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Identification of damage mechanism and validation of a fracture model based on mesoscale approach in spalling of titanium alloy

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Abstract

The subject of this paper is identification of the physical mechanisms of spalling at low impact velocities for Ti–6Al–4V alloy and determination of the macroscopic stress of spalling via meso-macro approach. Spalling is a specific mode of fracture which depends on the loading history. The aspects of the initial microstructure and its evolution during plastic deformation are very important. In order to identify the spalling physical mechanisms in titanium alloy, numerous pictures by the optical microscopy of the spall surfaces created by plate impact technique have been taken. The scenario of failure observed is in complete agreement with known physical micro-mechanisms: namely nucleation, propagation and coalescence by adiabatic shearing of micro-voids. The most interesting point in spall fracture of Ti–6Al–4V alloy is the nucleation of micro-voids. A significant amount of small micro-voids in the region of the expected spall plane has been observed. It appears that microstructural effects are important due to dual α–β phase microstructure, called Widmanstätten structure. The orientation of microstructure has a direct influence on nucleation mechanism by means of distribution of nucleation sites and decohesion between the softer particles (α-phase lamellae) and the harder lattice (β-phase). According to these observations, a fracture model has been developed. This model is based on the numerous post-mortem microscopic observations of spall specimens. The goal is to determine the macroscopic stress of spalling in function of loading time and damage level via a meso-macro approach.

Keywords: Dynamic fracture; Spalling; Titanium alloy; Microstructure

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1. Introduction

The spalling is a dynamic phenomenon which occurs when two plane waves, an incident and a reflected one are superimposed leading failure by tension. It manifests itself by creation of a free surface inside the material. A setup for plate impact experiment has been developed in the Laboratory of Physics and Mechanics of Materials (LPMM) of Metz University to study dynamic fracture by spalling at impact velocity up to $V_{\text{impact}} \approx 600$ m/s (strain rates up to $\sim 10^6\ \text{s}^{-1}$). The lowest impact velocity in plate impact experiments was searched in function of the pulse duration in order to determine when the incipient spall occurs. Application of the acoustic approximation allowed to determine the critical normal stress for different pulse durations. Since only the minimum stress of spalling is searched for, the acoustic approximation yields a correct value of the critical failure stress. Because spalling is a specific kind of fracture which is loading history dependent, the effects of the initial microstructure and its evolution during local plastic deformation in the spall area are very important. It appears that microstructural effects are important in the case of titanium alloy Ti–6Al–4V due to dual phase microstructure. The first purpose of this study was to examine physical mechanisms of spall fracture for Ti–6Al–4V alloy on the incipient level and to identify the main stages of spalling in the mesoscale.

Series of tests at different impact velocities (from 290 m/s to 460 m/s) have been performed, and the level of the normal stress σ_F for the incipient spall in a function of the incident pulse duration t_c has been determined. Such analysis has yielded the preliminary data in the form of the critical tensile stress vs. the pulse duration, $\sigma_F(t_c)$. In order to understand better the physical mechanisms of spalling, numerous scanning electron microscopy (SEM) pictures of the specimen surfaces after fracture have been taken for Ti–6Al–4V alloy. Some further observations and conclusions concerning the influence of microstructure on spall kinetics are presented in this paper.

Phenomenological or physical approaches, including micro-statistical one, can be applied to formulate fracture criteria for spalling, but still no universal one can be accepted. The approach by continuum damage mechanics, for example Cagnoux (1985), is based on introduction into the constitutive equations of one or more scalar or tensorial field quantities as measures of the material degradation. The micro-statistical approach is based on the microstructural description of damage by the continuum constitutive relations frequently formulated by notion of internal state variables. This approach is to some extent supported by experiments, Curran and Seaman (1987); Grady (1988). Because shorter times of loading produce higher values of the spall stress, which is typical feature for the spall phenomenon, Tuler and Butcher (1968) proposed a criterion based on the concept of cumulative process of failure. It was proposed by Dremin and Molodets (1985) that temperature and time dependence of the spall stress may be interpreted in terms of a modified Zhurkov's kinetic theory of fracture (Zhurkov, 1965). The early kinetic models of spalling based on thermal activation have also been discussed by Curran and Seaman (1987). In general, the cumulative criteria of spalling provide relatively good results in the macro-scale and they are quite useful in numerical codes (Hanim and Klepaczko, 1999).

It appears that, in the case of hard steels and hard titanium alloys, spalling involves as the first stage the mechanism of micro-crack nucleation and propagation and then coalescence of those micro-cracks by adiabatic shearing (Chevrier and Klepaczko, 1999). In order to gain a deeper insight on the material behavior during spalling, the initial microstructure of Ti–6Al–4V alloy has been examined by the optical microscopy and also by SEM observations, including chemical treatment of the surfaces.