Wave Motion 58 (2015) 77–100

Contents lists available at ScienceDirect

Wave Motion

journal homepage: www.elsevier.com/locate/wavemoti

Modeling of ultra-high-speed impact at the surface of an elastic half-space

Mandikizinoyou Taro, Thibaut Chaise, Daniel Nelias *

Université de Lyon, INSA-Lyon, LaMCoS UMR CNRS 5259, F69621 Villeurbanne, France

HIGHLIGHTS

- In some surface treatments the material may encounter ultra-high-speed impacts.
- Such as laser peening, cavitation peening or high frequency electromagnetic pulses.
- Impact of a few nanoseconds is intended to introduce compressive residual stress.
- Inertial effects have been introduced in the formalism of semi-analytical methods.
- The effect of material properties, temporal pulse profile and spot size is discussed.

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form 12 June 2015
Accepted 30 June 2015
Available online 8 July 2015

Keywords:
Elastic impact
Half-space
Semi-Analytical Methods (SAM)

ABSTRACT

A Semi-Analytical (SA) method is used to model impact loading at the free surface of an elastic half-space. The inertial effects are taken into account in the form of Green's functions, also called influence coefficients. The influence coefficients are first computed and the simulation of an elastic shock with time-dependent surface pressure is performed. The effect of material properties, characteristic wave speed, the spatial distribution of the load, the impact size and the temporal form of the load is analyzed. It is observed that the dynamic response of a material which is submitted to dynamic loading depends strongly on the characteristic wave speed. The influence of the pressure pulse duration and peak magnitude is found to be also very significant, whereas the effect of the spot size and spatial distribution of the pressure is less significant.

1. Introduction

Several industrial processes such as shot peening, laser peening and water jet peening are used to improve the surface fatigue resistance of mechanical parts by introducing compressive residual stresses. The simulation of these processes is useful to understand and identify the main parameters governing the process, avoiding costly experimental investigations. Shot peening can be modeled by neglecting inertial and dynamic effects [1] since the impact velocity is much lower than the sound wave velocity in metals [2]. However, this assumption does not hold anymore for laser peening and water cavitation processes for which the strain rate can reach up to 10^6 s^{-1} [3]. In such processes, the inertial effects become significant and should be accounted for in the simulation.

In rigid dynamics it is assumed that, when a force is applied to any point at the body surface, the resultant stresses set every other point in motion instantaneously, and the force can be considered as producing a linear acceleration of the whole body, together with an angular acceleration around its center of gravity. In the theory of elasticity, on the other

* Corresponding author.
E-mail address: daniel.nelias@insa-lyon.fr (D. Nelias).

http://dx.doi.org/10.1016/j.wavemoti.2015.06.006
0165-2125/

Nomenclature

C_1	Compressional wave velocity (m s^{-1})
C_2	Shear wave velocity (m s^{-1})
C_3	Rayleigh wave velocity (m s^{-1})
E	Young's modulus (GPa)
ν	Poisson's ratio
ρ	Mass density (kg m^{-3})
V_c	Characteristic wave speed (m s^{-1})
E_{el}	Elastic strain energy (J m^{-3})
λ and μ	Lamé constants
$\underline{\sigma}$	Cauchy stress tensor (MPa)
$\underline{\varepsilon}$	Elastic strain tensor
τ	Rectangular pulse duration (ns)
$a^{\star}$	spot radius (μm)
σ_{Ph}	Hydrostatic pressure or stress (MPa)
σ_{VM}	von Mises stress (MPa)
$\Sigma(t)$	potential plastic zone at time t

hand, the body is considered as in equilibrium under the action of applied force, and the elastic deformations are assumed to have reached their static values. These treatments are sufficiently accurate for problems in which the time between the application of a force and the setting up of effective equilibrium is short compared with the observation time. When, however, we are considering the effect of a force which is applied during a very short time-length, or if changing very rapidly, the propagation of stress waves in solids should be considered [4,5].

Some analytical solutions, numerical simulations and experimental studies of such dynamic processes can be found in the literature. The first analytical study on wave generation and its propagation in solids is due to Lamb [6]. He derived the first analytical solutions of wave motion in an isotropic elastic half-space submitted to a vertical pulse from the periodic solution applied on its free surface. He gave an exact and closed form expression of the normal component of displacement when the pressure pulse varies like the Heaviside unit function. Since then, several authors have been interested in wave motion and its propagation in various kinds of structure submitted to any source of excitation. For example Eason [7] derived analytically the exact solution of wave propagation in an elastic half-space submitted to a uniformly distributed pressure on a disc when suddenly applied on its surface at time $t = 0$ and maintained at this pressure thereafter. From this solution, he also deduced the solution for a normal point load when suddenly applied on the free surface at time $t = 0$ and maintained thereafter. As for internal excitation source or buried source, one can cite the works of Pekeris [8] and Chao [9]. Pekeris [8] derived a formal solution for the problem of the motion produced by a seismic source buried below the surface in an homogeneous and isotropic elastic half-space, when the pulse is varying with time as the Heaviside unit function. In his analysis he assumed a surface source, e.g. the depth of the source tends to zero. Chao [9] derived the exact and closed form solutions for the tangential and normal displacements at the surface of a homogeneous isotropic elastic half-space due to a tangential point load within the body and varying in time as the Heaviside step function. Again the source thickness (in depth) was assumed to be nil. Georgiadis et al. [10] proposed a numerical evaluation of the classical integral transform solution of the transient elastodynamic point-load for Lamb's problem. They showed that the results obtained agree quite well with those presented in the literature, thus they extended their analysis to sub-surface displacements. They also investigated the effects of a triangular space distribution. Other authors focused their attention on the response of non homogeneous material submitted to dynamic point load. For example Khojasteh et al. [11] identified Green's functions to solve the elastodynamic problems in a transversely isotropic bi-material. Later, they extended these functions to multilayered transversely isotropic half-space [12].

All these studies made by the authors cited above and others have shown three kinds of waves propagating in the material (elastic half-space). When the elastic half-space is submitted to a dynamic loading, the first waves propagating are called dilatational waves or longitudinal waves. These waves are followed by the distortional waves or shear waves. The last ones are called Rayleigh waves which will propagate along the surface and the disturbances associated with them decay exponentially with depth [4]. In the case of infinite space, only dilatational and distortional waves will be observed [13–15]. Lamb [16] obtained the complete solutions for the two types of plane waves propagating in infinite plate which he had called symmetrical and anti-symmetrical waves. These are longitudinal and flexural in character, respectively, and unlike the other waves considered above, these waves are dispersive i.e. their velocity of propagation depends on their wavelength or rather on the thickness of the plate. In cylindrical bars of infinite length, Pochhammer [17] and Chree [18] were the first to propose the solutions of wave motion and have shown that three waves can propagate along such bars. The three waves are named extensional waves, torsional waves and flexural waves. The theory shows that, in general, all these types of waves are dispersive, and in addition that waves of any wavelength may propagate in a number of different 'modes' along the cylinder [14]. If the elastic wave propagation in elastic space is interesting in engineering applications, many questions remained unanswered for materials which are deformed plastically when dynamic loads are applied. Donnell [19] was the first to