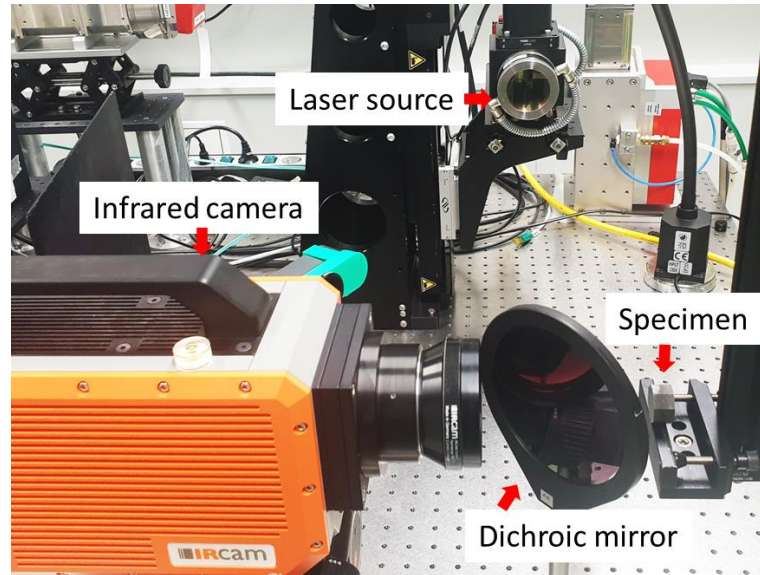


Fig. 1. Laser-spot infrared thermography experiment setup: MWIR camera is placed normal to the prism sample and laser source directed towards dichroic mirror at an angle of 45°

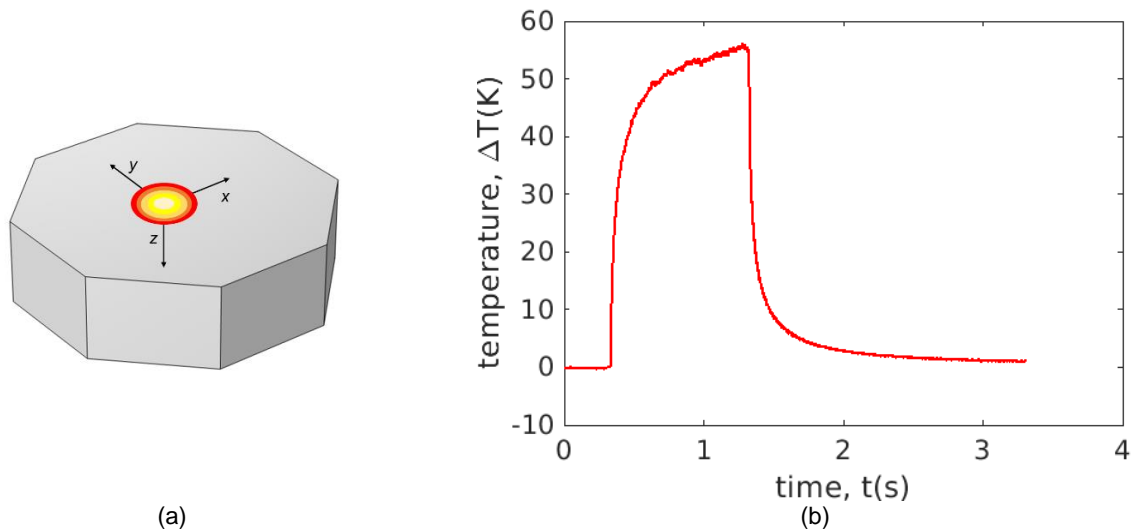


Fig. 2. (a) Schematic representation of laser-spot heating applied on the center of the prism sample, and (b) temperature difference vs time profile from the center of the sample during heating and cooling process

2.2 Data analysis

The temperature gradient profiles obtained from thermograms are used to evaluate the heat flux in all directions. Temperature profile is fitted to the Gaussian models to extract the components of thermal conductivity tensor. During the

excitation of sample using laser source, heat diffuses through lateral and axial direction within the sample. The thermal image recorded from the sample surface at each instant of time represents components of heat diffusion in both lateral and axial directions. The anisotropy is quantified by characterizing the heat diffusion pattern measured on the sample surface. The thermograms measured in the experiment are noise-filtered using a Gaussian filter [18-20]. Figure 3(a) shows the thermogram of the sample, and figure 3(b) shows an example of the Gaussian fit along the x and y directions of the temperature profiles in the center of the thermal image. The data is sampled along lines through the center of the excitation over all angles from 0° to 360° and on each a fit with a Gaussian distribution is performed. A single gaussian fit along an axis represent heat distribution along that line at a time instant and measured using standard deviation (σ). Similarly, heat distribution pattern along all angles or directions in the surface of the sample is studied with σ measure.

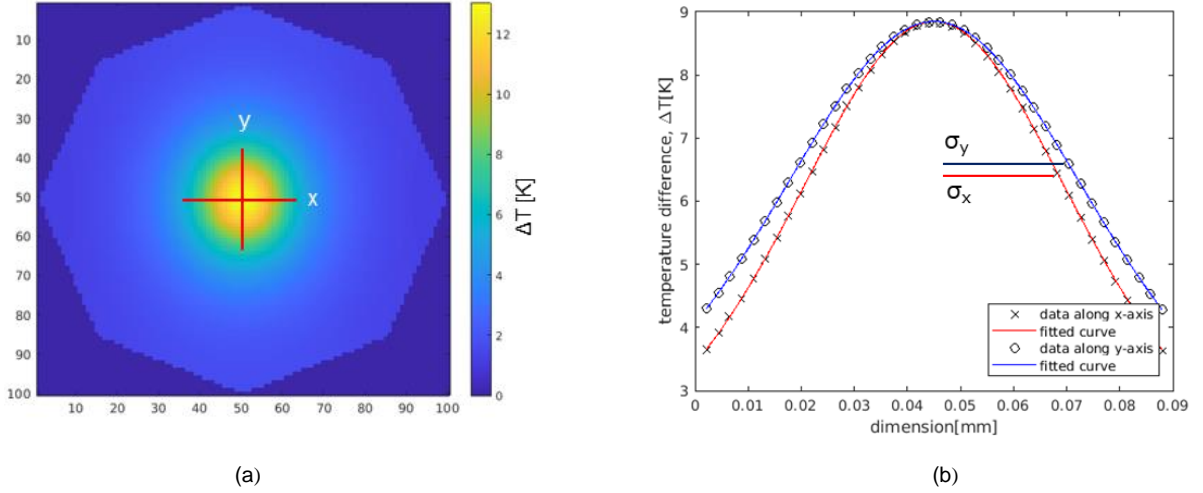


Fig. 3. (a) Thermal image of the sample recorded using the IR camera, and (b) Gaussian curves along the x- and y-axis of the center of the thermal image and the standard deviations along x- and y-axis are marked as

3. Theory

Thermal conductivity (k) is defined as the measure of ability of a material to conduct heat. In anisotropic materials, heat flux is dependent on the temperature gradients along all directions and thus k value varies with the direction [21-23].

Mathematically, heat conduction in an anisotropic material is governed by the Fourier law as:

$$q_i = -k_{ij} \frac{\partial T}{\partial x_j} \quad (1)$$

Where q_i is the heat flux, k_{ij} is the thermal conductivity tensor, T is the temperature, and x_j are spatial coordinates.

The thermal conductivity tensor is calculated from the measured in-plane thermal conductivity values [24]. The thermal conductivity tensor of a face-centered cubic system has the following form,

$$\mathbf{K} = \begin{bmatrix} k_{xx} & k_{xy} & 0 \\ k_{xy} & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \quad (2)$$

Where x , y and z in the indices correspond to the Cartesian axes. The \mathbf{K} tensor is symmetrical due to Onsager's reciprocity relationships and k_{xz} and k_{yz} are equal to zero due to the cubic symmetry. The directional thermal conductivity in the plane is,

$$K_{\parallel} = k_{xx} \cos^2 \theta + 2k_{xy} \sin \theta \cos \theta + k_{yy} \sin^2 \theta \quad (3)$$

where θ is the angle between the x-direction and the grain orientation in the x-y plane.

4. Results and discussion

The thermal conductivity is calculated from the standard deviation of the Gaussian fit, as the standard deviation and thermal conductivity is related as $\sigma_t = \sqrt{2 \frac{k}{\rho c} t}$, where k is thermal conductivity, ρ is density and c is specific heat capacity respectively. The calculated standard deviation plots are shown in figure 4. Figure 4(a) shows the standard deviations of temperature distributions approximated by the gaussian profiles around the laser spot at the peak of the laser excitation. In the figure 4(b), standard deviations for the temperature distributions from peak of the laser excitation to the few instances in the cooling phase. As the cooling proceeds, the standard deviation profiles spread away from the center of the laser excitation point due to the thermal diffusion in the lateral and axial directions of sample. From both graphs it is clear that standard deviations are non-uniform around the centre of laser excitation as it shows the non-uniformity in the temperature distribution in specimen. This highlights the non-uniformity in the thermal properties of the specimen as the standard deviation and thermal properties are correlated.

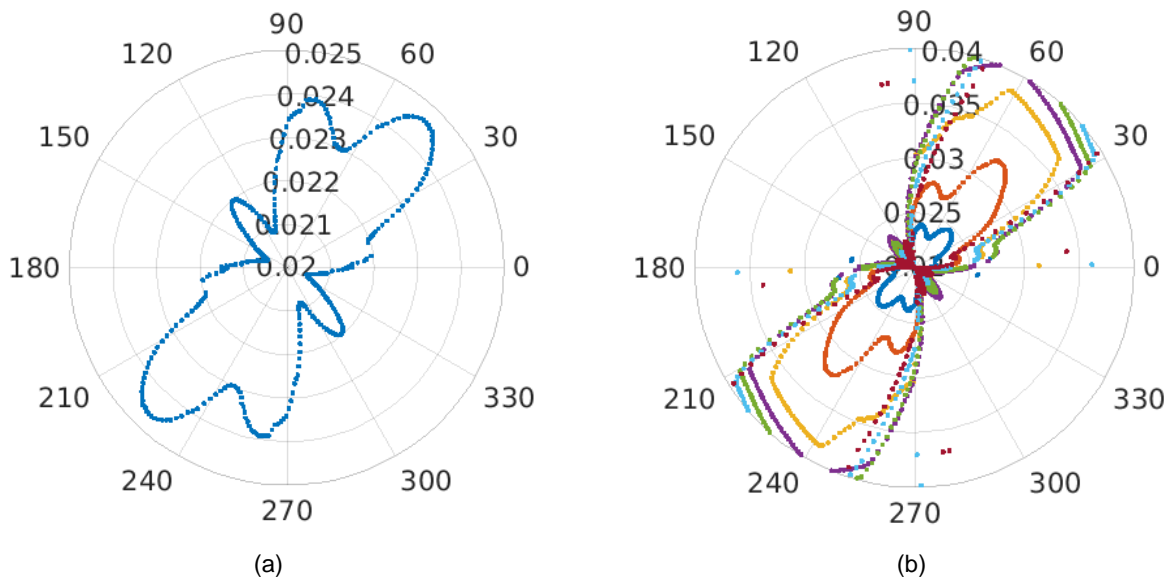


Fig. 4. Polar diagram of the standard deviations (σ) of the temperature distributions approximated by gaussian profiles around the laser spot on the surface (a) at peak & (b) from peak (blue near center) and time instances from cooling phase

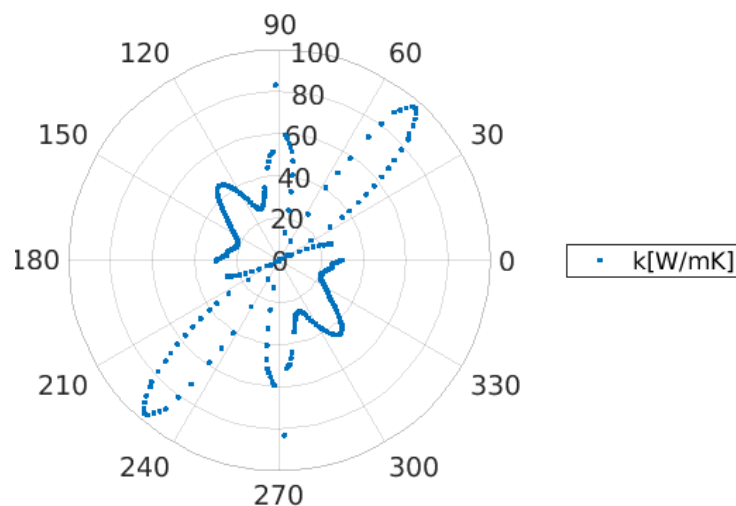


Fig. 5. Polar diagram of the thermal conductivity (k) in the x-y plane of the sample, measured using the laser TT method

The calculated thermal conductivity is plotted in polar form to show the behavior of heat propagation in the sample caused by the anisotropy. Figure 5 show the polar diagram of the thermal conductivity pattern in the x-y plane of the sample during the heating and cooling phases. The thermal conductivity values vary between both phases due to the non-uniform heat diffusion as a result of material anisotropy. Discontinuities and outliers in the thermal conductivity profile are mainly due to measurement and adjustment errors. The thermal conductivity values show a complex pattern due to the angular dependence of the temperature gradient in the x-direction, which also influences the heat flow in the y-direction and vice versa.

The thermal conductivity pattern created by the anisotropy in the samples varies with the change in the orientation angle of the sample. The samples are examined by rotating them in the x-y plane along the center with angles from -15° to 15° in a step of 5°. All resulting planar thermal conductivity profiles show a spatial deviation with respect to the angular change, indicating that the measured data lies in good agreement with the directional thermal conductivity observed in anisotropic materials. Laser thermography measurements are sensitive to the diameter of the laser spot, the pulse width, the laser power, and the acquisition rate. The calculated thermal conductivity values can vary due to the dependence on measurement errors, noise, local minima when fitting the data and other dependent factors and require a detailed investigation of the uncertainties affecting the calculation.

Solving equation 3 results in the thermal conductivity tensor for our thermography study [25],

$$K = \begin{bmatrix} 4.89 & 19.80 & 0 \\ 19.80 & 32.28 & 0 \\ 0 & 0 & 90.9 \end{bmatrix} \quad (4)$$

The negative values for k_{xy} represent the temperature gradient along the $+x$ direction, resulting in a deviation of the heat flow in the $-y$ direction. The thermal conductivity tensor shows the general directionality of the heat flow through the system and helps to better understand the mechanical properties of the entire material system.

The anisotropic thermal conductivity plays a crucial role in the performance of single crystal superalloys in real-world applications. The higher thermal conductivity along a direction indicates that components oriented in this direction can conduct heat more efficiently, improve material durability, and reduce thermal fatigue. In contrast, the reduced thermal conductivity in a direction may require the implementation of additional thermal management strategies to prevent localized overheating. The application of laser-spot thermography in this study demonstrates several advantages, including precise surface temperature measurements without damaging the sample, a focused laser spot, and a high-resolution camera that facilitates detailed mapping of heat diffusion. Compared to other NDT methods like the ultrasound technique, planar anisotropy is evaluated directly from thermal imaging, which gives us a direct correlation between the surface temperature gradient and the crystal orientation of the single crystal superalloys. In future works, extensive study, including a large number of samples of varying sizes and types of single crystal superalloys, will provide a comprehensive understanding of anisotropy. Advanced modeling techniques could help in the accurate calculation of the 3-D thermal conductivity tensor and provide insights into the heat transport mechanisms.

5. Conclusion

This work showcases the effectiveness of laser-spot infrared thermography in investigating the anisotropic properties of a single crystal superalloy. It provides valuable insights into the material's thermal behavior and structural integrity. The laser-spot thermography technique is mostly applied for defect detection, but it could possibly be applied to evaluate heat diffusion and in-plane thermal diffusivities of anisotropic materials. The objective of our study is to develop a technique that can accurately measure the thermal conductivity of anisotropic materials by using a time- and spatially resolved thermal imaging method. The initial findings show that the thermal diffusion pattern varies significantly along different crystallographic axes, emphasizing the directional dependency of thermal properties within the material. This study validates the correlation between the surface temperature gradient and the crystallographic orientation of the anisotropic material. A detailed investigation in this regard is needed for developing a thorough comprehension and accurate estimation of the degree of anisotropy, which is crucial for optimizing the design to improve the efficiency of the single crystal components.

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