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Quantitative infrared thermography applied to subgrain scale and the effect of out-of-plane deformation

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HIGHLIGHTS

- The quantitative infrared thermography is applied to the subgrain scale.
- The source of the radiometric artifacts on the microstructure scale is verified.
- A method is proposed for quantifying the geometrical dependence of emissivity.
- We demonstrate a correlation between apparent emissivity and surface profile.

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ABSTRACT

This paper is concerned with an application of infrared thermography to study the material behaviors on the microstructure scale. A single crystal specimen of pure nickel was investigated, and a thermographic methodology was developed for realizing a quantitative measurement on the subgrain scale. The nickel single crystal was plastically deformed in a tensile test, and notable out-of-plane deformation manifested on the material surface in the form of slip markings. The out-of-plane deformation introduced significant radiometric artifacts in the measured thermal fields, as a result of the modification of apparent emissivity on the material surface. The geometrical dependence of the apparent emissivity was analyzed quantitatively based on the measured emissivity and surface profile distributions. The study demonstrates that the apparent emissivity decreases with the increase of the variation of the angle of observation, which is in good agreement with the theoretical analysis.

1. Introduction

Infrared thermography is an emerging full-field measurement technique that to date has been used successfully for multiple applications, e.g., temperature measurement [1–3], thermoelastic stress analysis [4,5], fatigue monitoring and assessment [6–9], and non-destructive testing and evaluation [10,11]. In the field of experimental solid mechanics, infrared thermography is found particularly useful in evaluating the energy dissipation of deforming materials, which is usually a very sensitive indicator of the microstructural changes [12–14]. The assessment of the dissipated energy is crucial for establishing an experimental energy balance in a plastic deformation. And the full-field information provided by the thermographic measurement allows further understanding of the heterogeneous deformation mechanisms for a variety of materials [15–17].

Infrared thermography has long been expected to be applied to the microstructure level in the mechanical tests of materials. However, to the best of our knowledge, the finest spatial resolution of a commercially available infrared camera can reach only 15 μm per pixel (and in some cases 5 μm per pixel). They are still insufficient for realizing a microscopic scale observation. Nevertheless, recently an alternative solution has been proposed that allows conducting the microstructure scale study through a special kind of specimen with simple structures, e.g., oligocrystal, bicrystal and single crystal. These materials enable to demonstrate the microstructure-dependent phenomena on a macroscopic scale, facilitating, therefore, the observation by an infrared imaging system [18–21]. In this work, a pure nickel single crystal specimen is studied, and its plastic deformation behaviors are investigated by the thermographic measurement and analysis. In the public literatures, the quantitative infrared thermography (QIRT) has not yet been applied to a subgrain scale to our best knowledge.

This paper attempts to investigate the slip activation and development of pure nickel single crystal in a tensile test. The

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heterogeneous features of the plastic deformation at the subgrain scale are analyzed based on the measured thermal fields. And a metrological study on the measurement precision is performed. In particular, the out-of-plane deformation due to slip band emergence and its resulting radiometric artifacts in the thermographic imaging are analyzed quantitatively.

2. Material and methods

The studied material is nickel single crystal of very high purity (99.999%). The minor chemical compositions of the pure nickel single crystal are shown in Table 1 by weight. The material is possessed of a Young's modulus 200 GPa, shear modulus 80 GPa and Poisson ratio 0.31.

The pure nickel single crystal was obtained using the Bridgman technique [22] along the crystal growth direction [100], and was supplied in the initial form of the cylindrical rod of diameter 16 mm. Then it was further machined into dog-bone specimens via electrical discharge machining. The geometric dimensions of the final obtained specimen are illustrated in Fig. 1.

The observation surface of the specimen is in the crystallographic plane (100) and the axial loading direction is along [001], as shown in Fig. 1. As known that the nickel has 12 possible slip systems of type $\{111\}\langle 110\rangle$. According to the Schmid law [23], eight slip systems will be equally stressed in the tensile test and among them four active slip systems will intersect with the (100) plane. Hence, it enables the emergence of two groups of slip markings on the specimen surface, which are the intersections of the slip planes from two pairs of slip systems. This prediction has been previously verified in [24] on the same material.

In this work, a complete calibration procedure for realizing QIRT was established. It took into account of the most important factors in a thermographic measurement, including non-uniformity correction (NUC) [25,26], bad pixel detection, integration time selection, and emissivity measurement [27]. The core of this QIRT framework is the so-called pixel-to-pixel calibration. Its principle is to determine an optimal function that allows converting the measured digital level (DL) by the infrared camera into radiative flux Φ emitted by the observed object. The calibration is performed pixel by pixel. Thus each infrared sensor in the focal plane array (FPA) is possessed of a unique DL-flux relation for a given integration time.

Table 1
Chemical compositions of pure nickel single crystal.

Element	Co	Cr	Cu	Fe	Mg	Mn	Si	Ti	C	S
p.p.m (wt)	8	8	10	10	10	10	8	10	10	10

In the calibration test, the extended black body at k different temperatures is measured by the infrared camera, producing k corresponding thermal images in DL. For a given pixel $P(x,y)$ with measured $DL(x,y)$, it agrees to the following polynomial:

$$\Phi_k(x,y) = \sum_{i=0}^{p} \alpha_i(x,y)(DL_k(x,y))^i \tag{1}$$

where α are coefficients determined by the method of least squares and p corresponds to the degree of the solved polynomial.

With the calibrated Φ, the temperature T can be obtained according to the Stefan–Boltzmann law [1]:

$$\Phi = \sigma T^4 \tag{2}$$

where the Stefan's constant $\sigma = 2\pi^5 k^4/15c^2h^3 = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}.

The employed infrared camera in this study was the Cedip Jade III. It was calibrated in the temperature range [18 °C, 29 °C] by the proposed method. The calibration curves of all sensors in FPA are illustrated in Fig. 2. Here it is worthy to note that the exceptional curves with very high or very low DL values in Fig. 2 correspond to the bad pixels due to poorly-functional sensors. They should be replaced by the values of their neighboring pixels or be excluded in the analysis.

To further improve the thermographic measurement precision, a carbon black coating was applied to the specimen surface. It enables to provide an apparent emissivity as high as 0.97, which may contribute to reducing the reflection influences from the environment.

A tensile test was performed on the nickel single crystal specimen by a micro tensile test stage of Kammrath and Weiss. The test

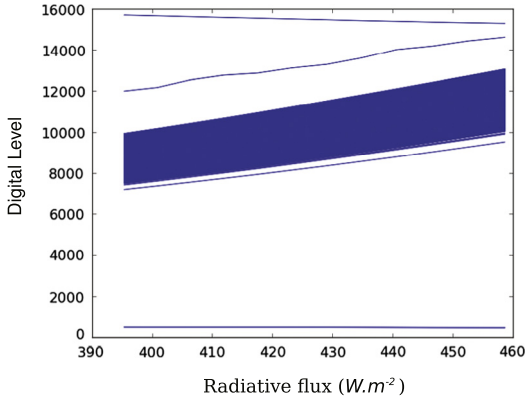

Fig. 2. Calibration curves for all sensors of FPA.

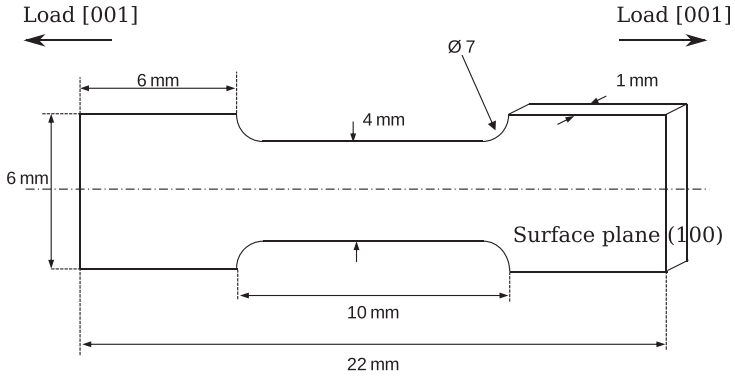

Fig. 1. The geometry of the nickel single crystal specimen.