Analysis of the thermomechanical response of granular materials by infrared thermography

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Abstract Granular materials are defined as a collection of solid particles whose macroscopic mechanical behavior is governed by the interaction forces between the particles. Full-field experimental data on these materials remain few compared to numerical results, even though a wide literature deals with optical imaging (combined with digital image correlation) and photoelasticimetry (to measure shear stresses in particles made of birefringent materials). We applied infrared thermography to analyze two-dimensional granular media composed of cylinders and subjected to confined compression. We analyzed the calorific signature of the contact forces, especially by revealing mechanical dissipation in the interparticle friction zones. Moreover, two constitutive materials featuring entropic and isentropic elasticity were employed to compare distinct types of thermoelastic couplings. Couplings and mechanical dissipation were separately identified at two observation scales. The perspective of this work is the experimental analysis of soft granular media.

Keywords Granular material · Infrared thermography · Thermoelastic coupling · Friction · Entropic coupling

2.1 Introduction

Granular materials are omnipresent in our daily life as well as in many industrial fields. They are defined as a collection of solid particles whose macroscopic mechanical behavior is governed by the contact forces between the particles. They generally consist of grains with wide distributions in terms of size, shape and base material. Their mechanical behavior strongly differs from that of continuum solids, liquids, and gases [1]. Numerical simulation has been carried out to investigate the influence of parameters such as the particle shape, density, polydispersity, particle elasticity, friction, etc. [2]. Several experimental techniques are also available. For measurements in the bulk, let us cite X-ray tomography [3, 4], flash X-ray shadowgraphy [5], magnetic resonance imaging [6], radar-based sensing [7] and positron emission particle tracking [8]. For two-dimensional (2D) measurements, particle image velocimetry and digital image correlation were widely employed [9–11]. For stress measurement in the particles, photoelasticimetry is a full-field experimental technique providing the shear stresses in particles made of birefringent materials [12–16]. In the present study, we employed infrared (IR) thermography to reveal the calorific signature of the contact forces, especially in the interparticle friction zones. Moreover, two base materials were employed to compare two types of thermoelastic coupling: *isentropic* coupling (typical of metallic materials and polymers below their glass transition temperature) and *entropic coupling* (typical of rubber-like materials).

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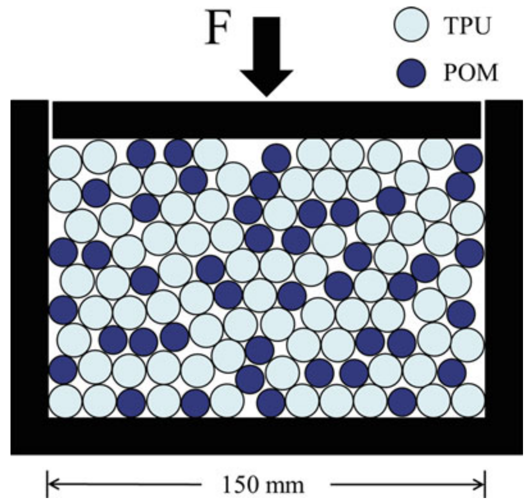
Fig. 2.1 Experimental configuration



2.2 Methodology

The experimental configuration is presented in Fig. 2.1. Cylinders made of two types of materials were employed: thermoplastic polyurethane (TPU) and polyoxymethylene (POM). These materials differ in terms of stiffness and thermoelastic coupling. TPU is much softer than POM (ratio of about 700 in tension). TPU is governed by entropic thermoelastic coupling [17, 18] while POM is governed by isentropic thermoelastic coupling [19–21] at ambient temperature and within the range of mechanical loadings applied in the study. TPU cylinders were molded by PCM Technologies S.A.S. (France). See Refs. [19–21] for the properties of POM cylinders. POM cylinders were 10.5 mm in diameter. TPU cylinders were 12.0 mm in diameter. All cylinders were 60 mm in length. The surface of each cylinder was painted in a matte black color to homogenize and maximize the thermal emissivity.

A cyclic mechanical loading was applied to the top of the granular sample using a MTS ±15 kN uniaxial testing machine: force-controlled sinusoidal signal, frequency of 0.5 Hz, force ratio of 0.1, maximum compression force of −10 kN. Ambient temperature was equal to 28 °C. A Cedip Jade III-MWIR camera was employed to capture the temperature fields on the surface of the cylinders at an acquisition frequency of 150 Hz.

2.3 Global Analysis

In order to reveal irreversible phenomena occurring during the cyclic loading, we assume that the heat produced by the thermoelastic response is equal to zero over a mechanical cycle (or an integer number of cycles). The heat produced by mechanical irreversibility is always positive. The corresponding heat power density is usually named *mechanical dissipation* or *intrinsic dissipation* [22–24]. For granular materials, mechanical dissipation can be due to friction at the contacts between particles. It can be also due to the stresses inside the particles, in particular in the stress concentration zones. Figure 2.2 shows a map of temperature differences for three mechanical cycles. It can be observed that the values are close to zero except at some contacts between particles. In particular, strong thermal activity is observed along some lines inclined with respect to the loading direction. It can be checked that the higher the number of mechanical cycles considered, the higher the temperature differences due to irreversible phenomena.

In order to reveal thermoelastic couplings in the material's response during the cyclic loading, we have considered a half-cycle. The heat due to thermoelastic couplings for loading and unloading are indeed equal but with opposite signs. Figure 2.3 shows a map of temperature differences for a compression stage. It can be noted that the values are greater than those obtained in Fig. 2.2 corresponding to three entire cycles. This shows that that the amplitude of the thermoelastic effects is much greater than the thermal signature of the irreversible phenomena. It can also be observed in Fig. 2.3 that heating is not visualized only at the contacts: it is distributed inside the particles. Hotter particles are mainly made of TPU. The entropic coupling is indeed stronger than the isentropic coupling. Next section provides information at a better spatial resolution.

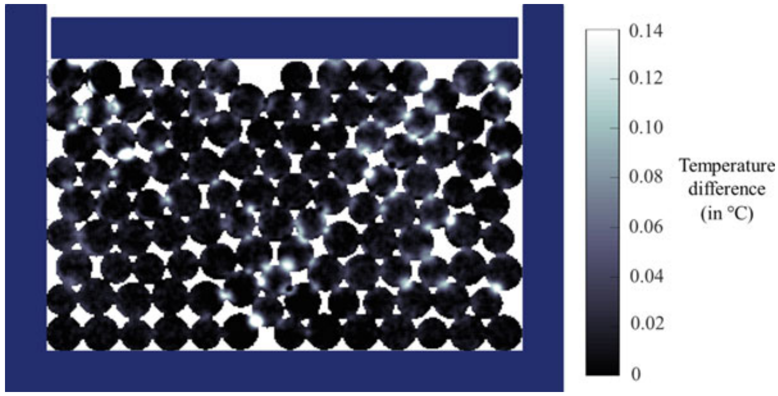


Fig. 2.2 Map of temperature differences for three mechanical cycles, revealing mechanical dissipation

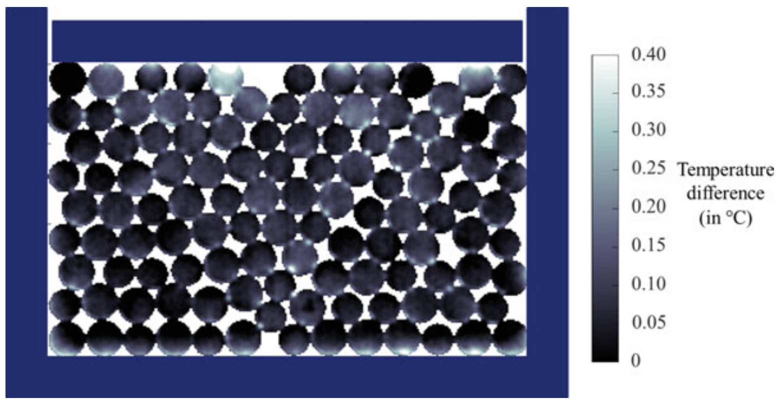


Fig. 2.3 Map of temperature differences for a half-cycle, revealing thermoelastic couplings

2.4 Local Analysis

The IR camera was then placed closer to the granular sample to obtain a better spatial resolution in a specific zone of the granular assembly. Similarly to the global analysis, the map of temperature differences for three mechanical cycles is presented in Fig. 2.4 to reveal mechanical dissipation. Hot zones are observed on both sides of the contact zones. This can be explained by the diffusion of the heat produced by the friction [25]. Heterogeneity in the intensity of the irreversible thermal response is clearly evidenced.

Similarly to the global analysis, the map of temperature differences for a half-cycle is presented in Fig. 2.5 to reveal thermoelastic coupling effects. The thermal patterns differ from those observed in Fig. 2.4 corresponding to irreversible phenomena. Indeed, the thermoelastic response depends on the type of material (POM or TPU) and on the local stress state, whereas the mechanical dissipation depends on the friction intensity at the contact. For example, it is possible to have a strong stress concentration (leading to strong thermoelastic effect) accompanied by low friction depending on the ratio between normal and transverse contact forces.

2.5 Conclusion

IR thermography is in principle applicable to any type of solid material to perform a thermomechanical analysis. However, the application to granular assemblies is difficult. The present study provides arguments for choosing constitutive materials for such analyses. It can be claimed that entropic elastic matters are excellent candidates as analogical materials for the analysis of granular media by IR thermography. Rubber-like entropic particles (such as TPU) provide strong thermoelastic responses that could be used to identify the contact force network. In addition, thermoelastic couplings and mechanical dissipation due to interparticle friction can be separately revealed. IR thermography thus provides two routes to analyze

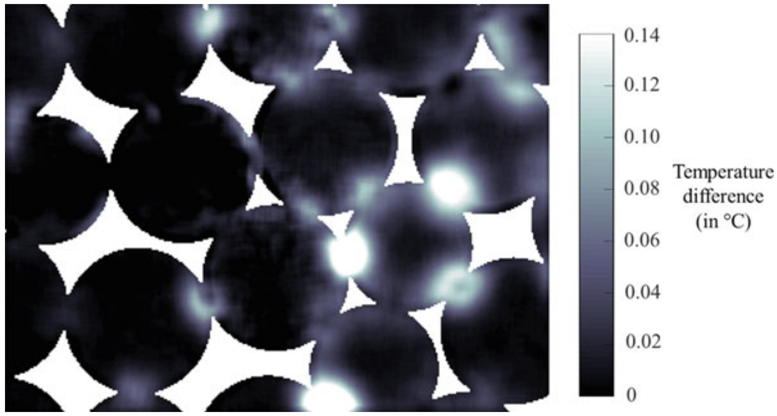


Fig. 2.4 Local analysis: map of temperature differences for three mechanical cycles, revealing mechanical dissipation

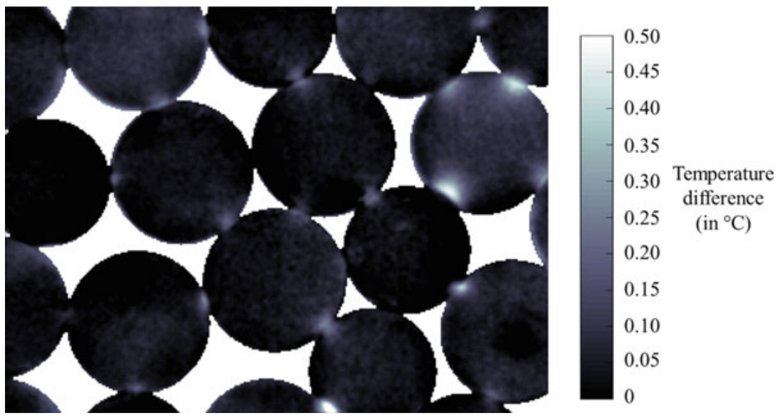


Fig. 2.5 Local analysis: map of temperature differences for a half-cycle, revealing thermoelastic couplings

granular materials. Compared to previous works performed with only isentropic materials [19–21], numerous mechanical cycles and high loading frequency are not required for the processing. Only a few mechanical cycles are necessary for the analysis: a half-cycle for revealing entropic thermoelastic coupling, and one cycle minimum for revealing irreversible phenomena. More generally, the study opens prospects for the experimental analysis of "soft" granular materials.

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