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DOI:
10.1063/1.4971642

Citation for published version (APA):

Published in:
SHOCK COMPRESSION OF CONDENSED MATTER

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Citation: 1793, 100017 (2017); doi: 10.1063/1.4971642
View online: http://dx.doi.org/10.1063/1.4971642
View Table of Contents: http://aip.scitation.org/toc/apc/1793/1
Published by the American Institute of Physics
Damage Development in Rod-On-Rod Impact Test on 1100 Pure Aluminum

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Abstract. Stress triaxiality plays a major role in the nucleation and growth of ductile damage in metals and alloys. Although, the mechanisms responsible for ductile failure are the same at low and high strain rate, in impact dynamics, in addition to time resolved stress triaxiality and plastic strain accumulation, pressure also contributes to establish the condition for ductile failure to occur. In this work, ductile damage development in 1100 commercially pure aluminum was investigated by means of rod-on-rod (ROR) impact tests. Based on numerical simulations, using a continuum damage mechanics (CDM) model that accounts for the role of pressure on damage parameters and stochastic variability of such parameters, the impact velocity for no damage, incipient and fully developed damage were estimated. ROR tests at selected velocities were performed and damage distribution and extent were investigated by sectioning of soft recovered samples. Comparison between numerical simulations and experimental results is presented and discussed.

INTRODUCTION

Cavity nucleation and growth (NAG) is the main mechanism of ductile damage in metals and alloys. In pure metals, voids develop preferentially at the grain boundaries and triple points although, in some cases, they can also develop inside the grains. Ductile rupture occurs as a result of void coalescence which accelerates the damage rate causing a rapid reduction of the net resisting area. The NAG process is controlled by plastic strain accumulation and stress triaxiality. In particular, stress triaxiality reduces the ability of material to plastically deform resulting in an apparent lower strain at failure. Mechanisms responsible for ductile damage are the same under quasi static and dynamic loading. Although strain rate and temperature have an effect on material ductility, under impact loading, pressure also contributes to establish the conditions for ductile failure to occur. Among available models, continuum damage mechanics provides a thermodynamically consistent constitutive framework to address ductile damage development in metals and alloys. Bonora [1] proposed a ductile damage model that accurately predicts ductile failure in pure metals and alloys under varying stress triaxiality conditions [2, 3]. Recently, Iannitti et al. [4] showed the possibility to use an extended version of the Bonora damage model (BDM) in order to predict ductile damage development under high stress triaxiality and dynamic pressure. They also showed that different conditions exist for ductile damage development in Taylor anvil and rod-on-rod (ROR) impact tests under equivalent velocity resulting in the fact that ductile damage can develop in ROR while it not necessarily can occur in not overdriven Taylor anvil impact test. Similar results were experimentally observed for other metals, [5, 6, 7].

In this work, the BDM was used to predict ductile damage development in pure aluminum 1100. Here, based only on simulation work, the minimum impact velocity for incipient damage has been estimated. Subsequently, ROR impact tests at different velocities were performed and metallurgical investigation were carried out on soft-recovered
samples in order to provide evidence of ductile damage development. Preliminary results seems to confirm that the proposed modeling approach is capable to accurately predict the condition for damage development under complex dynamic deformation paths.

**DUCTILE DAMAGE MODELING**

The BDM is derived in the framework of CDM proposed initially by Lemaitre [8]. Here, the damage D is defined as a state variable that accounts the degradation of material properties due to the irreversible processes occurring at the microscale. This model differs from other formulation due to the following features: damage only accumulates in tension, under compressive state of stress the damage effects are temporarily canceled, and damage only affects on the Young modulus, there is no softening effect on the material flow curve which makes the formulation mesh size insensitive in numerical simulation. The model requires four material parameters only. All of them have a physical meaning and can be determined according to the procedure given in [9]. The damage rate equation is given by

$$\frac{dD}{d\hat{\epsilon}} = \alpha \frac{D_{cr}^{1/\alpha}}{\ln(\epsilon_f/\epsilon_{th})} \frac{R_v}{\hat{\epsilon}} (D_{cr} - D)^{\alpha - 1}$$

(1)

where $\hat{\epsilon}$ is the “active” equivalent plastic strain (that accumulates under positive pressure only), $\epsilon_{th}$ is the uniaxial threshold strain at which damage process initiates, $\epsilon_f$ is the uniaxial failure strain, $D_{cr}$ is the critical damage at failure, $\alpha$ is the damage exponent and $R_v$ is the function that account for stress triaxiality effect given as,

$$R_v = \frac{2}{3} (1 + \nu) + 3(1 - 2\nu) \left( \sigma_m \sigma_{eq} \right)$$

(2)

where $\nu$ is the Poisson ratio and $\sigma_m$ and $\sigma_{eq}$ are pressure and von Mises stress, respectively. In quasi-static loading, pressure effect on the damage parameters can be neglected. In impact dynamics, such effect cannot be ignored. Bonora et al. [10] imposing the conservation of the dissipated damage work derived the following expression for the threshold and failure strain under a generic constant stress triaxiality load path,

$$p_{th} = \frac{1}{R_v} \left[ \frac{\sigma_m}{\sigma_{eq}} \left( \frac{\epsilon_f}{\epsilon_{th}} \right)^m - \left( \frac{\sigma_m}{\sigma_{eq}} \right)^m \right]^{\frac{1}{m}}$$

(3)

and

$$p_{f} = p_{th} \left( \frac{\epsilon_f}{\epsilon_{th}} \right)^{\frac{1}{m}}$$

(4)

where $p_{th}$ and $p_{f}$ are the damage threshold and failure strain for a generic triaxial state of stress, respectively; $m$ is the hardening exponent. This parameter can be estimated calculating the work hardening slope for given strain level or by the fitting of failure data obtained on round notched tensile bar samples (low stress triaxiality – low pressure) and flyer plate impact test at incipient spall condition (high stress triaxiality – high pressure). Increasing stress triaxiality, $p_{th}$ and $p_{f}$ get closer and closer, converging to the same value, indicating that failure occurs immediately after damage initiation.

**MATERIAL AND TESTING**

The material under investigation is commercially pure aluminum 1100. The material was received as bars with a diameter of 12.7 mm. As a result of the extrusion process, the bars showed highly deformed grains along the longitudinal direction in the outer region of the circular section, while the core of the section showed larger equiaxed gains. All specimens for characterization tests and ROR cylinders ($D_0=10.9$ mm and $L_0=55$ mm) were machined and then annealed at 350°C for 1/2 h. The average grains size in the core of the bar after annealing was 147 $\mu$m. The material was fully characterized performing quasi-static and dynamic tractions at different temperature on smooth and round notched specimens for constitutive model and damage parameters identification. ROR tests have been performed at velocity ranging from 270 to 550 m/s. Tests were performed using a single stage gas-gun in a vacuum chamber. Samples were soft-recovered using ballistic gel.
NUMERICAL SIMULATION AND RESULTS

A parametric simulation analysis on damage development in ROR of AA1100 was carried out using the commercial finite element code MSC MARC v2013.1. Dynamic transient analysis was performed by means of implicit time integration via the Houbolt operator. Single Step Houbolt procedure is unconditionally stable, second order accurate and asymptotically annihilating of the high-frequency response. Because of the symmetry, a 2D axisymmetric model was developed using fully integrated, four node isoparametric elements. The modified Rusinek-Klepaczko (MRK2) constitutive model was used. This model, which is physically based, assumes that the stress is the sum of the athermal, thermal and viscous drag terms. Details on the model formulation are given elsewhere (Bonora et al. [11]). The BDM with pressure sensitivity of damage parameters was implemented in the code and used to predict the occurrence of damage development with varying impact velocity. The summary of the parametric investigation is given in Fig. 1.

![Failure locus for AA1100 incorporating pressure effect: dot lines indicates the stress triaxiality path for the most critical point along the axis of ROR receiver as a function of the impact velocity.](image)

Here the calculated failure locus given as $p_{th}$ and $p_f$ as a function of stress triaxiality is shown. In order to magnify the differences the double-log plot was used. For each impact velocity, the evolution of the stress triaxiality at the most critical location along the symmetry axis of the receiver cylinder was extracted and plotted. It can be noted that for an impact velocity at which damage would not develop, the stress triaxiality as a function of the active plastic strain increases, reaches a maximum and then decreases as a result of the stress wave propagation in the sample. All this occurs within the time frame in which the first release wave, initiated at the free edge of the impacting cylinder; reaches the symmetry axis. Increasing the impact velocity, the stress triaxiality peak moves toward larger plastic strain values. Failure occurs when the stress triaxiality path crosses the failure locus. It should be noted that the stress triaxiality generated in the ROR is even higher than that occurring in the flyer plate impact experiment. Based on these numerical results, ductile damage is predicted to occur in the ROR for an impact velocity >250 m/s. ROR samples performed at 268 m/s were sectioned and investigated with optical microscopy. This revealed that damage in the form of nucleated voids indeed occurred in the sample along the symmetry axis at approximately 2 mm below the impact surface, Fig. 2. In particular, limited voids was observed as reported in the magnification of Fig. 2. At the impact velocity of 440 m/s, more numerous, larger coalesced voids were found in the same region indicating that the critical combination of stress triaxiality and active plastic strain occurs in a large volume of material, Fig. 3. In the magnification of Fig. 3, it can be noted that voids are now found closer to the impact surface because of the compression that occurs after voids development in the later stage of the cylinder deformation.
FIGURE 2. Nucleated void close to the impact surface of ROR receiver impacted at 268 m/s.

FIGURE 3. Nucleated void close to the impact surface of ROR receiver impacted at 440 m/s.

CONCLUSIONS

In the present work, the condition for ductile damage development in ROR of AA1100-O was investigated using a continuum damage mechanics model. The impact velocity at which ductile damage develops in ROR experiment was estimated performing a parametric numerical analysis. Numerical results were validated performing ROR experiments at the estimated velocity. Soft recovered samples, sectioned and polished, provided evidence of limited voids nucleation for 268 m/s impact consistently with computational results that indicate ductile damage development for velocity higher than 250 m/s. At higher impact velocity, it was found that voids nucleate over a more extended region below the impact surface, which is indicative of the occurrence of the critical combination of stress triaxiality and active plastic strain in a larger material volume.

REFERENCES