



Multiple necking during the dynamic expansion of hemispherical metallic shells, from experiments to modelling

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ABSTRACT

Expansions of hemispheres driven by explosive charge have been conducted for two materials: copper and tantalum. Owing to high speed camera, the time occurrence, the angular position and the number of necks have been identified at the onset of necking. Tantalum and copper have been characterized from quasi-static to dynamic conditions at different temperatures and their behavior has been modelled using three different thermoviscoplastic flow laws (powerlaw, Zerilli–Armstrong, Preston–Tonks–Wallace). From numerical simulations of the expansion process, it has been shown that the onset of necking is located in an axisymmetric layer where plane strain conditions prevail. Since the layer has a small extension in latitude and the shell is thin, the stability problem can be assimilated to that of a plate stretched under dynamic plane strain conditions. A stability analysis is developed based on the concept of an effective rate sensitivity parameter which merges the thermal and the visco-plastic material characteristics. From the evolution of this parameter during loading, a new criterion for the onset of instability is postulated. This criterion, which is different to the usual one based on the evolution of the growth rate of small perturbations, is used to characterize multiple necking observed during the dynamic expansion of copper and tantalum hemispheres. A good agreement with experiments is obtained concerning the number of necks and the time of occurrence of instabilities.

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1. Introduction

The fragmentation of structures has received a large attention during the last decades. The explosive behavior of bombs, warheads or casing was one of the point of interest in the 40–60 s. Nowadays, this field of research is still important, a large effort being made to understand the behavior of structures subjected to an intense blast. To ensure integrity of structures, the conditions for the onset of fragmentation as well as for delaying the occurrence of such phenomenon are analysed.

Well documented experimental works conducted to investigate the fragmentation of structures under intense loading can be traced back to the beginning of the nineteenth century. From an historical perspective, it is worth mentioning that, according to the historical review on high-strain rate experiments by [Rinehart \(1981\)](#): *the first carefully designed, controlled and documented studies involving explosively fragmented projectiles were those carried out at Metz by the French military establishment in the late 1830s*. More recent work can be found in [Niordson \(1965\)](#), where copper and aluminium thin rings are expanded at high strain rates by an intense electromagnetic field. Multiple necking is shown to develop and leads to the failure of expanded rings in multiple fragments. Electromagnetic devices were also adopted by [Wesenberg and Sagartz](#)

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(1977), Grady and Benson (1983) and Altynova et al. (1996) to capture the enhanced ductility of materials at high strain rate loading as well as to illustrate the fragmentation process on aluminium and copper thin rings. Recently, Zhang and Ravi-Chandar (2006) revisited the mechanics of dynamic necking and fragmentation of rings expanded by an electromagnetic field. Using high speed camera, the onset of instabilities could be precisely captured. It was shown that the sites of necking were spaced along the circumference following a Rayleigh distribution, see Zhang and Ravi-Chandar (2008). As the expansion is pursued, some necks do not further develop because of unloading waves. As a consequence, the number of fragments is lower than the number of necks. The expansion can be driven by other means than electromagnetic fields. Fyfe and Rajendran (1980) developed a specific device where an intense pressure pulse was generated by an exploding wire. This pressure loading, after propagation in a polyethylene cylinder, induced dynamic straining of rings and thin cylinders. During the ring expansion, the material is facing a state of uniaxial-stress. This stress-state prevails also in a jet formed by the collapse of a shaped liner under explosive loading. Fragmentation of the jet is sometimes observed, limiting the perforating capability, see for example Karpp and Simon (1976), Chou et al. (1977), and Petit et al. (2005). Note that other geometrical configurations have been tested in dynamic conditions. The fragmentation of explosively driven cylinders has been investigated by Taylor (1963), Hoggart and Recht (1968), Mock and Holt (1983) and recently by Hiroe et al. (2008) and Goto et al. (2008). In the work of Goto et al. (2008), a combination of experiments and numerical simulations via a 2D hydrodynamics code enabled to give a clear insight of the stress state during the deformation process. Rings were also expanded using an explosive charge. The authors observed that, for the two tested metals (AerMet100 alloy and AISI 1018 steel), the failure strain was larger in uniaxial-stress state than in plane strain. After testing, fragment widths were measured to evaluate the fracture strain. It was found that the failure strain for the fragments followed a Weibull distribution.

Concerning spherical shell expansions, one could mention the experimental work of Slate et al. (1967). Spheres were expanded by explosive. The fragmentation process was captured by camera frames. The effect of the wall thickness on the fracture strain was investigated for different metals (aluminium, copper, tantalum, zinc and copper-beryllium).

Recently, a new configuration was proposed by the Commissariat à l'Energie Atomique, centre de Valduc, France. In Juanicotena (1998), thin hemispheres are strained by explosive loading. The new device was designed in order to study the mechanical response of materials in biaxial loading. Note that the shell was fragmented at the end of the deformation. From simulations with a 2D hydrocode, the stress, strain and strain rate histories within the shell were determined.

Studies on fragmentation are not limited to experiments. Mott (1947) has investigated the expansion and the fragmentation of metallic casing. Based on a probabilistic theory and accounting for stress release originating at a fracture point, Mott was able to predict the fragment size distribution. Using still a statistical approach, Grady (1981) revisited the one dimensional Mott's problem and was able to determine the fragment size observed by Wesenberg and Sagartz (1977). Kipp and Grady (1985), assuming specific forms for the stress release during the necking process, obtained an explicit formula for the average fragment size and compared their results with experiments of Grady and Benson (1983). As an important finding, the fragment size decreases with higher strain rate loading, mass density and increases with larger fracture energy. Based on this approach, the time to fracture and the fracture strain is also explicitly found. Recently, Denoual and Hild (2000) have developed a probabilistic approach of the fragmentation of brittle materials. Multiple fragmentation could be modelled by considering crack interactions and obscuration mechanism. The relevance of this approach was demonstrated by comparison between Edge-On Impact data and numerical simulations. Taylor (1963) analysed the dynamic motion of thick walled cylinder strained by high explosive charge. The gas pressure generated by the explosion evolved in an isentropic way, so that the pressure could be linked to the current radius of the structure. Under this approach, the stress state in the cylinder wall could be computed, including inertia effects. The authors considered that fracture occurred when the hoop stress was positive (tension) in the entire wall thickness. Under this assumption, the complete fracture was shown to take place when the pressure at the inner surface decreased up to the yield stress of the material. This approach was used by Al-Hassani and Johnson (1969) for explosive driven expansions of sphere and compared to experiments of Slate et al. (1967). Electromagnetically driven expanding rings were theoretically investigated by Gourdin (1989). By considering field equations including electromagnetic and thermomechanical coupling, the expansion velocity, induced current, temperature and stress were predicted within the ring and compared well with experiments on several materials. Using this theory, Triantafyllidis and Waldenmyer (2004) proposed a two-zone model to explain the enhanced ductility due to electromagnetic loading. By comparing results of a fully coupled theory and of a theory without electromagnetic effects, it was shown that neglecting Lorentz body forces led to an underestimation of the necking strain. The case of electromagnetically expanded tubes was analysed in Thomas and Triantafyllidis (2007).

Bifurcation and stability analyses have also been conducted to model fragmentation and multiple necking. For rate independent material, Hill and Hutchinson (1975) have developed a quasi-static bifurcation analysis for a rectangular plate strained under plane strain tension. Under quasi-static loading, short wavelength modes could not be developed and long wavelength modes were favored. Following Sorensen and Freund (1998), Shenoy and Freund (1999) have extended the previous contribution by accounting for inertia contribution. A perturbation with a given mode (or wavelength) was added to the background solution. Owing to inertia in the momentum equation, the rate of growth of the bifurcation mode was evaluated. It was shown that inertia extinguished the long wavelength modes. Therefore, at each time of the deformation process, a particular mode was selected and characterized the necking interspacing. Recently, the stretching of bilayered plate was investigated in Guduru et al. (2006). In this contribution, cylindrical bars were also considered, see also Guduru and Freund (2002) and Mercier and Molinari (2003) for uncoated rods. As a result of the stability analysis, a soft outer layer displaying high strain hardening was shown to increase the bifurcation strain. The sandwich structure dissipated more

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