Using IR Thermography to Analyze the Mechanical Response of a Granular Material

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***Abstract*— The objective of the study is to analyze the thermomechanical response of a two-dimensional monodisperse granular system made of thermoplastic polyurethane (TPU) cylinders with elliptical cross-section. Cyclic confined compression tests were performed while an infrared (IR) camera measured the temperature changes at the surface of the cylinders. Thermoelastic coupling and mechanical dissipation were distinguished in the thermal evolution. The former was mainly evidenced as a consequence of stress concentrations in the interparticle contact zones. The latter was highlighted at specific contacts, which can be explained by strong friction in these zones. The higher the number of applied mechanical cycles, the higher the temperature rise as a consequence of an accumulation of heat due to mechanical dissipation production.**

***Index Terms*—infrared thermography, granular materials, thermoelastic coupling, mechanical dissipation, force rates**

I. Introduction

Granular materials are often found in our daily lives as well as in many industrial fields. Examples are sugar, coffee beans, rice, sand, soils, pharmaceutical products, *etc.* Granular materials can be defined in engineering terms as collections of solid particles which exhibit macroscopic mechanical behavior governed by the interparticle forces. Such a mechanical behavior is complex and significantly differs from that of ordinary solids, liquids, and gases [1, 2]. This complexity leads to a variety of phenomena, which is still not clearly understood.

Among the important characteristics of granular materials are the shape and size distribution of the particles. Numerical simulations have been widely used to study the effects of these parameters on packing, flow, strength, and fabric of granular media [3-8]. Some experimental approaches have also been carried out for this purpose [9-11]. Nevertheless, numerical and experimental studies still need to be developed further. The complex shapes of real particles cannot be easily reproduced in simulations, and advanced contour detection techniques are required. Another point concerns the base material used to create granular media. In most of the previous studies, particles were rigid or hard, and only contact stiffness was considered. Discrete systems composed of soft particles are currently becoming a very interesting topic [12]. The term “soft particles” refers to particles that undergo large deformations. Soft particles can be encountered in the pharmaceutical and food industries in the form of powders, cells, bubbles, *etc*. Research on soft granular materials is still rare, mainly due to a lack of appropriate numerical and experimental tools. In addition, the thermomechanical behavior of soft matters such as rubber-like materials is complex and is the subject of specific research in materials science.

Infrared (IR) thermography is a full-field measurement technique enabling to measure temperature changes at the surface of material samples subjected to mechanical loading. The technique is applicable in theory to any types of solid matter. Nevertheless, it is quite tricky to use IR thermography on discrete material systems, which explains a lack of knowledge about thermomechanical couplings in granular materials. A few studies have investigated the thermal response of two-dimensional (2D) granular systems made of polyoxymethylene (POM)

Manuscript received September 11, 2020; revised February 7, 2021.
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doi: 10.18178/ijmerr.10.4.189-195

cylinders with circular cross-sections (referred to as Schneebeli analogue materials [13]) during a confined compression loading: stress "paths" were successfully evidenced by the temperature changes caused by the thermoelastic coupling effect [14-16]. Recently, IR thermography was also employed to analyze "composite" Schneebeli materials by mixing POM particles and thermoplastic polyurethane (TPU) particles [17]. The authors evidenced the advantage of using a rubber-like entropic material such as TPU compared to materials with classical linear elasticity: the thermal response is indeed more marked. A practical consequence is that only some mechanical cycles with low loading frequency are necessary for the analysis.

In this context, the objective of the present study is to analyze the thermomechanical response of a 2D monodisperse granular system made of TPU cylinders with elliptical cross-section. For that purpose, cyclic confined compression tests were performed while an IR camera measured the temperature changes at the surface of the cylinders. The paper is organized as follows. Section II describes the experimental setup. The thermomechanical response is then analyzed in Section III, distinguishing between reversible and irreversible mechanical phenomena occurring in the granular material. Final comments close the paper in Section IV.

II. Material and Methodology

The experimental setup is presented in Fig. 1-a. A granular sample was prepared by randomly placing 16 cylinders with elliptical cross-section into a 50 mm wide aluminum rectangular frame: see schematic view in Fig. 1-b. It is worth mentioning that previous studies involving cylinders considered circular cross-sections [14-17] for the sake of simplicity. We consider here elliptical cross-sections as a first step towards more sophisticated shapes for the particles, which would more reliably mimic the response of actual granular media. The particles were made of TPU manufactured using an in-house device. This TPU was a commercial biresin grade (U1419-I1 for the isocyanate part and U1458 for the polyol part, Axson Technologies) composed of isocyanate and polyol. The density of TPU is approximately 1040 kg/m^3 according to the supplier's data sheet. The specific heat is about 1700 J/(kg.K) [18]. Particles were molded at ambient temperature in cylindrical holes made in POM block. During the reticulation process, the block was placed for 20 min in a vacuum bell to avoid bubble formation. For all the cylinders (26 mm in length), the minor and major axes of the elliptical cross-section were equal to 10 mm and 15 mm, respectively. One elliptical face of each cylinder was first polished to obtain a smooth surface perpendicular to the longitudinal axis. To maximize the thermal emissivity, the rectangular frame and the cylinders' surface were spray-painted with a matt black paint. As shown in the picture in Fig. 1-a, a black curtain was also placed around and behind the granular system to reduce parasitic reflections from the close environment in the IR range. A FLIR X6540sc camera was used to measure the temperature fields on the surface of each elliptical particle during the mechanical loading, with an acquisition frequency of 10 Hz.

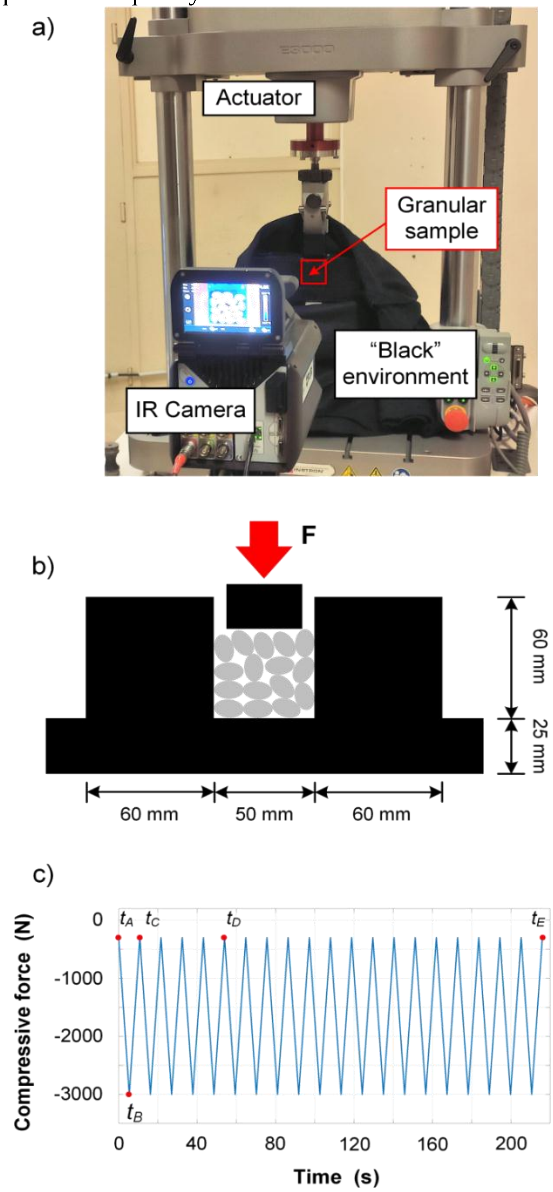

Figure 1. Experimental setup: a) picture of the device, b) a schematic view of the granular sample placed in the rectangular frame, and c) example of cyclic mechanical loading with five specific times used in the processing of the thermal data measured by the IR camera.

A compression loading consisting of twenty triangular cycles was applied to the top of the granular sample by using an Instron ElectroPuls E3000 fatigue testing machine. Fig. 1-c shows an example of such a signal with minimum and maximum forces equal to -300 N and -3000 N respectively. Three force rates were compared: 1 kN/s, 2 kN/s and 5 kN/s. Note that three preliminary mechanical cycles were first applied to compact the granular system. Then, the minimum load was kept constant for 20 minutes in order to ensure a steady

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thermal equilibrium before starting the cyclic loading and the measurement with the IR camera. A thermal image was captured just before starting the test in order to define the reference temperature field.

III. Analysis of the Thermomechanical Behavior

In this section, the temperature fields are analyzed by considering half of the first mechanical cycle (from t_A to t_B in Fig. 1-b) and whole numbers of cycles (one cycle from t_A to t_C, five cycles from t_A to t_D, and twenty cycles from t_A to t_E). Considering integer numbers of cycles enables us to evidence the calorific signature of the irreversible mechanical phenomena such as friction, viscosity, and material damage, referred to as the *mechanical dissipation* or the *intrinsic dissipation* in the literature [19, 20]. Indeed, heat quantities generated by reversible phenomena (here thermoelasticity) over each successive loading and unloading phases are equal in magnitude but opposite in sign. They are therefore null over an integer number of cycles. On the contrary, considering only the loading phase (here half of a first mechanical cycle) enables us thus to evidence the so-called *thermoelastic coupling* (assuming that the mechanical dissipation is low over half of a mechanical cycle). It must be noted that mechanical dissipation is always a positive quantity (corresponding to a production of heat) whereas the heat due to thermoelastic coupling can be either positive (heat release) or negative (heat absorption).

A. Reversible Phenomena

Fig. 2 shows the fields of temperature change occurring over half of the first mechanical cycle for the three considered force rates. “Hot” zones are clearly visible at each contact, as a calorific signature of the stress concentrations caused by the interparticle forces. Hot zones are also visible at the contacts with the rectangular frame. It can be observed that these zones are more and more spread out as the external load rate decreases. This can be explained by heat diffusion [21-23]. Indeed, heat generated locally by stress concentration (by thermoelastic coupling) has more time to diffuse when the period of the mechanical cycle increases. The 1 kN/s configuration shows rather blurred hot spots (with also slightly lower intensities) compared to the other two cases. Nevertheless, the temperature fields for the three configurations are actually quite similar, thus meaning that local adiabaticity is rapidly reached. Over the duration of each test, we can globally consider that the evolution of the granular system is non-adiabatic for the force rate of 1 kN/s, almost adiabatic for 2 kN/s, and quasi-adiabatic for 5 kN/s. Finally, it can be noted that temperature increases are not only observed in the contact zones. Indeed, temperature rises are detected inside the particles. Their intensity is however much lower because of the lower stress level in these zones.

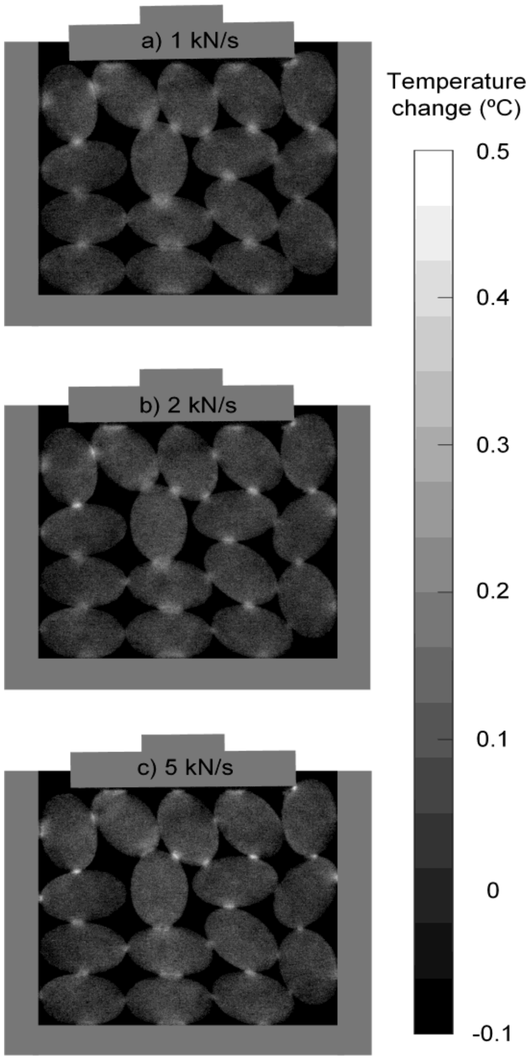

Figure 2. Fields of temperature change over half of the first mechanical cycle, revealing thermoelastic couplings: a) force rate of 1 kN/s, b) force rate of 2 kN/s, c) force rate of 5 kN/s.

The heat produced by the thermoelastic coupling effect can be then calculated. Let us consider first the heat diffusion equation in the Lagrangian configuration [24]:

$$\overbrace{\rho C\dot{T}}^{(a)} - \overbrace{\mathrm{Div}(\kappa_0 \mathrm{Grad}T)}^{(b)} = \underbrace{D_{\mathrm{int}}}_{(c)} + \underbrace{T\frac{\partial \mathbf{P}}{\partial T}:\dot{\mathbf{F}} + T\sum_{\beta=1}^{m}\frac{\partial \boldsymbol{A}_\beta}{\partial T}:\dot{\xi}_\beta}_{(d)} + \underbrace{R}_{(e)} \quad (1)$$

where ρ, C, T, κ_0, $\mathbf{P}$, $\mathbf{F}$, ξ_β and $\boldsymbol{A}_\beta$ are the density, the specific heat, the temperature (expressed in Kelvin), the thermal conductivity, the first Piola–Kirchhoff stress tensor (or nominal stress tensor), the deformation gradient tensor, the m potential internal variables (such as plastic strain, viscous strain, or phase fractions) and their associated thermodynamic forces, respectively. In (1), the first term (a) is the heat power density associated to the change in temperature of the material. Heat exchanges by conduction are represented by term (b). Term (c) is the heat power density D_{int} produced by the material due to irreversible mechanical phenomena. It is always positive and called *mechanical dissipation* or *intrinsic dissipation*. It must be distinguished from the thermal dissipation D_{the} in the Clausius-Duhem inequality $D_{\mathrm{int}} + D_{\mathrm{the}} > 0$. Term (*d*) is associated with reversible mechanical phenomena. In particular, thermoelastic couplings exist in all materials. The first term of term (*d*) corresponds to the heat source due to entropic coupling, while the latter corresponds to the other potential thermomechanical couplings. The last term (*e*) is the external heat rate R associated to radiation.

To calculate the heat power density due to thermoelastic coupling, the following assumptions were considered:

- Heat exchanges by conduction and convection can be neglected at the force rate of 5 kN/s (adiabatic evolution, see above);
- There is no significant thermomechanical coupling associated to internal state variables ξ_β;
- The radiation term R is considered to be low and constant during the measurements thanks to the precautions taken in the experimental setup.

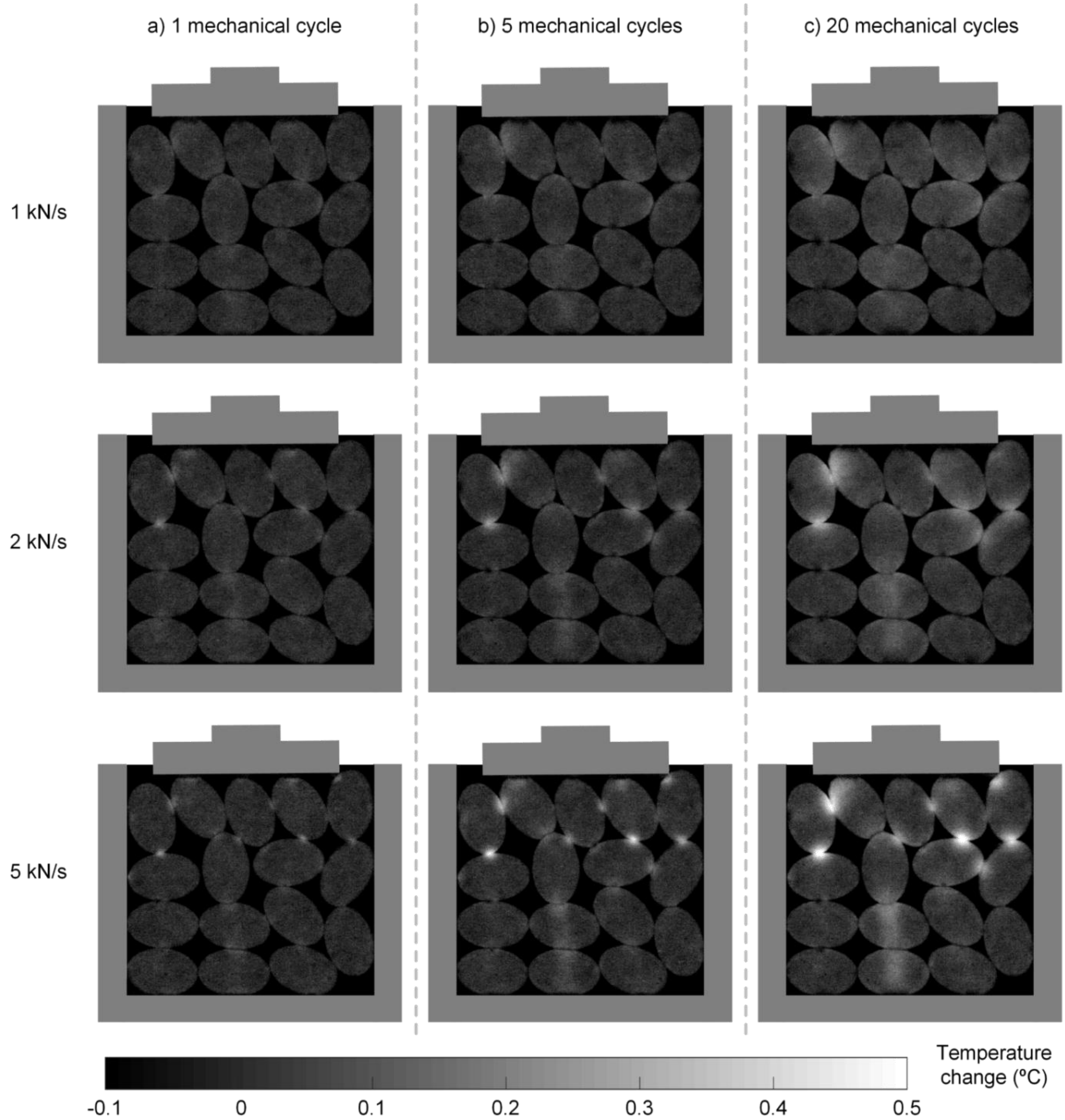

Figure 3. Fields of temperature change revealing mechanical dissipation: a) over one mechanical cycle from times t_A to t_C in Fig. 1-b, b) over five cycles from t_A to t_D, and c) over twenty cycles from t_A to t_E.

Let us denote Θ as the temperature change with respect to the equilibrium temperature T_0 which, in practice, is measured just before starting the mechanical loading. Under the above assumptions, the heat diffusion equation (1) can be rewritten into the following simplified form:

$$\rho C \dot{\Theta} = D_{\mathrm{int}} + W_{\mathrm{the}} \tag{2}$$

where W_{the} is the heat power density due to the thermoelastic coupling, corresponding to the term (*d*) in

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(1). It must be noted that entropic coupling in rubber-like materials results in heat release ($W_{the} > 0$) upon loading and heat absorption ($W_{the} < 0$) upon unloading [17, 20]. The mechanical dissipation D_{int} can be considered to be much lower than the thermoelastic coupling term W_{the} over a mechanical half-cycle, *e.g.* during the loading phase (see below for the quantitative verification of this hypothesis). Considering the force rate of 5 kN/s, the heat density magnitude due to thermoelastic coupling was extracted at all the interparticle contact zones in Fig. 2. The minimum, maximum and average values are equal to 40 kJ/m^3, 635 kJ/m^3 and 299 kJ/m^3, respectively. Note that decreasing the force rate leads by construction to lower values because of the heat exchanges (non-adiabatic evolution) penalizing the calculation.

B. Irreversible Phenomena

Fig. 3 shows the fields of temperature change for different integer numbers of cycles. Based on the assumption that the heat due to thermoelastic coupling is null over a mechanical cycle, these maps thus reveal mechanical irreversibility. For granular materials, mechanical dissipation can be associated to friction at the contacts, as well as to viscosity and damage within the material itself, particularly in the zones subjected to high stress levels. Several comments can be drawn from the thermal maps in Fig. 3. For the three loading rates under consideration, the temperature change increases in amplitude with the number of mechanical cycles. This can be explained by the accumulation of mechanical dissipation over the cycles (let us recall that mechanical dissipation is a positive quantity, both during the loading and unloading phases). It is interesting to note that all the contacts are not subjected to mechanical dissipation: the intensity is much greater in the upper part of the granular system, which could be due to the presence of high friction between the particles in this zone. Concerning the lower part of the granular system, a continuous “path” of high mechanical dissipation is visible across two particles in contact, which can be attributed to higher stresses. Finally, it can be noted that the temperature rise increases with the external loading rate. This can be explained by the decreasing duration for heat exchanges with the environment when the loading frequency increases for the same number of cycles. Viscous effects could also be involved.

Next, the heat density associated to mechanical irreversibility was assessed. Over an integer number of mechanical cycles, the heat associated to thermoelastic coupling is null. Over 20 mechanical cycles for the force rate of 5 kN/s (see Fig. 3-c), the minimum, maximum and average values of the heat density due to mechanical dissipation in the interparticle contact zones are equal to 266 kJ/m^3, 1316 kJ/m^3 and 647 kJ/m^3, respectively. These values must be divided by 40 to be compared with those corresponding to the thermoelastic coupling over half a cycle (see Section III-A). This respectively gives 7 kJ/m^3, 33 kJ/m^3 and 16 kJ/m^3, thus confirming that mechanical dissipation D_{int} is much lower than the heat power density W_{the} due to thermoelastic coupling in (2). Obviously, mechanical dissipation accumulates over the cycles.

As a general remark, Figs. 2 and 3 show very different thermal signatures, meaning that our processing succeeds *a priori* in distinguishing thermoelastic coupling and mechanical dissipation. Indeed, the latter have no reason to be activated in the same zones of the granular system. Mechanical dissipation is by construction high at the contacts subjected to friction (*i.e.* with high tangential forces), whereas thermoelastic coupling is high in any stress concentration zones (in particular due to normal interparticle forces).

IV. CONCLUSION

For the analysis of thermomechanical phenomena, IR thermography is in principle applicable to any material types. However, applying this measuring technique to granular materials remains tricky and sophisticated. This is probably the main reason why only a few researchers employed this technique for studying granular media [25-27]. Recently, our previous study [17] proposed to use rubber-like materials to create analogical materials for the analysis by means of an IR camera. An advantage compared to materials with classical linear elasticity is that the thermoelastic coupling in entropic materials leads to much higher temperature signals. Moreover, their thermal diffusivity is low. As a practical consequence, only a few mechanical cycles with low loading frequency are required for the thermomechanical analysis.

The present study aimed at analyzing the thermomechanical response of a 2D monodisperse granular system made of TPU cylinders with elliptical cross-section. Cyclic confined compression tests were performed while an IR camera measured the temperature changes at the surface of the cylinders. Thermoelastic coupling and mechanical dissipation were distinguished in the thermal evolution. The former was evidenced in the interparticle contact zones as a consequence of stress concentrations. The latter was evidenced at specific contacts, which can be mainly explained by the presence of strong friction in this zone. The higher the number of applied mechanical cycles, the higher the temperature rise as a consequence of an accumulation of mechanical dissipation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

K. Jongchansitto performed the experiments, analyzed the data, and prepared the manuscript; P. Jongchansitto established the concept of this research, analyzed the data, and prepared the manuscript; I. Preechawuttipong contributed to the manuscript revision; X. Balandraud established the concept of this research, performed the experiments, analyzed the data, and revised the manuscript; M. Grédiac contributed to the manuscript revision; J.-B. Le Cam performed the experiments and revised the manuscript; F. Blanchet manufactured TPU particles used in the experiments; All authors have approved the final version of the manuscript.

ACKNOWLEDGMENT

P. Jongchansitto gratefully acknowledges Chiang Mai University for the support during this research through CMU Junior Research Fellowship Program. The authors would also like to acknowledge the National Research Council of Thailand (NRCT) through the Royal Golden Jubilee Ph.D. program (grant no. PHD/0100/2561) for theirs support during this research. The authors also gratefully acknowledge the Ministère de l'Europe et des Affaires Etrangères (MEAE) and the Ministère de l'Enseignement supérieur, de la Recherche et de l'Innovation (MESRI) in France, as well as the Office of the Higher Education Commission (OHEC) of the Ministry of Education in Thailand. The authors also gratefully thank the French Embassy in Thailand and Campus France for their support during this research (PHC SIAM 2018, Project 40710SE).

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