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# Investigation on Grain Size Effect in High Strain Rate Ductility of 1100 Pure Aluminum

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**Abstract.** The effect of the initial grain size on the material ductility at high strain rates in 1100 pure aluminum was investigated. Dynamic tensile extrusion (DTE) tests, at different impact velocities, were performed. Samples have been annealed at 350°C for different exposure times to induce grain growth. Extruded fragments were soft-recovered and the overall length of the extruded jets was used as a measure of material ductility at high strain rates. Numerical simulation of DTE test at different velocity was performed using the modified Rusinek-Klepaczko constitutive model. Results indicates that, as reported for pure copper, the overall ductility of the aluminum increases when grain size decreases. Numerical simulation results were in quite good agreement with experimental data.

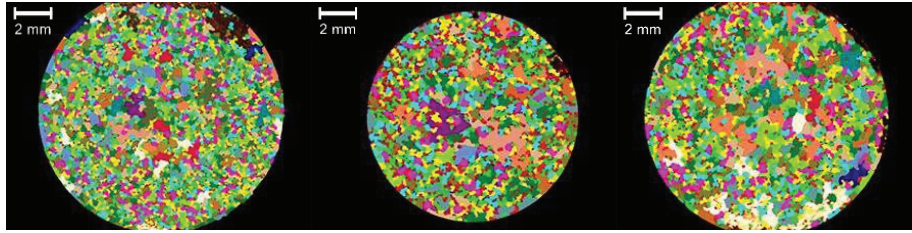
## INTRODUCTION

When the material is subjected to large plastic deformation at very high strain rates, the role of the microstructure in determining the overall response at continuum scale becomes more relevant. The effect of the initial grain size on the material response has been investigated for decades. Renewed interest in this field is motivated by the need to study the mechanical behavior of materials in the sub-micron and nanocrystalline grain-size range. Such type of microstructure can be achieved in tensile extrusion processes, as in shaped charge, where a jet of material is stretched as a result of the difference in velocity between the tip and the tail. The effect of grain size on ductility of pure metals, such as OFHC copper and tantalum, has been investigated using the Dynamic Tensile Extrusion test developed at LANL, [1]. For what concerns pure aluminum, available data on the grain size effect are mainly obtained at low strain rates. The yield strength has been seen to increase with decreasing grain size, often in agreement with a Hall-Petch relationship. Similarly, the grain size has been seen to have a relevant effect on the material ductility (strain to failure) too. In this case, it was observed that elongation at rupture decreases when grain size decreases [2-3]. The scope of the work is to investigate the effect of the initial grain size on the ductility of 1100 pure aluminum at high strain rate. To this purpose, DTE tests at different impact velocities were performed. Ejected fragments were soft-recovered and the overall length of the jet was used as a measure of material elongation [4]. Preliminary numerical simulation of DTE test was performed in order to verify the predicting capabilities of the modified Rusinek-Klepaczko constitutive model [5].

## MATERIAL

The material investigated in this work was AA1100-O commercial pure aluminum received in form of bars with a diameter of 12.7 mm. The specimens were machined and then annealed, for 0.5 h at 350 °C, in Argon atmosphere. Successively, to increase the size of the grain, samples were heat treated at 350°C for additional 1.5 and 3 hours, respectively. The resulting microstructures are shown in Fig. 1. The grain size was found to be not uniform throughout the specimen cross section which showed coarse grains at the inner core surrounded by smaller grain, as a result of

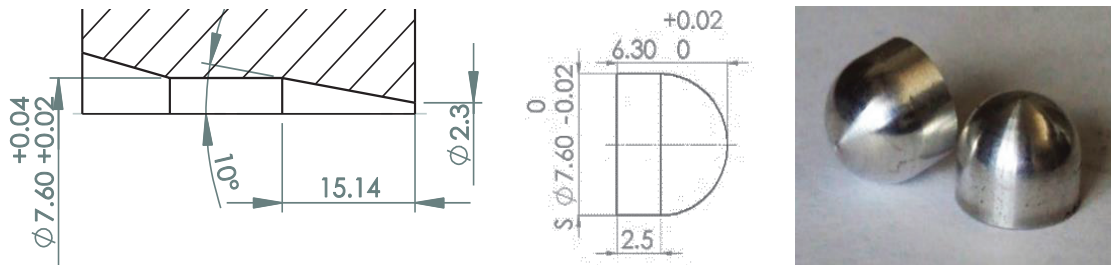
the bar extrusion process. Using the intercept method, the measured average grain size were 147, 159 and 189  $\mu\text{m}$  for 0.5, 2.0 and 3.5 h annealing time, respectively.



**FIGURE 1.** Cross section maps of grains distribution after annealing (a): 0.5 h @ 350°C; (b): 2 h @ 350°C, (a): 3.5 h @ 350°C.

## EXPERIMENT SETUP

The DTE test was introduced by Gray III, et al. [1] and used to investigate the grain size effect on material ductility in OFHC copper and tantalum. The test consist in launching a projectile into a conical extrusion die at given velocity. During its travel in the die, the material is subjected to pressure and shear stress waves of magnitude of  $\sim 1$  GPa and  $\sim 3$  GPa, respectively, (these values are reached with an impact velocity of 600 m/s and an impact angle of  $10^\circ$ , using an aluminum projectile). The material is deformed and extruded from the exit bore. As a result of the difference in velocity between the tip and the rear, the jet is stretched and multiple necking occurs resulting in the formation of several fragments. In the present work, the same conical extrusion die geometry, as given in Gray III, et al. [1], was used. Here, a bullet-shape projectile with the same volume of the spherical specimen used in [6] was used, Fig. 2. Tests were performed using a gas-gun with 7.62 mm bore in vacuum chamber. Extruded fragments were soft-recovered in a ballistic gel block. For 147  $\mu\text{m}$  grain size, DTE tests were performed at different velocities ranging from 340 to 690 m/s, while for the other two grain sizes tests were performed at 500 m/s, approximately.



**FIGURE 2.** Internal dimension of die and DTE samples.

## CONSTITUTIVE MODEL AND NUMERICAL SIMULATION OF DTE TEST

Numerical simulation of DTE were performed using the modified Rusinek-Klepaczko (MRK2) constitutive model. This is a physically based model, which assumes that the Huber–Mises stress is the sum of three terms accounting for different deformation mechanisms:

$$\bar{\sigma} = \frac{E(T)}{E_0} [\bar{\sigma}_{ath} + \bar{\sigma}_{th}] + \bar{\sigma}_{vd}. \quad (1)$$

Here,  $E(T)/E_0$  defines the temperature dependence of elastic modulus as:

$$\frac{E(T)}{E_0} = 1 - \frac{T}{T_m} \exp \left[ \theta^* \left( 1 - \frac{T}{T_m} \right) \right] T > 0, \quad (2)$$

where  $E_0$  is the elastic modulus at 0 K,  $T$  is the temperature (K),  $T_m$  is the melting temperature (K), and  $\theta^*$  is the characteristic homologous temperature.

Here,  $\bar{\sigma}_{ath}$  is the athermal stress component, which depends on the grain size as:

$$\bar{\sigma}_{ath} = Y + \frac{k}{\sqrt{d_0}}, \quad (3)$$

where  $Y$  is the yield stress at 0 K and infinite grain size,  $d_0$  is the reference grain size and  $k$  is a material constant.

Here,  $\bar{\sigma}_{th}$  is the flow stress component defining the rate-dependent interactions with short-range obstacles and it is equal to

$$\bar{\sigma}_{th} = \sigma_0^* \left\langle 1 - \xi_1 \left( \frac{T}{T_m} \right) \log \left( \frac{\dot{\epsilon}_{max}}{\dot{\epsilon}_p} \right) \right\rangle^{1/\xi_2}, \quad (4)$$

where  $\dot{\epsilon}_p$  is the equivalent plastic strain rate,  $\xi_1$  and  $\xi_2$  are material constants defining the temperature and strain rate sensitivities of the material, respectively, and  $\dot{\epsilon}_{max}$  is the strain rate at which the strain rate effect becomes zero. When

$\dot{\epsilon}_p \geq \dot{\epsilon}_{max}$ , the flow stress  $\bar{\sigma}_{th}$  becomes equal to  $\sigma_0^*$ . Here,  $\sigma_0^*$  is the plastic flow at 0 K and is described by a voce type law:

$$\sigma_0^* = A_0 \left( 1 - \exp \left( - \frac{\epsilon_p}{t_0} \right) \right) \quad (5)$$

Finally,  $\bar{\sigma}_{vd}$  accounts for saturating viscous drag given as:

$$\bar{\sigma}_{vd} = \chi_{lim}^0 \left\{ 1 - \frac{T}{T_m} \exp \left[ \theta^* \left( 1 - \frac{T_m}{T} \right) \right] \right\} \left[ 1 - \exp(-\dot{\epsilon}_p \dot{\epsilon}_{lim}^\nu) \right], \quad (6)$$

where  $\chi_{lim}^0$ ,  $\dot{\epsilon}_{lim}$  and  $\nu$  are material parameters. Details on the derivation of these equations can be found elsewhere (Bonora, et al. [5]). The parameters of the MRK2 model for AA1100-0 were calibrated using the experimental data given in Khan and Huang [6] and are reported in Table 1. The value of  $k$  was taken according to [7].

TABLE 1. Summary of MRK2 model parameters for AA1100-O

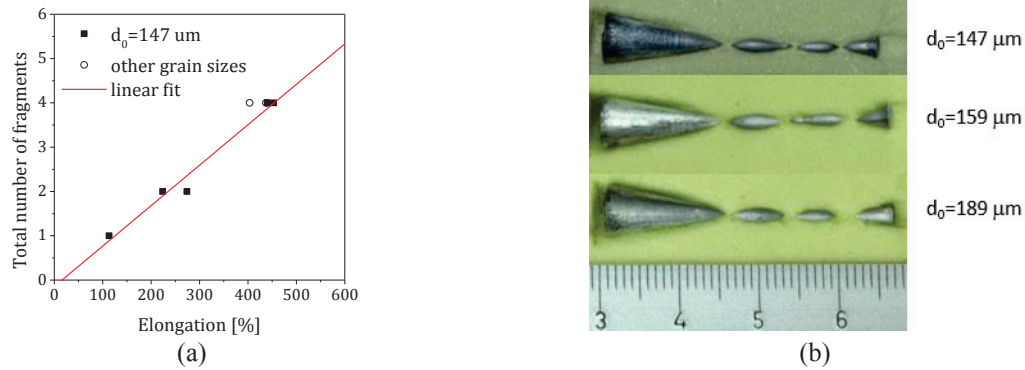
| Y<br>(MPa) | k<br>(MPa<br>$\mu\text{m}^{1/2}$ ) | $\xi_1$ | $\xi_2$ | $\dot{\epsilon}_{max}$<br>(s <sup>-1</sup> ) | R <sub>0</sub><br>(MPa) | t <sub>0</sub> | $\chi_{lim}^0$ | $\theta^*$ | $\dot{\epsilon}_{lim}$<br>(s <sup>-1</sup> ) | $\nu$ | E <sub>0</sub><br>(MPa) | T <sub>m</sub><br>(K) | Poisson's<br>ratio |
|------------|------------------------------------|---------|---------|--|-------------------------|----------------|----------------|------------|--|-------|-------------------------|-----------------------|--------------------|
| 42.3       | 42                                 | 1.16    | 8.45    | 1.0E7  | 101.1                   | 0.072          | 60             | 0.6        | 5.0  | 1.0   | 6.9E4                   | 944.3                 | 0.34               |
|            |                                    | E-3     | E-3     |  |                         |                |                |            | E-3  |       |                         |                       |                    |

The MRK2 model was implemented in the commercial finite element code MSC MARC v2013.1.0 used for simulation of DTE test. Since the DTE specimen and the extrusion die are axisymmetric, a 2D FEM model, using four node isoparametric elements was developed. Both the projectile and the die were simulated as deformable bodies in contact with friction. Dynamic transient analysis was performed using Single Step Houbolt procedure, large displacement, finite strain formulation and Lagrangian updating. During the extrusion, the elements are subjected to excessive distortion and then global remeshing was used in order to avoid premature termination of the analysis and to improve the solution. A thermomechanical analysis was carried out to account for the increment of temperature due to quasi-adiabatic process.

## RESULTS AND DISCUSSION

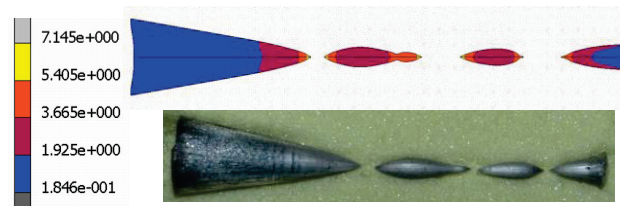
In DTE tests the material ductility was calculated as the difference between the sum of the lengths of the fragments (included the fragment trapped in the die) and the initial length of the projectile  $L_0$ , divided by  $L_0$ ,

$$Elongation[\%] = \frac{\left( \sum L_{frag} \right) - L_0}{L_0} \times 100. \quad (7)$$



**FIGURE 3.** (a) DTE total number of fragments as a function of elongation. (b) DTE test fragments for different grain size at 500 m/s impact.

The experimental results showed that, increasing the impact velocity, the elongation increased almost linearly, similarly to what found for tantalum by Cao, et al. [4]. Also the number of extruded fragments, which correspond to the number of plastic flow localizations, increased with increasing velocity. It was found that fragment formation (that is, neck development and fracture) occurs when the elongation of the jet reaches 100% Fig. 3(a). At nominal impact velocity of 500 m/s, measured elongations as a function of the grain size were 440% (147 $\mu\text{m}$ ), 437% (159 $\mu\text{m}$ ) and 403% (189 $\mu\text{m}$ ), Fig. 3(b). This result was found consistent with observation in OFHC reported by Hörnqvist, et al. [8]. Numerical simulation of DTE showed a good agreement only for impact velocity in the range of 450 m/s. At higher velocity impact, simulation predicted a larger number of fragment. A qualitative comparison between calculated extrusion and experimental results is given in Fig. 4. Lack in performance in predicting accurately the number of fragments as a function of the impact velocity is probably to be ascribed to the selection of the material flow curve at 0 K that was estimated from data retrieved in the literature that may be suitable for the material under investigation.



**FIGURE 4.** Qualitative comparison between numerical simulation and the experimental test at 490 m/s (grain size: 147  $\mu\text{m}$ ) showing plastic strain contours.

## CONCLUSIONS

In this work, the effect of the initial grain size on the dynamic deformation of 1100 pure aluminum was investigated. DTE test results showed that, similarly to OFHC copper, increasing the initial grain size, material ductility (defined as the elongation of the jet) decreases. It was observed that fragment formation occurs when the length of the extruded jet exceeds 100%. Preliminary numerical simulation using the MRK2 constitutive model were in good agreement with experimental results only for selected impact velocity probably due to the difference in the reference material flow curve at 0K that was derived from data reported in the literature. This result seems to confirm the use of DTE as robust test for material modelling validation as discussed in [5].

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