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Dynamic vs. quasi-static shear failure of high strength metallic alloys: Experimental issues

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ABSTRACT

Ductile fracture of metals by void nucleation, growth and coalescence under positive stress triaxiality is well admitted. This is not the case when metals are submitted to negative stress triaxiality. The present work aims at contributing to a better understanding of the competition between micro-mechanisms at the origin of failure of metals when submitted to shear-pressure loading at low and high strain rates. With this aim in view, experiments were carried out on Ti–6Al–4V shear-compression samples involving a stress triaxiality range comprised between -0.2 and -0.5. Results show that the material failure is the consequence of a void growth induced process. At high strain rate, due to the localization of the deformation within adiabatic shear bands, the failure of the material occurs earlier, leading to maximum shear strain smaller at high strain rate than at low strain rate. Impact tests were also carried out on Kalthoff and Winkler type double notched plates. They showed that the interaction between tension and shear waves leads to a complex Mode I–Mode II crack propagation.

1. Introduction

In engineering applications, structures are generally submitted to complex loading paths. Predicting the conditions for their potential catastrophic failure consequently requires the knowledge of the dependence of the material ductility on the loading parameters, including notably the loading magnitude, the loading rate, the temperature, etc. In view of incorporating the influence of all these parameters (and others) within a failure criterion, or better within a constitutive model, the microscopic mechanisms governing the ductility of the materials at stake have to be investigated previously.

Whereas the metal fracture under positive stress triaxiality is quite well understood – resulting mostly from void germination, growth and coalescence, see e.g. Hancock and Mackenzie (1976) and Goods and Brown (1979), there remain gaps to fill in the comprehension (and description) of metal failure under low (near zero) and negative stress triaxialities.

At low strain rate, studies available in literature mostly focus on determining the macroscopic conditions for failure of metals under combined shear-tension loading, with the development of specific sample geometries and/or experimental devices, see e.g. Osakada et al. (1977), Manach and Favier (1997), Mohr and Oswald (2008), Driemeier et al. (2010). Macroscopic failure criteria are accordingly proposed, accounting for the effect of stress triaxiality, strain rate and temperature, see e.g. Johnson and Cook (1985), or of stress triaxiality and Lode parameter, see e.g. Bao

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and Wierzbicki (2004), Barsoum and Faleskog (2007), Coppola et al. (2009), Papasidero et al. (2014). In parallel, scarce are the experimental investigations aiming at identifying the micromechanims at the origin of shear failure. Under zero and low negative triaxiality, the failure is mostly ascribed to micro-shear decohesion, see Bao and Wierzbicki (2004) and Brünig et al. (2011), whereas it has been observed to result from micro-void growth by Longère and Dragon (2013).

Comparatively, literature dedicated to shear failure investigation at high strain rate is paradoxically much more abundant, in particular when dealing with the dynamic shear localisation phenomenon known as adiabatic shear banding (ASB), see e.g. Bai and Dodd (1992) for a description of the phenomenon. Possibly, in order to optimise the ballistic properties of high strength metals and alloys, ASB-related studies often include microstructural aspects. For example, ASB in high strength metallic materials has been investigated in high strain rate torsion by Marchand and Duffy (1988) and Bai et al. (1994), punching by Mazeau et al. (1997), combined shear-compression by Beatty et al. (1992), Longère et al. (2005), and Vural et al. (2003), this list being far from being exhaustive.

The present work aims at contributing to a better understanding of the competition between micro-mechanisms at the origin of failure of metals when submitted to overall shear-pressure loading at low and high strain rates. Shear-pressure loading involving negative stress triaxiality is encountered in many engineering problems including notably metal cutting and thick plate impact. As the strain rate may significantly vary all along the loading duration, its influence on shear failure is herein particularly investigated.

Due to their low mass density and high resistance, titanium alloys are nowadays widely used as structural materials in many industrial sectors, such as aeronautics and defense. The material under consideration in the present work is the Ti–6Al–4V ELI titanium alloy.

This experimental investigation is split in two parts.

The first part (Section 2) is devoted to the identification of the micro-mechanisms leading to shear failure at low and moderate strain rates. Experiments were carried out with hat shape samples (HSS), as designed by Meyer and Manwaring (1986) and Couque (2003), respectively, and shear-compression specimens (SCS), as designed by Rittel et al. (2002). The stress triaxiality values involved in the samples are negative, ranging typically from −0.2 to −0.5 depending on the specimen considered. Low strain rate shear-pressure tests were performed using a conventional tension/compression testing machine and high strain rate ones employing split Hopkinson pressure bar (SHPB). In order to identify the current and ultimate material degradation states, some tests were (if possible) interrupted before failure and other ones were carried out until complete fracture. In parallel, in view of evaluating the possibility of obtaining shear stress–shear strain curves from tests using these three sample geometries, a calibration was conducted via finite element numerical simulation.

At low strain rate, involving quasi isothermal conditions, the material failure has been seen to result from void growth and further dimple formation, in spite of the overall pressure applied. At high strain rate, involving quasi adiabatic conditions, the material failure has been found to result from the adiabatic shear banding (ASB) localisation mechanism, as expected for this class of alloys, followed by void growth along the band.

The second part (Section 3) deals with Kalthoff and Winkler (KW) impact test, see Kalthoff and Winkler (1987), carried out in view of evaluating the dynamic crack arrest ability of double notched structures. In some cases, this test and its single notched structure variant, as proposed by Zhou, Rosakis and Ravichandran (ZRR), see Zhou et al. (1996) and Kalthoff and Bürgel (2004), allow to identify a critical impact velocity, associated to a dynamic 'brittle–ductile' failure mode transition. The 'brittle–ductile' failure mode transition velocity is the velocity below which the crack propagation operates in (opening) Mode I at a significant angle (around + 70°) wrt the notch and beyond which the crack propagation operates in (ASB-assisted slip) Mode II at a negligible (slightly negative) angle wrt to the notch. This definition of 'brittle–ductile' transition velocity may slightly vary depending on the aforementioned authors. Unlike the works quoted previously, impact tests performed in the present study on Ti–6Al–4V double notched (KW) plates have shown that at low impact velocity the crack propagates at a negligible (slightly negative) angle wrt the notch, and that at higher impact velocity the crack, which has firstly propagated at a negligible (slightly negative) angle wrt the notch, propagates at a significant (positive) angle wrt the notch. Microscopic observation of the fracture surface moreover shows no evidence of ASB but the presence of dimples whose shape indicates a complex loading path.

Finally, relying upon the experimental results obtained in the present work, concluding remarks propose a list of indications in view of elaborating a constitutive model aiming at reproducing the shear failure of metallic materials when submitted to a wide range of strain rates.

2. Shear failure at low and moderate loading rates

As mentioned in the introduction, literature on shear-compression experiments at low strain rate is scarce while being paradoxically rich at high strain train rate. In the sequel, we are using different specimen geometries initially proposed by different authors to study the dynamic shear behaviour of high strength materials.

The core of the present work is devoted to the identification of the damage mechanisms operating at low and high strain rates, which is the purpose of Section 2.3, in view of further constitutive modelling (not presented here). Section 2.2 is accordingly considered as a complement attempting to give (more qualitative than quantitative) information on the shear-pressure behaviour of the material at stake.

2.1. Experimental procedure

Shear-compression tests were carried out at room temperature at low and moderate strain rates using conventional