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A review on the strain rate dependency of the dynamic viscoplastic response of FCC metals

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ABSTRACT

The response of structures and materials subject to impulsive loads remains a field of intense research. The dynamic loading and temperature increase affect the material's mechanical/failure response. For example, strains due to explosive blast will increase at rates from 10^2 to $10^4\,s^{-1}$, leading to regimes of elastic/plastic wave propagation, plane stress and adiabatic deformations. Few constitutive models consider high strain rate effects, however some constitutive approaches that were developed and tested at low strain rate regimes will also be addressed here due to their relevance. Specific reference will be made to strain rate regimes close to $10^4\,s^{-1}$, where shock waves may develop. The paper focuses on constitutive models for polycrystalline face-centred-cubic (FCC) metals since their behaviour under high strain rate regimes is not yet fully understood mostly due to path loading dependency. Reference is also made to aluminium alloys since they are widely used in virtually all fields of industry and in armour and protective structures and systems. A basic review of the main theoretical aspects that constitute the basis for most of the constitutive models described is also presented and the main features of each model are thoroughly discussed.

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1. Introduction

Considerable effort is being devoted to the investigation of the response of structures and materials subject to ballistic impacts or blast loads, due to public awareness about terrorist threats or the prevention of accidents such as in offshore oil and gas or chemical industries, where unwanted gas or fuel deflagrations can happen.

In general a blast or impact load will manifest itself by means of a sharp pressure wave travelling at ultrasonic speed impinging on the structure surface. The energy will be transmitted so quickly that deformation will develop at very high rates and stress waves may form and travel through the body. High temperature changes may also be present and both the dynamic loading and the temperature increase will affect the mechanical and failure response of the material. This rate dependent behaviour has been very intensely investigated for a number of materials, namely metals and composites. In broad terms, strains due to explosive blast will increase at rates from 10^2 to 10^4 s^{-1}, leading to a regime of elastic and plastic wave propagation, plane stress and deformation heating [1].

One important aspect in the research effort needed to understand the response of engineering materials to blast loads involves the definition of suitable constitutive models that can be used in numerical analysis. It is important to emphasize the relevance of numerical computations in these analyses since experiments may reveal themselves unpractical or expensive. Under blast loads, deformations will be quite large meaning that the elastic component of strain will be comparatively smaller than the plastic strain. This led many researchers to focus their attention on plastic constitutive expressions. However, many constitutive models for the response of metals in high speed and loading regimes exist and a compilation may be of some help for those involved in the field. Few models consider high strain rate effects but some others that were developed and tested at low strain rate regimes will also be addressed due to their relation with other models. Nonetheless, reference will be made to regimes around 10^4 s^{-1}, where shock waves may be present in the material. For the reader interested in extreme strain rate regimes, reviews are available [2].

The variety of engineering materials of interest (steel, non ferrous alloys, composites, foams, etc.) is too wide to be tractable and since studies on steel and ferrous alloys have been widely reviewed [3] the scope of this review will restrict itself to those constitutive models that can be used for the simulation of the dynamic behaviour of non-ferrous alloys (e.g. aluminium alloys) since the use of these materials spans for virtually all fields of industry (aeronautical, automotive, marine and civil), including in protective structures and armour. However, non-ferrous metals may exhibit different behaviour under dynamic loading and a preference will be made to those models that have been tested with aluminium. Aluminium is a widely used material in all sorts of civilian and military crafts, has a polycrystalline face centred cubic (FCC) structure, which is the main reason for its ductility. For plastic deformation at least five independent slip systems are needed, as pointed by von Mises by the first time [4], but although both FCC and BCC (body centred cubic) have those systems, FCC metals have a higher packing efficiency and the slip planes are more closely packed than BCC metals, which makes them more ductile as the energy required to move atoms along denser planes is smaller than for lesser packed planes. Emphasis will be put on those constitutive models that work better for FCC metals and, consequently, this review may ignore models and variants developed for other crystallographic structures such as BCC or hexagonal closed packed (HCP). The main difference is that in BCC metals the yield stress is determined by strain rate hardening and temperature softening and in FCC metals by strain rate hardening [5]. The plastic deformation of FCC metals is less sensitive to temperature than for BCC metals. Dislocation movement in BCC metals is more thermally activated than in FCC metals, meaning that the latter will maintain ductility at lower temperatures. In BCC metals dislocation motion is increasingly influenced by the periodic lattice potential such as the Peierls stresses while for the FCC there are the short range stresses induced by forest dislocations and solute atoms that mostly affect dislocation motion. BCC metals are also more strain-rate sensitive than FCC metals.

The problem of the simulation of explosively driven deformation of metals and alloys is a complex one, that requires suitable and realistic models of plastic constitutive behaviour [6]. The range of variation of mechanical and thermodynamic state variables can be extremely wide (plastic strain of several hundreds per cent, pressures exceeding 10 GPa and plastic strain

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