On the modelling of impulsive pressures and residual stresses induced by cavitation peening

Emmanuel SONDE [a,c], Thibaut CHAISE [a], Daniel NELIAS [a], Cyril MAUGER [b], Nicolas BOISSON [a]
[a] Univ Lyon, INSA-CNRS UMR5259, LaMCoS, F-69621 Lyon, FRANCE, abayomi-emmanuel.sonde@insa-lyon.fr ;
[b] Univ Lyon, INSA-CNRS UMR5509, LMFA, F-69621 Lyon, FRANCE; [c] AREVA NP, F-69456 Lyon, FRANCE

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Introduction

Residual stresses are those remaining in mechanical parts free of any external loading. They generally come from thermal effects, mechanical loading and/or metallurgical phase transformation during the manufacturing steps. When these stresses are of tensile type, they can have negative consequences on the lifetime of the component by helping cracks initiation and propagation phenomena like Stress Corrosion Cracking (SCC). In order to improve the fatigue life and avoid the premature failure of metallic components, surface treatment processes are carried out to introduce residual stresses of compression in materials and to raise the critical value of operating tensile stress. Conventional Shot Peening (SP), Ultrasonic Shot Peening (USP) and Laser Shock Peening (LSP) are some of these surface treatment methods which have been widely studied both experimentally and numerically.

Water Cavitation Peening (WCP) is a similar process of surface treatment [1]. During WCP, cavitation bubbles are created by a high-speed submerged water jet directed toward the workpiece surface. The cavitation phenomenon occurs in low static pressure (lower than vapour pressure of water) zones due to the turbulence generated, at a given temperature. The collapse and/or the impact of these bubbles on the treated surface induce high loading pressures and thereby plastic deformation of the superficial layers of the material. Superficial compressive residual stresses are then introduced in the material. This process is known to provide a better surface finish with less roughness than that of the conventional shot peening because there is no solid – solid contact involved [2].

Many experimental studies have proven the efficiency of the present process to introduce compressive residual stresses into relatively high yield strength materials and enhance their fatigue strength [3]. However, the modelling of cavitation peening is very challenging, because of the complex behaviour of cavitation phenomenon. Very few studies concerning the modelling and simulation of WCP have been reported. A mechanical model based on finite element method have been proposed by Han and Hu [4] to predict the residual stress profile obtained after WCP. The authors measured experimentally the affected surface diameter. Then, they supposed a constant spatial distribution and trapezoidal temporal variation, for the loading pressure. As the above-mentioned study, most of the numerical studies about the modelling of cavitation peening employed theoretical values for pressure magnitude and pressure pulse duration with no direct link to the process parameters. The main reason and issue is the difficulty to determine the impulsive pressure distribution of cavitation peening.

Objectives

The global objective of this study is to propose an approach of modelling for cavitation peening. For that, three items must be considered: the localisation of cavitation zone, the impulsive pressure distribution on the surface and the residual stress calculation. The most important and complicated step is the determination of the pressure spatial and temporal distribution from process parameters. This paper will focus on the study and comparison of the different types of loading pressures. The influence of some parameters on the pressure magnitude and duration will also be studied. The ultimate goal is the prediction of residual stresses due to these pressures.

Methodology

As for shot peening, whose modelling is based on the contact between the shot and the workpiece surface, the study of cavitation peening requires the analysis of cavitation bubble dynamics. Two mechanisms could potentially be at the origins of mechanical loading of the workpiece surface during WCP. The first one is the pressure pulse emitted in the liquid during the spherical collapse of cavitation bubbles. When reaching the surface, this pressure pulse can be sufficiently high to induce plastic deformation in the superficial layers of the material. The second one is the micro-jet impacts resulting from the aspherical collapse of cavitation bubbles near a solid surface. This type of impact produce a water hammer pressure on the surface which magnitude depends on the micro-jet velocity.

The pressure wave emitted during the collapse of a spherical cavitation bubble is first considered. When a cavitation bubble is subjected to an external pressure higher than its internal pressure, the bubble radius decreases rapidly. It is the collapse phase during which the bubble keeps its spherical shape, when it is far from a solid surface. This phase is characterised by an increase of the pressure at bubble – liquid interface and the emission of a pressure wave at bubble rebound. To study this case, an analytical cavitation model was built on the basis of Keller-Miksis equation which takes into account the compressibility of the liquid. If one considers a cavitation bubble submitted to an external far pressure P_∞, the evolution of the bubble radius R(t) as a function of time is given by the following system of differential equations:

$$\left(1-\frac{\dot{R}}{C}\right)R\ddot{R}+\left(\frac{3}{2}-\frac{\dot{R}}{2C}\right)\dot{R}^2=\frac{1}{\rho}\left(1+\frac{\dot{R}}{C}\right)P_s+\frac{R}{\rho C}\dot{P}_s$$

$$P_s=P_{go}\left(\frac{R_o}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-\frac{4\mu}{R}\dot{R}-P_\infty \tag{1}$$

In these equations, C represents the speed of sound in the liquid, σ the surface tension, ρ and μ respectively the liquid density and viscosity. The bubble is supposed to contain, at initial time, a non-condensable gas (air for example) of heat capacity ratio γ. The initial partial pressure of the gas P_{go} is assumed. Equations (1) were resolved by the classical Runge – Kutta method RK4 (fourth-order) with the following initial conditions: $R(0) = R_o$ and $\dot{R}(0) = 0$. To calculate the impulsive pressure due to the bubble collapse, the first order acoustic approximation is made [5]. It means that the pressure wave travels through the liquid at the local speed of sound. The following relationship (2) between the pressure $P(r, t)$ and the velocity potential ϕ is considered. To fully resolve the problem, the equation of state employed for the water is Tait equation. The impulsive pressure is then determined in terms of temporal and spatial distributions.

$$\frac{\partial\phi}{\partial t}+\frac{1}{2}\left(\frac{\partial\phi}{\partial r}\right)^2+\int_{P_\infty}^{P}\frac{1}{\rho}dP=0$$

$$\phi=-\frac{1}{r}\left[R^2\dot{R}-\frac{1}{C}\left(R^3\ddot{R}+2R^2\dot{R}^2\right)\right] \tag{2}$$

Computational fluid mechanics calculations are also performed to simulate the micro-jet impact. This comes from the aspherical collapse, near the solid surface, of a cavitation bubble submitted to an external pressure P_∞. It is commonly acknowledged that cavitation bubbles don't remain spherical when they start to collapse at a distance lower than three times their radius. The bubbles are assumed to contain an amount of non-condensable gas with an initial partial pressure P_{go}. Then, the problem is a gas-liquid biphasic problem with deformable interface. It was modelled by one-fluid approach. That means the two phasis are treated as one liquid with fluctuating physical properties (density, viscosity, etc.), as a function of the volume fraction of each specie. In the numerical model built using ANSYS Fluent, the flow domain is assumed to be 2D axisymmetric without swirl. The liquid phase is assumed to be incompressible while the gas is compressible following the ideal gas law. The two phasis are immiscible and mass transfer phenomena (condensation and evaporation) are neglected. As the bubbles involved are expected to have small diameters, surface tension is taken into account. The numerical model is based on the resolution of well-known Navier-Stokes equations and Volume of Fluid (VOF) method is used to track the gas-liquid interface. After the simulation, the velocity of the micro-jet is obtained at each time step and the peak of velocity V_{jet} is taken to calculate the impact pressure. Actually, the velocity of the jet, at the impact on the surface, is slightly lower than the maximum velocity. The impact pressure magnitude is given by water hammer pressure formula: $P = \rho C V_{jet}$. The impact duration is such as $\Delta t = 2r_{jet}/C$, with r_{jet} the micro-jet radius.

The two types of pressure loading are compared and are finally used as loading conditions for a solid mechanics calculation, in order to get the residual stresses distribution.

Results and analysis

For the purposes of validation of the proposed analytical model for bubble evolution and pressure pulse calculation, a comparison have been made with Direct Numerical Simulation (DNS) by resolution of Navier-Stokes equations. The dynamics of a cavitation bubble of maximal radius $R_o = 10$ μm, which is submitted to an external pressure of 10.13 MPa (100 atm), have been studied. Figure 1 shows that the temporal evolution of the bubble radius obtained with present model is in good agreement with the DNS results taking from literature [6]. Similarly, the pressure at bubble wall calculated with the proposed model fits well with simulation (Figure 2). The full analysis of bubble dynamics shows that the highest pressure pulse is emitted at bubble first rebound. The magnitude of this pressure is maximum at the bubble interface when its radius is minimal. The pressure pulse is characterized by its maximum value P_{max} and its duration at half-height δt. Some parametric studies have been carried out and have shown that P_{max} increases with the external liquid pressure P_∞ while δt decreases. This denotes the importance of surrounding water pressure in the effectiveness of WCP process. Indeed, with low P_∞, the impulsive pressure magnitude was not high enough. But when P_∞ was too high, the duration of the pressure wave was too small to induce significant changes. So, there is an optimum value of external pressure for WCP. This conclusion is in accordance with several experimental observations. The maximal radius had little influence on the pressure magnitude. However, large bubbles induced longer pressure pulses.

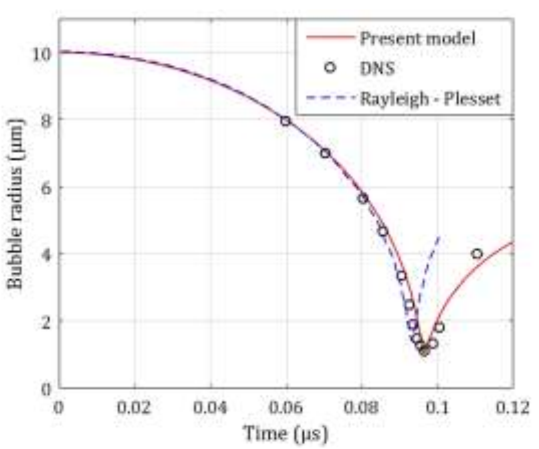

Figure 1: Bubble radius as a function of time. Comparison with results from DNS and Rayleigh – Plesset model.

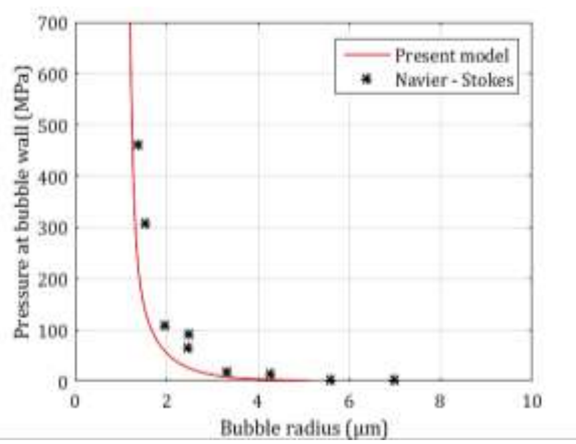

Figure 2: Pressure at gas – liquid interface as a function of bubble radius during the collapse. Comparison with results from DNS.

To compare the two sources of mechanical loading involved in WCP, the dynamics of a cavitation bubble is studied in two situations. In the first case, the bubble is supposed to be isolated and evolve spherically. It is assumed that, in the best-case scenario, the bubble rebounds and the pressure wave is emitted at a distance from the surface equals to $3R_{min}$, the bubble minimum radius at the end of the collapse (Figure 3). This hypothesis is made because the bubbles in cavitation jet are dragged towards the solid surface, at a relatively high speed proportional to the inlet jet pressure (higher than 30 MPa). For the second situation, the bubble is initially spherical and placed at a distance equals to $1.1R_o$ from the solid boundary (Figure 4). In both cases, the bubble is assumed to contain non-condensable gas (air) of partial pressure $P_{go} = 1035$ Pa. They have an initial and maximal radius $R_o = 2$ mm and are subjected to an external far pressure of 0.42 MPa. This value of pressure was chosen because it is the ambient pressure for the WCP process in Odhiambo and Soyama experimental study [3]. The non-dimensional radial and temporal distributions of the loading pressure obtained for the first case are represented in figures 5 and 6. The pressure maximum value calculated in this case was equal to $P_{max} = 1295$ MPa. For the second case, the simulations gave a micro-jet velocity of 270.7 m/s. This corresponds to a water hammer pressure of 406 MPa. The comparison of the two kinds of loading has shown that the pressure pulse magnitude from spherical bubble collapse is higher than the impact pressure of the micro-jet.

The calculated pressure pulse represented in figures 5 and 6 have been used as loading conditions for a mechanic computation. The structural analysis is a finite element based computation performed with the commercial code ABAQUS/Explicit. An axisymmetric configuration has been adopted for the mechanical model. The workpiece material considered is nickel-based alloy 690 which has a static yield strength $\sigma_Y = 305$ MPa and a strain hardening rate of 2065 MPa [7]. The strain-rate effects have been neglected and the isotropic work-hardening is assumed. At the end of the explicit calculation, a final static equilibrium calculation is performed with ABAQUS/Standard, in order to get the residual stresses. Figures 7 and 8 show respectively the equivalent plastic strain and the mean stress profiles in the workpiece as a function of the depth. It can be seen that compressive residual stresses are effectively introduced in the material thanks to the pressure pulse emitted by a cavitation bubble. A maximum compressive residual mean stress as high as 50% of the material yield strength is observed. However, the compressive depth is lower than those observed experimentally. Then, the full model of WCP must take into account many others bubbles according to the cavitation zone of the jet.

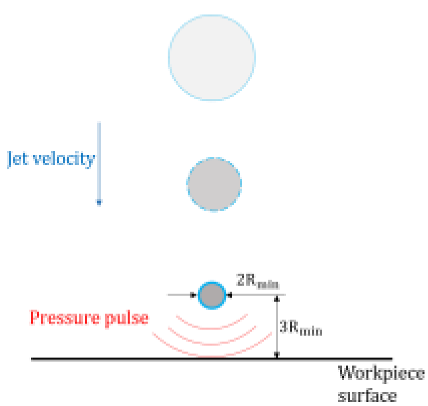

Figure 3: Spherical bubble collapse far from the solid surface and pressure pulse emission (Case1).

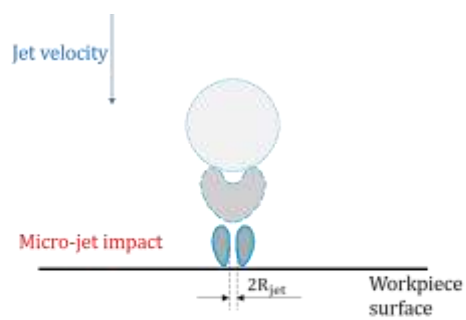

Figure 4: Bubble collapsing near the solid boundary: micro-jet formation and impact (Case 2).

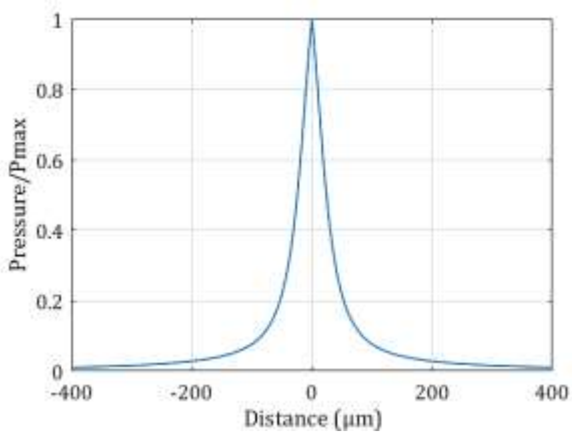

Figure 5: Radial distribution of the loading pressure. The pressure is normalized by its maximum value P_{max}.

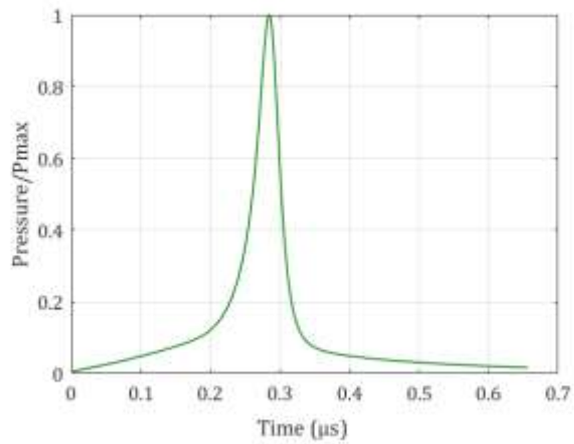

Figure 6: Temporal distribution of the loading pressure. The pressure is normalized by its maximum value.

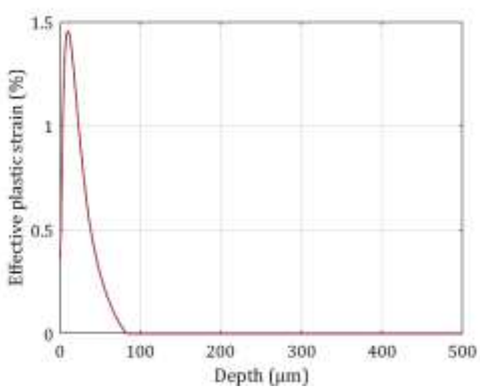

Figure 7: Effective plastic strain profile on the axis of symmetry

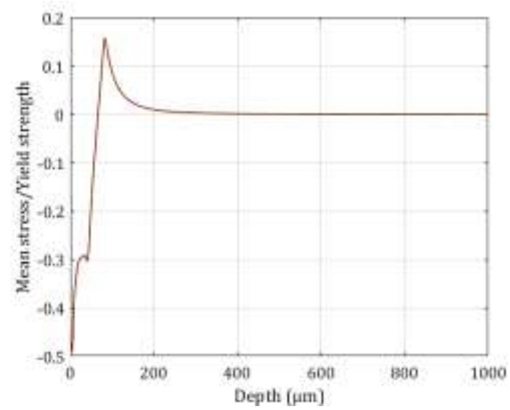

Figure 8: Residual mean stress profile normalised by the material yield strength

Conclusions

An analytical cavitation bubble model have been presented. This model permits to study spherical bubble and to determine quickly and accurately the pressure pulse emitted. The numerical modelling and simulation of the aspherical collapse of a bubble near a solid boundary, conducting to a micro-jet, have also been carried out. The loading pressure coming from these two cases, which are involved in WCP, have been determined and compared. It was shown that the pressure pulse due to spherical collapse is more efficient than the micro-jet impact pressure in WCP process. Finally, the mechanical calculations have shown that the compressive residual stresses induced by one cavitation bubble are in the range of experimental results in terms of magnitude. However, to predict the compressive depth and have a full WCP model, the present model must be generalised by associating many bubbles. The computation of cavitation zone in the jet should be very helpful to determine these bubbles repartition. This is the principal perspective of this work.

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