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Study of the intrinsic dissipation associated to the plastic work induced by a ball impact

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Abstract

This paper presents a measurement method of the thermal dissipation in metallic samples submitted to a plastic strain. Its interest is to extend the field of experimental investigation of the irreversible plastic transformations. The method is applied to the quantification of the thermal dissipation effects associated to the impact of a ball on a thin metallic sample. The final aim of the study consists in proposing a complementary method for controlling and monitoring the shot-peening process.

The temperature rise at the rear face after the impact of the ball at the front-face is measured by infrared thermography. Then, the dissipated heat is deduced from the registered thermograms, *via* a parameter estimation procedure, by a comparison with a specially developed heat diffusion model.

The first results presented here show that a preliminary shot-peening of the samples induces a reduction in the energy dissipated during the impact. Then, a specific study has been carried out in order to point out the diminution of the dissipated heat with the number of previous shots.

Keywords: Shot-peening; Mechanical impacts; Residual stresses; Dissipation measurements; Thermal modeling thermography

1. Introduction

In most materials, one can find micro-cracks and other crystalline defects, that lead to mechanical weakness. So, many applications (technical parts in aeronautics or automotive industry, machine tools, devices submitted to the risk of corroding) require a specific treatment decreasing this density of "weak points", in order to enhance their mechanical strength and improve their lifetime.

Shot-peening is a treatment which consists in bombarding the surfaces with small balls (in general of steel or ceramics). The aim of this technique is to induce a beneficial field of compressive stresses in the vicinity of the surface, so that the crystalline defects are filled. This process being, like any irreversible phenomenon, accompanied by a strong emission of heat, it seems interesting to try to connect this heat source with the level of introduced residual stresses.

We propose here to take advantage of the high sensitivity of the new-generation infrared cameras, in order to measure the temperature rise at the rear face of a steel plate, in the instants following the impact of a steel ball. Then, a thermal model based on the Green's functions is developed, where the heat source is considered as punctual and instantaneous. This model, together with a Gauss–Newton parameter estimation procedure, allows the identification of the energy dissipated during the plastic deformation.

The compressive stresses induced by the shot-peening process modify significantly the structure of the material and then its mechanical properties. Actually, a ball impact on a shot-peened surface does not produce the same heat source as it does on a non-treated sample. In the first part of this work, it is shown that the dissipative part is less important on an already shot-peened sample; then, a more academic study

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Nomenclature

a	thermal diffusivity .... $m^2 \cdot s^{-1}$	E_i	incident ball energy .... J
$A_k \dot{V}_k$	power associated to the set of internal state variables V_k .... $W \cdot m^{-3}$	T	temperature .... K
C_ε	specific heat at constant strain .... $J \cdot kg^{-1} \cdot K^{-1}$	x, x', y, y'	space coordinates, in the plane of the sample surface .... m
f	dissipative fraction of the plastic work	z, z'	space coordinate, normal to the surface of the sample .... m
k	thermal conductivity of the sample .... $W \cdot m^{-1} \cdot K^{-1}$	ε	strain tensor
e	sample thickness .... m	$\dot{\varepsilon}_p$	plastic strain rate tensor.................. s^{-1}
q	volumic heat source .... $W \cdot m^{-3}$	ρ	density .... $kg \cdot m^{-3}$
t, τ	time .... s	σ	stress tensor .... MPa
E_p	plastic work .... J	$\delta(x)$	Dirac's distribution (spatial)............. m^{-1}
E_d	dissipated energy.......................... J	$\delta(t)$	Dirac's distribution (temporal) .... s^{-1}
E_s	stored energy .... J	$\boldsymbol{\varphi}$	Conductive heat flux................. $W \cdot m^{-2}$

presents the evolution of the ratio dissipated energy/kinetic energy of the ball for successive impacts at the same point.

2. Heat diffusion equation in the presence of plastic dissipation

The volumic heat source associated to a plastic deformation is given by the Clausius–Duhem's inequality:

$$q = \sigma : \dot{\varepsilon}^p - A_k \dot{V}_k - \boldsymbol{\varphi} \cdot \frac{\mathbf{grad}\, T}{T} \geqslant 0 \tag{1}$$

The first two terms correspond to the intrinsic dissipation, that is the sum of the plastic deformation and the dissipation associated to the variation of the internal parameters. The last term is the thermal conductive dissipation. According to Lemaître and Chaboche [1], this term is not to be taken into account as a heat source. Then, the local and instantaneous heat source can be written as:

$$q = \sigma : \dot{\varepsilon}^p - A_k \cdot \dot{V}_k \tag{2}$$

and represents the part of the mechanical power which is converted into heat in an irreversible way. The heat diffusion equation in the presence of plastic dissipation is usually formulated as (Chrysochoos and Dupré [2]):

$$\rho C_\varepsilon \dot{T} - \mathrm{div}(\mathbf{k} \cdot \mathbf{grad}\, T) = \sigma : \dot{\varepsilon}^p - A_k \cdot \dot{V}_k \tag{3}$$

However, these dissipative mechanisms induce a field of temperature variations that can be interesting to observe and correlate with the level of induced residual stresses. The energy balance is:

$$E_i = E_{el} + E_p = E_{el} + E_s + E_d \tag{4}$$

where E_i is the incident energy of the ball, E_{el} the elastic work, E_p the plastic work, E_s the stored energy and E_d the dissipated energy. Saix and Jouanna [3] introduced the notions of "dissipative part" and "stored part" of the plastic work:

The plastic work is:

$$E_p = \iiint\limits_V \int\limits_t \sigma : \dot{\varepsilon}_p \, \mathrm{d}V \, \mathrm{d}t$$

The dissipative part is:

$$f = \frac{E_d}{E_p} = \frac{\iiint_V \int_t (\sigma : \dot{\varepsilon}_p - A_k \dot{V}_k) \, \mathrm{d}V \, \mathrm{d}t}{\iiint_V \int_t \sigma : \dot{\varepsilon}_p \, \mathrm{d}V \, \mathrm{d}t}$$

The stored part is thus:

$$1 - f = \frac{E_s}{E_p} = \frac{\iiint_V \int_t A_k \dot{V}_k \, \mathrm{d}V \, \mathrm{d}t}{\iiint_V \int_t \sigma : \dot{\varepsilon}_p \, \mathrm{d}V \, \mathrm{d}t}$$

The experimentally relevant parameter in the present situation should be the dissipative part; however, since we were, up to now, not able to measure the elastic part of the shock, we had only access to the ratio of the dissipated heat relatively to the kinetic energy of the incident ball. Indeed, the present device is not able to determine if a variation of the dissipated heat is induced either by a variation of the plastic work or by a variation of the stored energy: it only allows the identification of the ratio dissipated energy (E_d)/incident energy (E_i) that can be written:

$$\frac{E_d}{E_i} = \frac{\iiint_V \int_t \sigma : \dot{\varepsilon}_p \, \mathrm{d}V \, \mathrm{d}t - \iiint_V \int_t A_k \dot{V}_k \, \mathrm{d}V \, \mathrm{d}t}{E_{el} + \iiint_V \int_t \sigma : \dot{\varepsilon}_p \, \mathrm{d}V \, \mathrm{d}t} \tag{5}$$

where E_{el} is the elastic energy. However, it constitutes a first step for a more global study of the thermo-mechanical behavior associated to an impact.

3. Experimental device

The experimental device (Fig. 1) consists in a vertical guiding column in which a ball of 20 mm diameter falls and hits a smaller one (3 mm diameter), maintained by a centering ring. A hole in the massive sample support allows the measurement of the rear face temperature rise. These temperature measurements are carried out thanks to an infrared

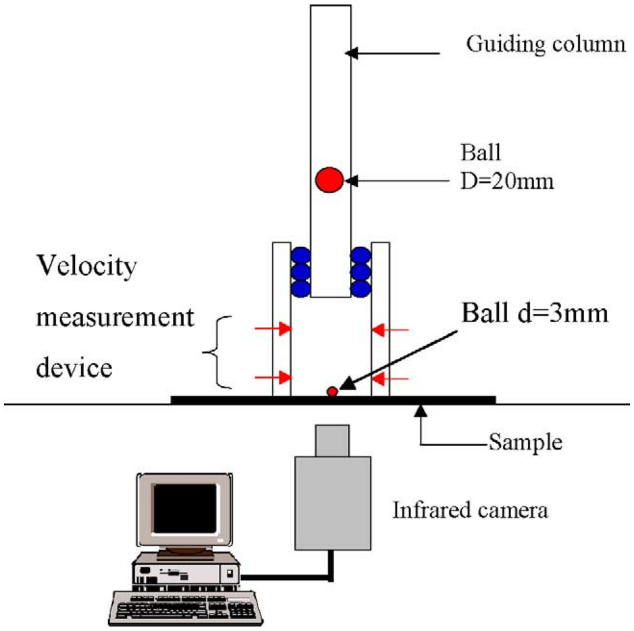

Fig. 1. Experimental device.

focal plane array camera (CEDIP IRC 320-4 LW). It records temperature maps at high speed (1 kHz) on the rear face, which is covered with black paint in order to increase and make uniform its emissivity. Two infrared sensors (distant of 60 mm) located close to the sample allow the measurement of the ball velocity in order to determine its energy.

The material used for these tests is a 316 L stainless steel, which has an elastic limit of about 200 MPa, a hardness of 160 HB and a thermal conductivity of $16.3\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$. The plates used in our study are 140 mm length, 75 mm width and their thickness is 3 mm.

4. Thermal modeling

In order to take advantage of the experimental thermal measurements, a specific heat diffusion model has been developed. The shock occurring at the sample surface, its energy could be introduced as a heat flux in the boundary condition. However, it is equivalent to consider a (volumic) point source located at $z = 0$; moreover, the measurement being realized at the rear face, these second formulation is especially justified.

This model is based on the percussional answer to the dissipation of 1 Joule in the form of an instantaneous point source represented by a space-time Dirac's distribution (Pron [4]).

At any instant, the temperature of the medium $T(x, y, z, t)$ must check:

$$\begin{cases} \Delta T - \frac{1}{a}\frac{\partial T}{\partial t} = -\frac{q(x,y,z,t)}{k} \\ \text{Homogeneous or inhomogeneous} \\ \text{boundary conditions} \end{cases} \tag{6}$$

The percussional response of the medium checks a similar system (Özisik [5]):

$$\begin{cases} \Delta G - \frac{1}{a}\frac{\partial G}{\partial t} = -\frac{\delta(\vec{r}-\vec{r}\,')\delta(t-\tau)}{k} \\ \text{Homogeneous boundary conditions} \end{cases} \tag{7}$$

Then, the expression of $T(x, y, z, t)$ is deduced from that of the Green's function G and the source field q [5]:

$$T(x,y,z,t) = \frac{a}{k}\int_0^{\tau}\int_{x'}\int_{y'}\int_{z'} G(x,y,z,t \mid x',y',z',\tau) \times q(x',y',z',\tau)\,\mathrm{d}x'\,\mathrm{d}y'\,\mathrm{d}z'\,\mathrm{d}\tau \tag{8}$$

where $q(x', y', z', \tau)$ represents the heat source distribution.

The thermal phenomenon linked to a ball impact being very quick, an adiabatic condition at $z' = 0$ can be considered. Then, in the case of a semi-infinite medium, the G function can be expressed as follows (Özisik [5]):

$$G(x,y,z,t \mid x',y',z',\tau) = \frac{1}{\sqrt{4\pi a(t-\tau)}} e^{-\frac{(x-x')^2}{4a(t-\tau)}} \frac{1}{\sqrt{4\pi a(t-\tau)}} e^{-\frac{(y-y')^2}{4a(t-\tau)}} \times \frac{1}{\sqrt{4\pi a(t-\tau)}} \left[e^{-\frac{(z-z')^2}{4a(t-\tau)}} + e^{-\frac{(z+z')^2}{4a(t-\tau)}}\right] \tag{9}$$

The energy dissipated during the impact is, according to Eq. (2):

$$E_d = \iiint_V \int_t q\,\mathrm{d}V\,\mathrm{d}t \tag{10}$$

In the present situation, the energy is deposed at the front surface, and the impact can be chosen as origin of both space and time:

$$q(x',y',z',\tau) = E_d \cdot \delta(x') \cdot \delta(y') \cdot \delta(z') \cdot \delta(\tau) \tag{11}$$

One can note that it would be equivalent to consider a heat flux $\varphi(x', y', \tau) = E_d \cdot \delta(x') \cdot \delta(y') \cdot \delta(\tau)$ at the front face of the sample, corresponding to the same energy $E_d = \iint_S \int_t \varphi\,\mathrm{d}V\,\mathrm{d}t$; in this case, however, this energy would appear in the boundary condition and the Green's function should be integrated over the surface.

Then, the following expression is obtained for the temperature:

$$T(x,y,z,t) = \frac{a}{k}\int_0^{\tau}\int_{x'}\int_{y'}\int_{z'} G(x,y,z,t \mid x',y',z',\tau) \times \bigl(E_d \cdot \delta(x') \cdot \delta(y') \cdot \delta(z') \cdot \delta(\tau)\bigr)\,\mathrm{d}x'\,\mathrm{d}y'\,\mathrm{d}z'\,\mathrm{d}\tau \tag{12}$$

And, finally:

$$T(x,y,z,t) = \frac{a}{k}\frac{2E_d}{(4\pi a t)^{3/2}} e^{-\frac{(x^2+y^2+z^2)}{4at}} \tag{13}$$

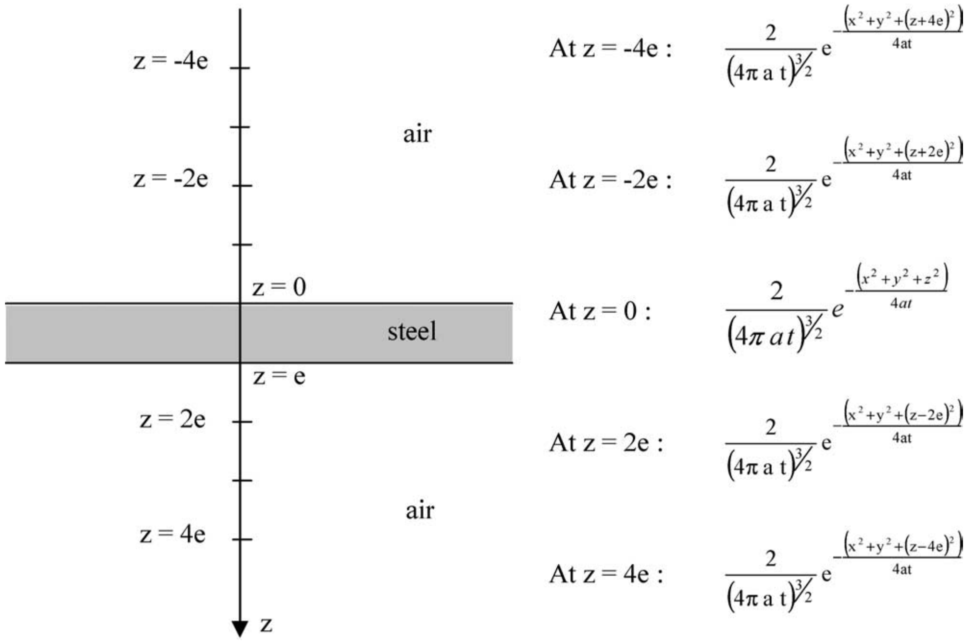

Fig. 2. Images of the thermal source relatively to the different interfaces.

However, the considered medium is necessary finite in the z direction, at least to be able to realize a measurement on the rear face. Once more, considering the time scale, the losses can be neglected. Then, the plane $z = e$ is adiabatic and the solution of the heat conduction equation is necessarily the same as the one of a semi-infinite medium with a second source, symmetrical to the first one relatively to this adiabatic plane (the "image" source). Then, the same argument has to be considered for each adiabatic plane (front face and rear face) and each source (Fig. 2), leading to a series of "image-sources" the sum of which would give the exact solution of the problem.

The general solution has to be written as the sum of the solution in semi-infinite medium and the solutions resulting from each image-source:

$$T(x, y, z, t) = \frac{a}{k}\frac{2E_d}{(4\pi at)^{3/2}}\left[e^{-\frac{(x^2+y^2+z^2)}{4at}} + \sum_{n=1}^{\infty}\left(e^{-\frac{(x^2+y^2+(z+2ne)^2)}{4at}} + e^{-\frac{(x^2+y^2+(z-2ne)^2)}{4at}}\right)\right] \tag{14}$$

However, in practical situations, only a finished number of terms is used in the sum; in the present case, $N \approx 10$ (this value being determined by the influence of one $(N + 1)$th term on the final value: if the induced variation is lower than the desired precision, then the number of terms is regarded as being sufficient).

5. Experimental results

5.1. Identification of the dissipative source

As it can be seen above, the dissipated energy is a multiplying factor of the percussional answer. The quantification of this dissipated energy results from the adjustment of the theoretical and experimental values by a Gauss–Newton algorithm (parameter estimation procedure based on the nonlinear mean-squares method); further details concerning this procedure are given by Beck and Arnold [6]. The results of the adjustment presented on Fig. 3 hereafter are relative to a steel plate of 3 mm thickness. The incidental energy of the ball (obtained by the measurement of its velocity) is 584×10^{-3} J and the thermally dissipated power is 86×10^{-3} J, that is to say 14.8% of the incident energy.

5.2. Effect of previous shot-peening on the thermal answer to an impact

In order to study the effect of shot-peening on the thermally dissipated power during the impact, we carried out the same measurement on two steel plates of 3 mm thickness, one of them having been shot-peened before. The experiment was realised with a ball of 32.6×10^{-3} kg and a ball velocity of $5.98\ \text{m}\cdot\text{s}^{-1}$, that is an energy of 584×10^{-3} J. The results of this first test are presented in Fig. 4 hereafter. One can note that the effect of shot-peening affects significantly the temperature rise. Indeed, for the non-treated plate, the dissipated energy is about 86×10^{-3} J, while it reaches only 72×10^{-3} J for an already shot-peened plate.

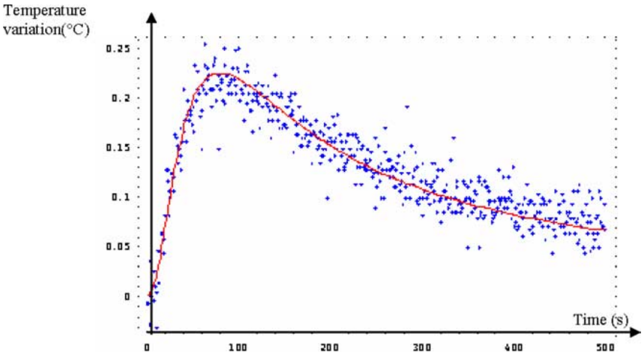

Fig. 3. Adjusted (line) and experimental (points) thermal responses.

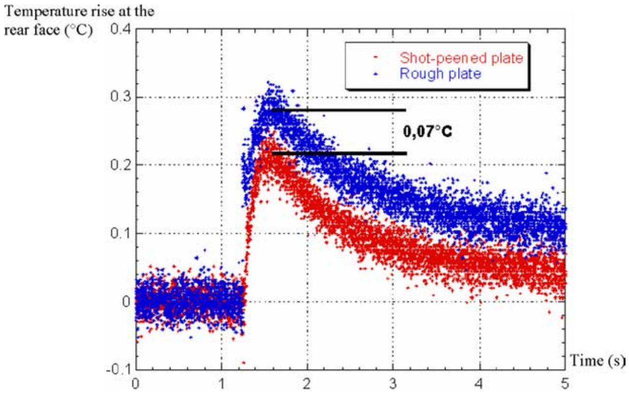

Fig. 4. Thermal responses of a shot-peened sample and of a reference sample.

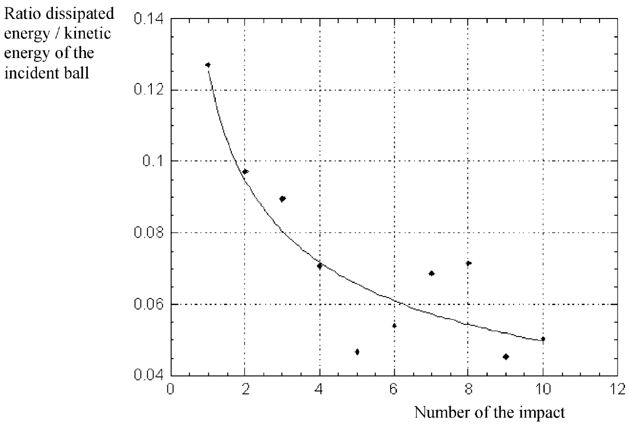

Fig. 5. Influence of the number of impacts on the thermal response.

A more academic study has then been carried out: successive impacts have been realised at the same point of the sample, and the heat source has been determined at each time. Fig. 5 presents the evolution of the dissipated part of energy as a function of the number of impacts.

For the first impacts, the dissipated heat decreases regularly, as the surface is reinforced by the shots: the material becomes harder so that the shocks become more elastic. After several impacts, this behavior is not evident any more: the ratio dissipated energy/kinetic energy of the ball seems to stabilize. This can be due to the fact that the following impacts do not induce significant residual stress any more. Moreover, this phenomenon has already been observed in the industrial applications of shot-peening: further treatments do not warrant better results and a “saturation” of the residual stress induced by shot-peening is taken into account in the “Almen bending method” (see, for example, Pron et al. [7]).

However, it is important to note that an experimental problem is also to be considered: it is technically difficult to ensure that all successive impacts will be strictly at the same point, so that the deformed area can shift slightly, and the dissipated energy values can scatter.

6. Conclusion

The heating of a sample associated to a plastic deformation at its surface was measured by infrared thermography. This technique allowing to measure the kinetics of the thermal phenomenon of dissipation, it is then possible, using an adapted thermal model and a parameter identification procedure, to quantify the heat sources produced.

Initially, the effect of a preliminary shot-peening on the rate of dissipated energy at the moment of an impact was highlighted; in a second study, more academic, successive impacts were realized at the same point of the sample, and the evolution of the heat source was studied.

It comes out from these two studies that previous shot-peening induces a reduction in the energy dissipated at the time of an impact. This decrease can be due to a reinforcement of the surface (the shocks becoming more elastic), but also to an increase of the stored energy, this second hypothesis seeming less plausible to us. Then, only the knowledge of either the plastic or the elastic energy could allowa univocal conclusion; however, only the elastic energy seems to be easily accessible experimentally, by the measurement of the ball energy after the shock. However, these first observations lead us to consider that thermal measurements could become a complementary technique to quantify the level of introduced residual stresses.

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