THERMO-ELASTO-PLASTIC MODEL FOR SHOT PEENING : A NUMERICAL AND EXPERIMENTAL APPROACH

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Abstract:
It is well known that the temperature of a shot peened part notably increases during the treatment. These thermal effects are seldom considered in experimental or numerical work related to shot peening. It is of interest to evaluate precisely the quantity of kinetic energy of the shot that is transformed into heat during the impact. This could be of interest to develop non-destructive methods to evaluate the shot peening process and to improve the existing numerical models for shot peening.
The purpose of this paper is to present a model of a single shot impacting a part and to analyze the thermal effects due to the shot. A dedicated experimental device has been developed in order to realize thermal measurements during and after the impact: a high-frequency infrared camera records thermal maps of the rear face of the steel plate submitted to the impact; then, an adapted thermal model, together with a Gauss-Newton parameter identification procedure allows the identification of the heat source. The experiment is modeled using finite element analysis including a thermo-elasto plastic model. This allows to quantify the thermal history of various parts of the specimen and to evaluate the coupling between the mechanical behavior and the temperature field.

Introduction

Shot peening is widely used to increase the resistance of mechanical parts in industry. While thermal effects exist in the material (the temperature of the part clearly increases during the treatment), existing models do not consider this aspect of the process [1]. A model for shot peening has been proposed which allows a detailed analysis of the mechanical fields [2]. Experiments have been carried out to quantify the temperature rise of the surface during the impact of a sphere on a plate [3, 4]. In the present paper, a finite element model is presented using the methodology proposed for the shot peening process. The thermal and mechanical variables are studied with two objectives:

- Obtain a better understanding of residual stress generation during shot peening, and evaluate the coupling between the mechanical behavior and the temperature field.
- Obtain a thermal history of the entire system during the impact to further develop a control method of the shot peening process based on temperature measurements.

Experiments [4]

Experiments have been carried out to measure the heat generated by the impact of a shot on a plate; the heat is measured by an IR camera on the opposite face of the plate as presented Figure 1. The plate is 2 mm thick and constituted of 304L steel. The material has been chosen to guarantee good thermal behavior with respect to the measurements, while being relatively close to materials being shot-peened in industry. A large shot is thrown on a small shot (diameter 3 and 6 mm) from a given height to increase the energy of the impact; it is assumed that all the kinetic energy of the large shot is transferred to the small shot. The small shot is plastically deformed by the impact but we don't consider it here. The considered energies are 0.3, 0.48 and 0.63 J. The profiles of the impacts are also measured after the impact.

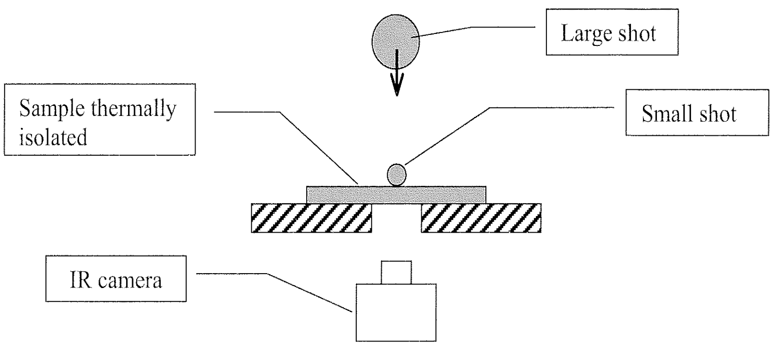

Figure 1: experimental set up

Finite Element Model

In the model, a semi-infinite massif is chosen which corresponds to a first approach of the problem; this frees the mechanical problem from considerations on boundary conditions (mechanical or thermal boundary conditions). The system has been modeled with an axi-symmetrical scheme and a 2D mesh is used. Mesh and elements have been optimized to guarantee computational efficiency. The contact between the shot and the part is assumed to be without any friction. The analysis is static and a criterion based on the total strain energy in the solids has been used following the method described and validated in [2]. The models have been solved using the finite element package Zebulon. The constitutive law used for the massif is a thermo-elasto-plastic law with linear isotropic hardening, the shot is considered rigid. The parameters used are given in the table below.

Steel	304L
Density (kg.m^{-3})	7900
Young modulus (MPa)	200 000
Poisson's Ratio	0,28
Yield stress (MPa)	280
Hardening slope (MPa)	2290
Conductivity coefficient (W.m^{-1}.K^{-1})	16
Thermal dilatation coefficient K^{-1}	16,3 10^{-6}
Calorific capacity (J.kg^{-1}. K^{-1})	500

The considered diameters for the shot are 3 and 6 mm, the considered equivalent kinetic energies for the impacting shot are 0.3, 0.48 and 0.63 J. The computation corresponds thus to the impact of one shot onto the semi-infinite massif. The shot is driven into the massif until the total strain energy reaches the kinetic energy of the impacting shot; this corresponds to "maximal penetration". In this work, we have assumed that 90% of the plastic strain work is converted in thermal energy. This assumption is in good agreement with the literature [5,6]. At this instant, it is interesting to look at the temperature field. It is supposed that the initial temperature of the system is 20°C and it is the increase in temperature that is studied. Then the shot is driven out of the massif; then, the residual fields are also studied.

Results and analysis

Figure 2 shows a typical field of temperature increase obtained at the instant of maximal penetration of the shot. It is clearly shown here that the size of the area affected by the temperature increase is rather large, of the same order in size than the size of the shot. The maximal increase in temperature is located below the surface of the shot.

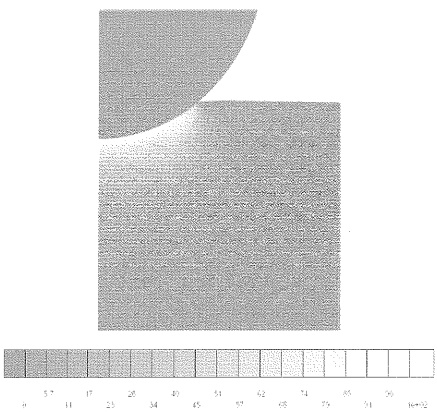

Figure 2: Field of the increase in temperature due to the impact of a shot of 3 mm in diameter on a steel massif. This field corresponds to the instant of maximal penetration of the shot. A quarter of the shot is shown on the figure for geometrical scaling, the temperature scale goes from 0 to 100 °C. The energy of the incident shot is 0.63 J.

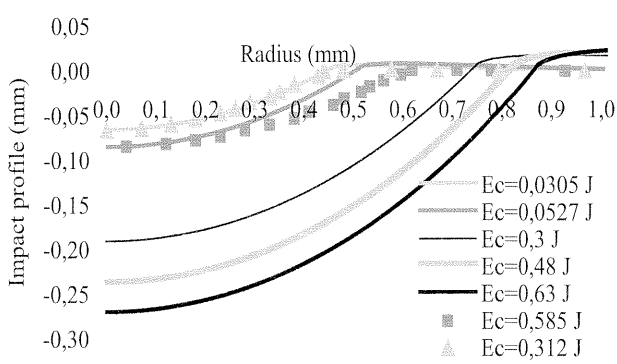

Figure 3: Impact profiles left on the surface after the impact. The diameter of the shot is 3 mm; the respective energies of the impacting shots are given in the caption. The lines correspond to numerical results while the marks correspond to experimental results.

Figure 3 presents the profile left after the impact for various kinetic energy cases; the figure also presents the experimental values obtained. The computed profiles are larger than the ones experimentally observed. Indeed, a kinetic energy ten times smaller than the kinetic energy of the impacting shot is needed for the experimental and numerical profiles to be similar. This observation is analyzed below.

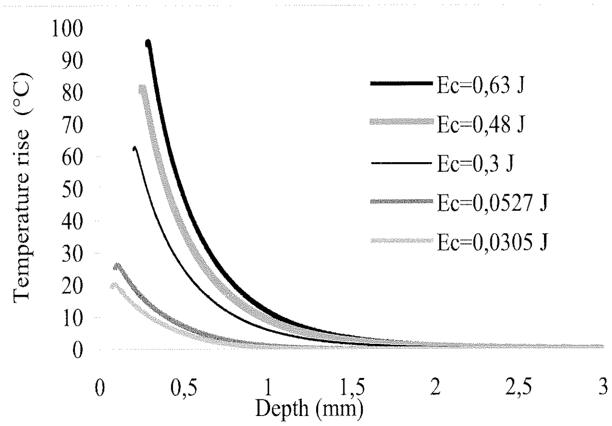

Figure 4: Increase in temperature as a function of the depth on the axis of symmetry of the system at the moment when the shot is at its maximal level of penetration. The radius of the shot is 3 mm. The respective energies of the impacting shots are given in the caption.

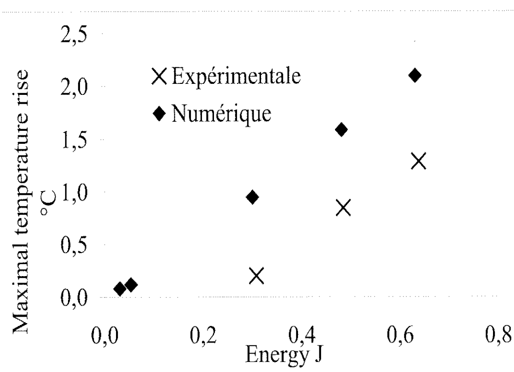

Figure 5: Maximal increase in temperature at a point of depth 2 mm as a function of the energy of the incident shot, comparison between experimental and numerical results for a shot of diameter 3 mm.

Figure 4 presents the temperature increase as a function of the depth into the massif for several kinetic energies of the incident shot. The highest temperature increase is 101 °C. The temperature increase measured experimentally on the rear surface of the plates and the temperature computed at the point that corresponds to a depth of 2 mm in the massif are presented in Figure 5 as a function of the energy; the numerical results overestimate the measured temperature. The approximation that all the energy of the incident shot is transferred into the massif is probably wrong. Shot peening computation have shown that a large part of the kinetic energy of the shot could be transformed into energy of deformation in the shot itself [7]. In the case studied, a large part of the energy of the incident shot is probably used for the deformation of the incident shot itself as well as the intermediary shot. This is why we present numerical results for which the penetration of the shot is similar to the experimental results. In this case the incident energy is ten times smaller than the one used in the experiments, the temperature is then smaller than the one observed experimentally (Figure 5).

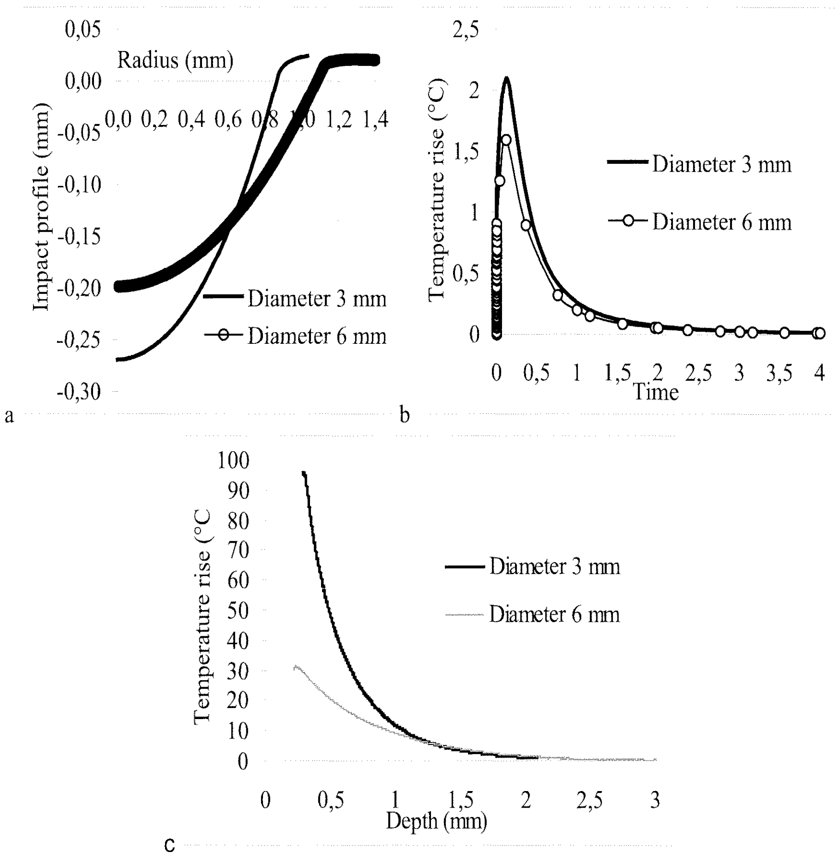

Figure 6: Comparison of various profiles for two shot diameters and the same energy for the impacting shot (0,63 J). a) Comparison of the impact profiles left on the surface. b) Increase in temperature as a function of time. The temperature is taken at a point located on the axis of symmetry of the system and at a depth of 2 mm; it is given as a function of time. The contact between the shot and the semi-infinite body starts at 1 µs, the maximal shot penetration is obtained at 1.8 µs then the shot is withdrawn and the computation stops at 4 s. c) Temperature increase as a function of the depth.

Figure 6a presents the profiles obtained after an impact of a shot of 3 mm and 6 mm and for the same impacting shot energy. Because these kinetic energies are the same, the smaller shot penetrates more into the massif and leaves a deeper impact. Figure 6b presents the evolution of the temperature increase as a function of time for a point located at 2 mm below the surface, which corresponds to the thickness of the plates used in the experiments. During the loading phase, the temperature increase is zero as long as the area is not plastically deformed. When the unloading begins, the temperature continues to increase to a maximum (2.1°C for the larger shot and 1.6°C for the smaller shot); this is due to diffusion effects from areas that have reached a higher temperature. Figure 6c shows the temperature as a function of the depth. The increase in temperature is much higher for the smaller shot; this is because the maximal penetration depth is more important for a small shot, the incident energies being the same for both diameters, thus the plastic deformation is higher for the case of the small shot. As observed in the experiments, the temperature rise increase with the increase of kinetic energy and the depth of the profile decrease for large diameter of shot.

Conclusion

A thermomechanical model of shot impacts on a metallic body has been proposed and compared to experimental studies. Several kinetic energies have been investigated for the shot impacts.. The model overestimates the depth of the profiles and the temperature rise. This can be explained by the fact that a significant part of the incident kinetic energy is used to deform the shots themselves due to the system with two shots in the experiments. Also, the temperature of the shots probably increases as well due to plasticity and conduction effects, which is not included in the model. These results show that numerical results for the distribution of the temperature in the semi-infinite body can helpfully complete the experimental measured temperature on the surface of the plate.

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