



**HAL**  
open science

# Continuum damage modeling for ductile metals under high strain rate deformation

Christophe Husson, Saïd Ahzi, Loïc Daridon, Thierry Courtin

## ► To cite this version:

Christophe Husson, Saïd Ahzi, Loïc Daridon, Thierry Courtin. Continuum damage modeling for ductile metals under high strain rate deformation. *Journal de Physique IV Proceedings*, 2003, 110, pp.63-68. <10.1051/jp4:20020671>. <hal-00447243>

**HAL Id: hal-00447243**

**<https://hal.science/hal-00447243v1>**

Submitted on 30 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

# Continuum damage modeling for ductile metals under high strain rate deformation

C. Husson<sup>1,2</sup>, S. Ahzi<sup>1</sup>, L. Daridon<sup>1</sup> and T. Courtin<sup>2</sup>

<sup>1</sup> *Université Louis Pasteur, IMFS, UMR 7507 du CNRS, 2 rue Boussingault, 67000 Strasbourg, France*

<sup>2</sup> *FCI – Corporate Research Center, rue Robert Surmont, BP. 50, 72402 La-Ferté-Bernard cedex, France*

**Abstract.** The accuracy of the computational investigation on the response of ductile materials under dynamic condition depends on the capability of the constitutive model in accounting for strain rate, temperature and micro-structural effects. In this work, we propose a damage evolution law, valid for a wide range of strain rates, based on the theory of continuum damage mechanics (CDM). This model implicitly accounts for the three stages of damage: the nucleation, the growth and the coalescence. This non-linear isotropic CDM model for ductile damage is developed by assuming the existence of a new ductile damage dissipation potential. The proposed damage law is coupled with an evolution law for the flow stress. Like in the mechanical threshold stress (M.T.S.) model, the flow stress is decomposed as the sum of an athermal component and a temperature and strain rate dependent component. Results from our model are in agreement with the existing experimental results for stress-strain behavior and damage evolution in oxygen-free high-conducting (OFHC) copper under both quasi-static and dynamic loading conditions.

## 1. INTRODUCTION

To predict the damage evolution of ductile materials subjected to dynamic loads, the flow stress model must account for the effects of the temperature  $T$ , effective accumulated plastic strain  $p$ , effective plastic strain rate  $\dot{p}$  and the micro-structure as formally expressed by the following relation :

$$\sigma_{eq} = f(p, \dot{p}, T, \text{microstructure}) \quad (1)$$

The proposed model is based on the continuum damage mechanics (CDM). In this model, the presence of voids, or cracks are accounted for by introducing a single damage variable  $D$ . For simplicity, the present study concentrates on isotropic plasticity and damage. The proposed non-linear dynamic damage model is studied in section 2. In section 3, the validity of the model is evaluated by a parametric study.

## 2. MODELING

Using the Legendre-Fenchel transformation, in the framework of continuum damage mechanics, it is possible to formulate the total dissipation potential,  $F$ , as the sum of the dissipation potential associated with plastic deformation,  $F_p$ , and the dissipation potential associated with the damage process,  $F_D$  :

$$F = F_p(\sigma, R, X; D) + F_D(Y; p, D) \quad (2)$$

Here  $\sigma$  is the stress tensor,  $R$  is the isotropic hardening stress,  $X$  is the kinematic hardening stress,  $D$  is the damage variable (as defined by Kachanov [1]),  $Y$  is the internal variable associated with damage, and  $p$  is the effective accumulated plastic strain.

Based on the work of Bonora [2], we propose a new expression for the damage dissipation potential,  $F_D$  :

$$F_D = \frac{Y^2}{2S_0(1-D)} \frac{(D-D_0)^{\frac{k-1}{k}}}{(p)^h} \quad (3)$$

where  $S_0$  is the initial damage energy strength,  $Y$  is the damage energy release rate,  $k$  is the damage exponent characteristic of the material,  $h$  is a material exponent, and  $D_0$  is the initial amount of damage.

In the following, we set  $h = 0$  which gives a damage dissipation potential  $F_D$  that was successfully used to predict damage evolution in face centred cubic metals [3]. The evolution rate of the damage,  $\dot{D}$ , is expressed in the general form proposed by Chaboche and Lemaitre [4]

$$\dot{D} = \frac{\partial F_D(Y, p, D, \dots)}{\partial Y} \dot{p} (1-D) H(p - p_{th}) \quad (4)$$

where  $H(p - p_{th})$  is the Heaviside function, and  $p_{th}$  is the onset strain for damage nucleation. Using the definition of the internal variable  $Y$  associated to damage [4]:

$$Y = \frac{\sigma_{eq}^2 R_v}{2E(1-D)} \quad (5)$$

where  $E$  is the Young modulus.  $R_v$ , function of  $(\sigma_H/\sigma_{eq})$ , is the triaxiality factor into  $\sigma_{eq}$  the von Mises equivalent stress and  $\sigma_H$  the hydrostatic stress.

By substituting equation (5) into equation (4), we obtain the following damage kinetic evolution:

$$\dot{D} = \left( \frac{\sigma_{eq}}{1-D} \right)^2 R_v \frac{1}{2ES_0} (D-D_0)^{\frac{k-1}{k}} H(p - p_{th}) \dot{p} \quad (6)$$

where  $k$  is the degree of non-linearity of damage evolution,

Like in the M.T.S. (mechanical threshold stress) model [5], the effective equivalent von Mises flow stress is modelled as the sum of two components: one temperature and strain rate dependent  $\bar{\sigma}$ , and one athermal  $\sigma_{ath}$  :

$$\frac{\sigma_{eq}}{1-D} = \bar{\sigma}(p, \dot{p}, T, \text{microstructure}) + \sigma_{ath}(\text{microstructure}). \quad (7)$$

The athermal stress  $\sigma_{ath}$  depends on the strengthening mechanisms and grain size. The grain size influences on the flow stress at low homologous temperatures ( $T < 0.25 \times T_{meit}$ ) and is modelled by the Hall-Petch relation:

$$\sigma_{ath}(\text{microstructure}) = \sigma_{sm} + k_{HP} \cdot (\sqrt{d})^{-1} \quad (8)$$

where  $\sigma_{sm}$  is the contribution from strengthening mechanisms [6],  $d$  is the mean grain diameter and  $k_{HP}$  is the Hall-Petch constant.

The thermal stress  $\bar{\sigma}$  is mainly induced by the interaction between dislocations and obstacles [7]. We assume that  $\bar{\sigma}$  is given by the following multiplicative decomposition :

$$\bar{\sigma}(p, \dot{p}, T, \text{microstructure}) = \sigma_{kv}(p) \cdot R(\dot{p}, T) \cdot S(\dot{p}, T) \quad (9)$$

where  $\sigma_{kv}(p)$  is the monotonously increasing stress function with a maximum value at a finite “strain” proposed by Kovacs and Vörös [8] for polycrystalline f.c.c. metals in the quasi-static case:

$$\sigma_{kv}(p) = \sigma_0 + \beta (1 + \ln p_m) \cdot (p) - \beta (p \cdot \ln p). \quad (10)$$

Here  $p_m$  is the strain corresponding to the maximum stress,  $\beta$  and  $\sigma_0$  are fitting parameters.

The term  $R(\dot{p}, T)$  is a scaling function which depends on the normalized hardening coefficient, the temperature  $T$  and the equivalent plastic strain rate  $\dot{p}$ . The proposed form for  $R(\dot{p}, T)$  is a modification of that proposed by Maudlin et al. [9] where we include temperature effects in a similar way to the Johnson-Cook model [10]:

$$R(\dot{p}, T) = \theta_0(\dot{p}) \cdot \left( 1 - \left( \frac{T - T_{ref}}{T_{melt} - T_{ref}} \right)^m \right) / H_{max}. \quad (11)$$

$T_{ref}$  is the reference temperature (in our case room temperature),  $T_{melt}$  is the melting temperature,  $m$  is a softening exponent,  $H_{max}$  is the maximum value at the hardening due to dislocation accumulation and  $\theta_0(\dot{p})$  is the initial strain hardening rate given by

$$\theta_0(\dot{p}) = a_1 + a_2 \cdot \ln(\dot{p}) + a_3 \cdot \sqrt{\dot{p}} \quad (12)$$

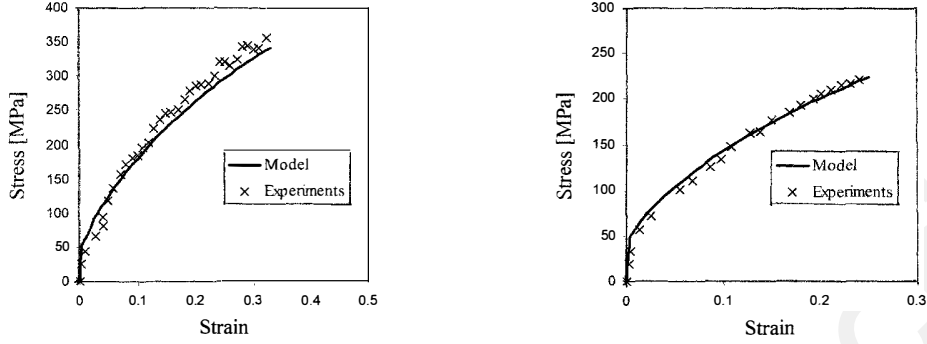
where  $a_1$ ,  $a_2$ , and  $a_3$  are model parameters.

The term  $S(\dot{p}, T)$  is a scaling function that accounts for temperature and effective accumulated plastic strain rate dependence defined by:

$$S(\dot{p}, T) = \left[ 1 - \left( \frac{k_B T}{\mu b^3 g_0} \cdot \ln \left( \frac{\dot{p}_0}{\dot{p}} \right) \right)^{1/\eta} \right]^{1/\delta} \cdot I. \quad (13)$$

where  $k_B$  is the Boltzmann constant,  $b$  is the magnitude of the Burgers vector,  $g_0$  is a normalized activation energy (which is expected to remain constant providing the obstacle character does not vary),  $\dot{p}_0$  is a reference strain rate,  $\mu$  is the shear modulus, and  $\delta$  and  $\eta$  are statistical parameters that characterize the average shape of the barriers that oppose dislocation glide (Kocks et al. [11]). The parameters involved in equation (13) are defined in the work of Follansbee and Kocks [5] for OFHC f.c.c. copper (99.99% pure)

The proposed model is used to predict stress-strain curves for OFHC Cu deformed under uni-axial load in the quasi-static case and dynamic case. Husson et al. [12] have studied the quasi-static case. In the present study, we focus on high strain rate. The comparison between experimental data [5] and our model is presented in figure 1 for different temperatures and strain rates for uni-axial compression.



a)  $T = 298 \text{ K}$ ,  $\dot{\varepsilon}_{eq}^p = 6000 \text{ /s}$ .

b)  $T = 542 \text{ K}$ ,  $\dot{\varepsilon}_{eq}^p = 5200 \text{ /s}$ .

**Figure 1.** Comparison between experimental data [5] and proposed model for OFHC Cu [Table 1].

Regarding the uniaxial loading, and according to the form of kinetic damage evolution law (equation 6) in which we insert the stress-strain constitutive model including the temperature, the strain rate and the micro-structure (equation 7), we obtain the following damage evolution law in polycrystalline f.c.c. metals:

$$\left[ \begin{array}{l} \varepsilon_{eq}^p < \varepsilon_{th} \rightarrow D = D_0, \\ \varepsilon_{th} < \varepsilon_{eq}^p < \varepsilon_{cr} \rightarrow D - D_0 = (D_{cr} - D_0) \left[ \frac{\int_{\varepsilon_{cr}}^{\varepsilon_{eq}^p} [\sigma_{ath} + \bar{\sigma}]^2 d\varepsilon}{\int_{\varepsilon_{th}}^{\varepsilon_{cr}} [\sigma_{ath} + \bar{\sigma}]^2 d\varepsilon} \right]^k, \\ \varepsilon_{cr} < \varepsilon_{eq}^p \rightarrow D = D_{cr}. \end{array} \right. \quad (14)$$

where  $\varepsilon_{cr}$  is the critical uniaxial strain to failure,  $\varepsilon_{th}$  is the damage threshold strain (uniaxial),  $D_0$  is the initial damage, and  $D_{cr}$  is the critical damage at failure.

### 3. PARAMETERS ANALYSIS

#### 3.1 Constitutive damage parameters

Table 1 lists the values of the physical constants and parameters. The experimental data for OFHC Cu is obtained from Follansbee and Kocks [5], Maudlin and Davidson [9], Johnson and Cook [10] and Husson et al. [3].

The initial amount of damage  $D_0$  is assumed to be zero for a virgin material. Johnson and Cook [10] investigated the behavior of metals under several load rates and temperature. Recently, Poizat et al. [13] investigated the effect of strain rate on the damage process (due to nucleation and growth) on the OFHC Cu under several dynamic loading. From these studies, it is concluded that the critical damage  $D_{cr}$ , the damage threshold strain  $\varepsilon_{th}$ , the critical strain to failure  $\varepsilon_{cr}$ , and the damage exponent  $k$  depend on the strain rate  $\dot{p}$ , the temperature  $T$  and the micro-structure.

Table 1. Values of physical constants and non-adjustable model parameters for OFHC Cu.

Parameters	Dimension	Values	Parameters	Dimension	Values	Parameters	Dimension	Values
$k_{HP}$	MPa.mm <sup>1/2</sup>	4.6	$a_0$	MPa	2370.7	$T_{room}$	K	1356
$\sigma_{sm}$	MPa	20	$a_1$	MPa	8.295	$H_{max}$	MPa	2370.7
$d$	mm	$5 \cdot 10^{-2}$	$a_2$	MPa	3.506	$\mu$	GPa	42
$\sigma_0$	MPa	198	$k_B/b^3$	MPa/K	0.823	$g_0$		1.6
$\beta$	MPa	185.88	$m$		0.8	$\delta$		2/3
$\epsilon_m$		1.7	$T_{ref}$	K	300	$\eta$		1

### 3.2 Investigated parameters

The experimental data for the damage evolution under high strain rate deformation is not available. Hence, we propose a parametric study to evaluate the effect of several parameters on the damage evolution.

Several constitutive damage parameters were varied in the non-linear continuum damage mechanics model under constant high strain rate deformation ( $10^{+3}$  /s) at room temperature (298 K). This procedure enabled us to illustrate how the damage curve is influenced by the following parameters: - the critical damage  $D_{cr}$ , - the damage threshold strain  $\epsilon_{th}$  - and the critical strain to failure  $\epsilon_{cr}$ .

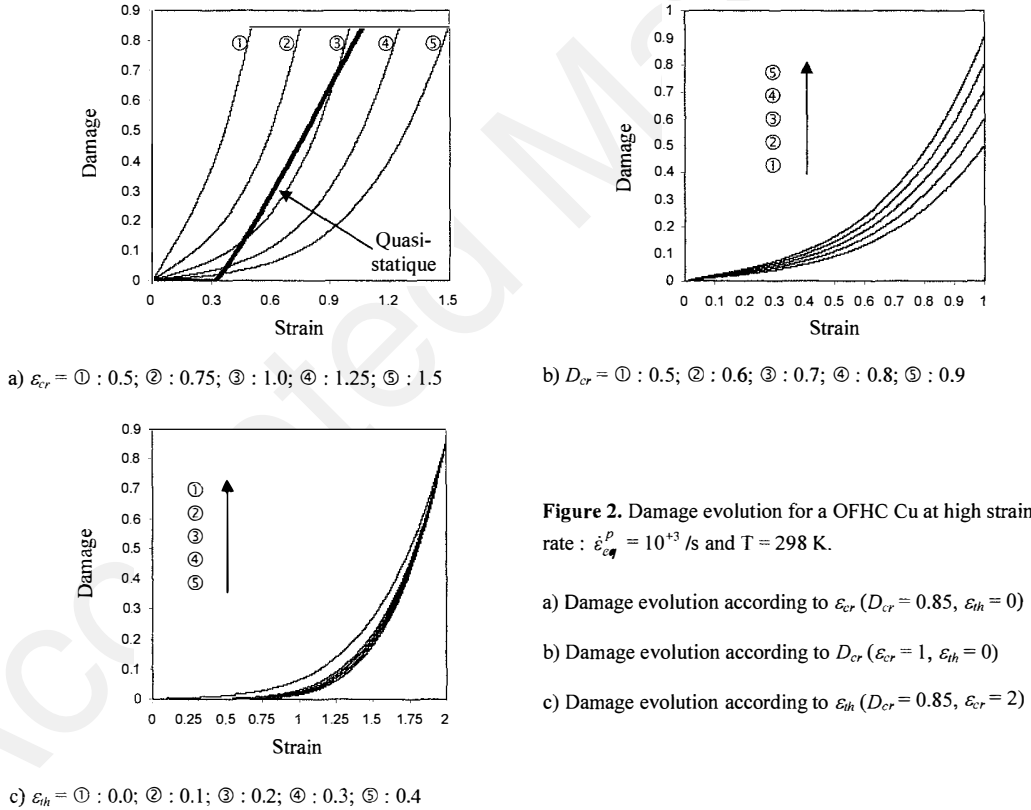


Figure 2. Damage evolution for a OFHC Cu at high strain rate :  $\dot{\epsilon}_{eq}^p = 10^{+3}$  /s and  $T = 298$  K.

- a) Damage evolution according to  $\epsilon_{cr}$  ( $D_{cr} = 0.85, \epsilon_{th} = 0$ )
- b) Damage evolution according to  $D_{cr}$  ( $\epsilon_{cr} = 1, \epsilon_{th} = 0$ )
- c) Damage evolution according to  $\epsilon_{th}$  ( $D_{cr} = 0.85, \epsilon_{cr} = 2$ )

Figures 2a and 2b shows that the response of the proposed model is very sensitive to the critical damage  $D_{cr}$  and the critical strain to failure  $\varepsilon_{cr}$ . Figure 2c shows that the model response is not sensitive to the parameter  $\varepsilon_{th}$ .

The parameter sensitivity study shows that the developed damage model is mostly sensitive to the failure parameters.

#### 4. CONCLUSIONS

In this paper, in order to model the degradation of a material under high train rate deformation for ductile metals, a non-linear damage model is derived. Here strain rate, temperature and micro-structure have been taken into account in the work hardening behaviour of polycrystalline f.c.c. metals using a micro-structural approach. Our motivation for this work is the finite element simulation of the manufacturing processes and the impact tests. Based on the continuum damage mechanics, the proposed non-linear damage model is valid for a broad range of strain, strain rate and temperature.

#### References

- [1] Kachanov L.M. Izv. Akad. Nauk. SSR Otd., Teekh. Nauk **8** (1958) 26-31.
- [2] Bonora N. Engng. Fract. Mech. **58**, No. 1/2 (1997) 11-28.
- [3] Husson C., Ahzi S., Bahlouli N. (2003) To be submitted.
- [4] Lemaitre J. and Chaboche J.L. Mechanics of Solids Materials. Cambridge University Press, Cambridge (1990) pp. 355.
- [5] Follansbee P.S., Kocks U.F. Acta. Metal. **36** (1) (1988) 81-93.
- [6] Chandrasekaran D., "Aspect on the modelling of strengthening mechanisms in metals", Stockholm Royal Institute of Technology 2001, Licentiate thesis.
- [7] van Liempt P., Onink M., Bodin A. Adv. Engng. Mat. **4**, No. 4 (2002) 225-232.
- [8] Kovacs I., Vörös G. Int. J. of Plasticity **12**, No. 1 (1996) 35-43.
- [9] Maudlin P.J., Davidson R.F., Henninger R.J. Los Alamos National Laboratory, LA – 11895 - MS (1990).
- [10] Johnson G.R., Cook W.H. "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures", Netherlands, 7<sup>th</sup> Int'I Symp. Ballistics (1983) 541-547.
- [11] Kocks U.F., Argon A.S., Ashby M.F. Prog. Mater. Sci. **19**, Pergamon Press, Oxford (1975).
- [12] Husson C., Poizat C., Bahlouli N., Ahzi S., Courtin T., Merle L. "On plasticity and damage evolution during sheet metal forming", IUTAM symposium : Multiscale modeling and characterization of elastic-inelastic behavior of engineering materials, Marrakech, Morocco 20-25 october 2002, Ahzi et al. Eds. (Kluwer Academic Publishers, 2003). In press.
- [13] Poizat C., Campagne L., Daridon L., Husson C., Merle L., Ahzi S. Int. J. of Forming Processes (2003). In press.