

# Damage analysis of the liner during copper extrusion

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Keywords: hot extrusion, damage evolution, lifetime prediction, hot work tool steel

## Abstract

The lifetime estimation of tools made of hot work steels during hot extrusion application, where cyclic thermo-mechanical loads occur, is considered in this work. A copper extrusion process was simulated in steady state by means of the FE-program DEFORM<sup>TM</sup>2D, to obtain the temporal boundary conditions, i.e. stress and temperature distributions at the most critical area, namely at the interface billet-liner. These boundary conditions were used to simulate the creep-fatigue behaviour of the tool steel Böhler W750 (1.2779) in service with ABAQUS Standard<sup>TM</sup>v.6.7-1 software, where an elastic-viscoplastic material model was fully coupled with the FE-calculation by use of Z-Mat libraries. Both the resulting inelastic strain rate as well as the local stress state was the input parameter for a lifetime model. The influence of the local stress as well as the coupling state on time to failure was investigated.

## Introduction

Cyclic thermo-mechanical loading conditions are responsible for complex strain-time patterns in extrusion tools, which can lead to a combination of both fatigue as well as creep damage [1]. Tool failure due to creep-fatigue processes is time dependent and often involves deformation path dependent interactions of cracks with grain boundary cavities. The extrusion industry tries to accelerate the manufacturing process by increasing the billet temperature and/or by accelerating the press speed that raise the loading of the tools. Additionally the tool steel producers develop enhanced more homogeneous and cleaner materials in order to increase tools lifetime. Finite element simulation of the extrusion process to get the temperature and stress evolution in the container, coupled with constitutive equations as well as lifetime consumption models in order to calculate both the inelastic strains and the tools lifetime, help to optimise the extrusion process and to compare the operating times of different hot work tool steels [2]. Viscoplastic constitutive models were developed in the past to take into account the inelastic behaviour of the material during creep-fatigue loads [3-4]. For the lifetime prediction of highly stressed extrusion tools during service, taking into account the inelastic strain rate during a cycle, it is necessary to be able to assess the inelastic stress-strain response of the material. The influence of the thermo-mechanical history on the current stress-strain behaviour can be described with internal (non-measurable) variables, beside the measurable (external) variables of deformation,

time, temperature and stress. A creep-fatigue lifetime rule for complex processes was investigated that is independent of single loading parameters, like stress or strain ranges or corresponding maxima, for the description of an entire cycle. Instead this rule evaluates the total damage in each time increment and accumulates that to the lifetime consumption.

### Modelling and Simulation

To predict damage, the accurate knowledge of the unsteady local thermal and mechanical loading within one extrusion cycle onto the inner diameter of the liner is of particular importance. Hence the thermo-mechanical load the container has to carry during extrusion of a billet was analysed with DEFORM<sup>TM</sup>2D. The container assembly is symmetrical and therefore a 2D axisymmetric model of the container was used.

For the liner material the high temperature resistant austenitic hot work tool steel Böhler W750 (~X6NiCrTi26-15) was used (Table 1), for the mantle Böhler W300 (X38CrMoV5-1) and the billet material was electro copper with 99.95% purity.

Grade	C	Si	Mn	Cr	Mo	Ni	V	Ti	Al	B
W750	0.02	0.20	1.40	15.0	1.30	25.0	0.30	2.70	0.25	0.005

Table 1: Chemical composition of the considered tool steel in weight percent

The configuration of the extrusion model is related to an experimental extrusion device, which was constructed to perform extrusion tests in laboratory scale to verify both pressure and temperature boundary conditions (see Figure 1) [5-6]. The ram was assumed to be rigid, die and mantle were assumed to be elastic.

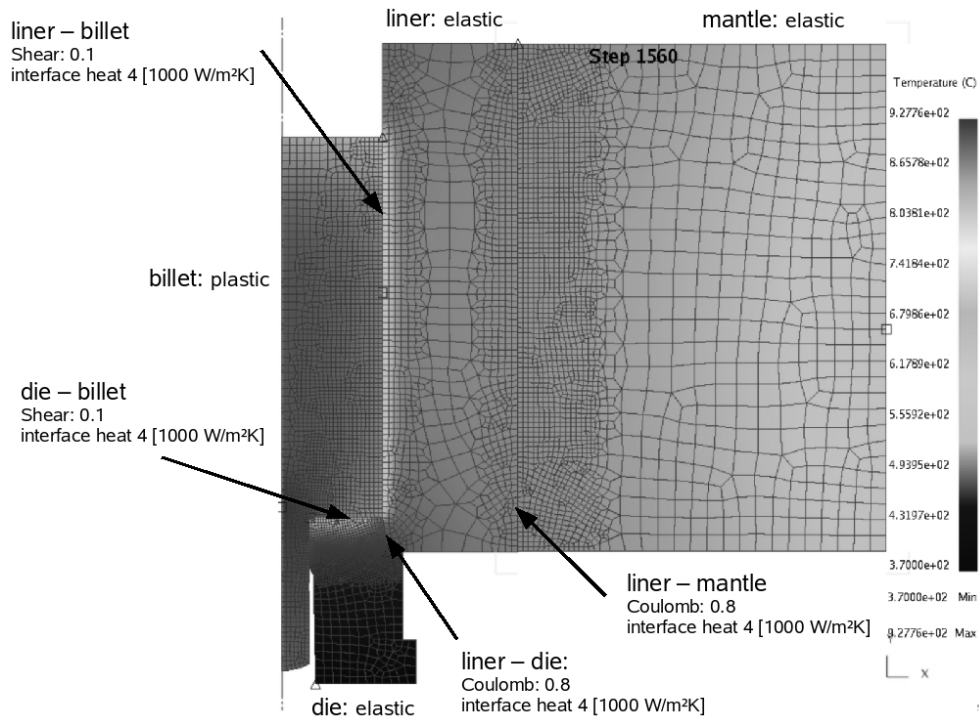


Figure 1: Axisymmetrical model for the extrusion of a 900°C copper billet in DEFORM<sup>TM</sup>2D.

The simulated extrusion process in DEFORM<sup>TM</sup>2D includes the whole loading history, namely the shrink-fitting of the mantle (0.8‰), the preheating of the container to a working temperature of 500°C, the pressing on the container against the die and the forward extrusion of the billet with a ram speed of 7 mm/s, which cause complex load cases. Temperature and pressure values were used as boundary conditions in ABAQUS Standard<sup>TM</sup> v.6.8 standard calculations. For the liner, the elastic-viscoplastic material model [7], including both isotropic hardening/softening laws and two back stress tensors as well as a lifetime consumption model (see below) was implemented. The implicit FE-calculation with ABAQUS Standard<sup>TM</sup> v.6.8 was fully coupled with the explicit material model by the aid of Z-Mat package [8]. Figure 2 shows a snap shot of the temperature (a) and the von Mises stress (b) distribution in the container during the third extrusion cycle. The non-uniform stress distribution is a reason of the occurring complex load cases.

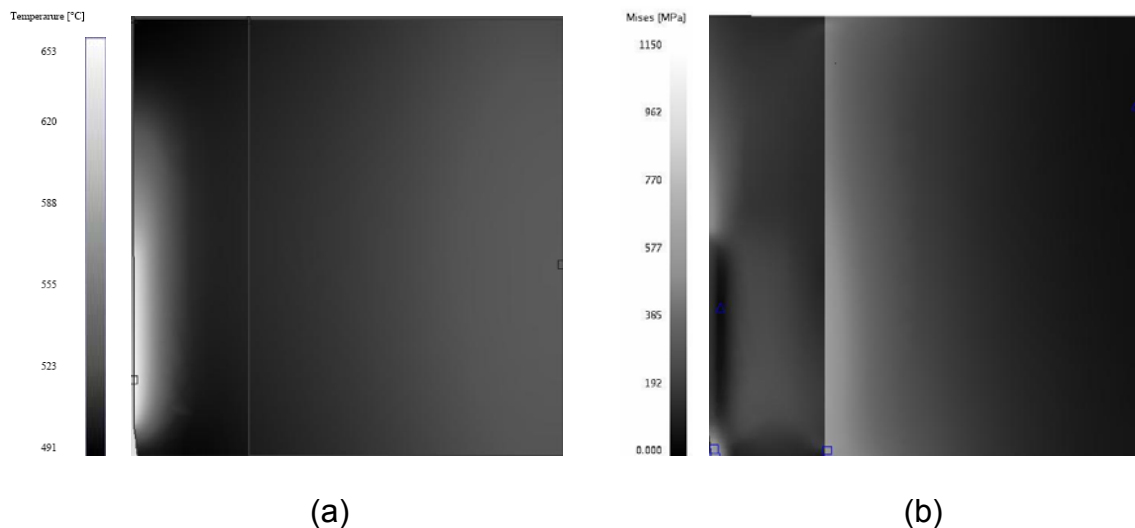


Figure 2: Temperature [°C] (black: 491°C, white: 653°C) (a) as well as von Mises equivalent stress [MPa] (black: 0 MPa, white: 1150 MPa) (b) distribution in the container at the end of the third extrusion cycle. The inner liner wall has to withstand cyclic high thermo-mechanical load amplitudes. Remarkable are the high stresses at the inner mantle due to the shrinking process (b) and the thermo-mechanical amplitude loading at the inner liner wall (a, b).

### A lifetime rule for complex processes

Cyclically loaded structures suffer fatigue failure. Fatigue lifetime means in a macroscopic model the initiation of a macro-crack (typically a fraction of millimetre). Fatigue lifetime rules are usually formulated on the basis of mean quantities of a cycle, like stress or strain ranges. In contrast, time incremental lifetime rules evaluate the total damage in each time increment and, thus, can be applied also to complex multiaxial loading paths, for which the definition of a single loading parameter describing the entire cycle could be difficult. Furthermore, a time incremental lifetime rule can easily be implemented in a material sub-routine for finite element analysis of structures just as an evolution equation for an additional internal variable, the lifetime consumption  $D$ ,  $0 \leq D \leq 1$ . The following lifetime rule has been used:

$$\frac{dD}{dt} = \left( \frac{\sigma_{d\_eq}}{A} \right)^{m_l} \left( \frac{\dot{p}}{\dot{p}_0} \right)^{n_l} \dot{p}_0, \quad \sigma_{eq} := \sqrt{\frac{3}{2} \|S\|} \quad (1),$$

where  $\dot{p}$  is the inelastic Mises equivalent strain-rate and  $\dot{p}_0$  is a normalisation constant. The loading history and time dependent value of  $\dot{p}$  was calculated by the explicit Chaboche-type model. The material parameters  $A$  and  $m_l$  denote the stress dependence of the lifetime behaviour.

The parameter  $n_l$  describes the time-dependence of the lifetime: for rate-independent behaviour is  $n_l$  equal to 1;  $n_l$  equals zero means that a fully time-dependent lifetime behaviour is present.  $n_l$  was found to be positive but significantly lower than 1 for the investigated high temperature loading. The parameters  $A$  and  $m_l$  were determined from LCF tests with strain-rates of  $10^{-3} \text{s}^{-1}$  and without hold-times. The parameter  $n_l$  was identified by the influence of hold-times in LCF tests on the lifetime behaviour. More details can be found at Sommitsch et al. [9]. To consider the influence of the stress triaxiality  $R_v$ , the damage equivalent stress  $\sigma_{d\_eq}$  was used, which is a one-dimensional stress that for the same value of the damage yields the same value of the elastic strain energy density as that of a three-dimensional state:

$$\sigma_{d\_eq} = \sigma_{eq} \sqrt{R_v} \quad (2)$$

and

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

where  $\sigma_H$  denotes the hydrostatic stress. The numbers of cycles to failure  $N_f$  were hence calculated for the seek of simplicity by

$$N_f \approx 1/(\Delta D)_3 \quad (4),$$

where  $(\Delta D)_3$  is the lifetime consumption within the third extrusion cycle. Both model adaptation and validation always referred to the third cycle. At the investigated high temperatures, subsequent cyclic softening appeared without any saturation of the hysteresis loops, but integration of the time-incremental lifetime-rule over all cycles up to the fatigue failure ( $D = 1$ ) would be too costly for a real component. Nevertheless, the damage rate takes into account the whole loading complexity within a cycle.

### Damage evolution and lifetime prediction

The configuration, which is depicted in Figure 1, was used to predict the damage evolution for a selected point in the liner (Point 1) with maximum lifetime consumption at the inner liner wall during the copper extrusion process. The lifetime consumption of the third cycle (see  $\Delta D$  in Figure 4b) was chosen representatively to calculate the lifetime to failure, which leads to 1355 cycles until failure occurs according to the coupled calculation and 3886 cycles for an uncoupled calculation (i.e. no addition of inelastic strain to total strain); compare Figures 3b and 5a. Additionally, the influence of triaxiality on failure was

investigated by using the von Mises stress  $\sigma_{eq}$  instead of the damage equivalent stress  $\sigma_{d\_eq}$  in Equation 2. The coupled calculation without consideration of triaxiality yields to a total lifetime of 6986 cycles (Figure 3a).

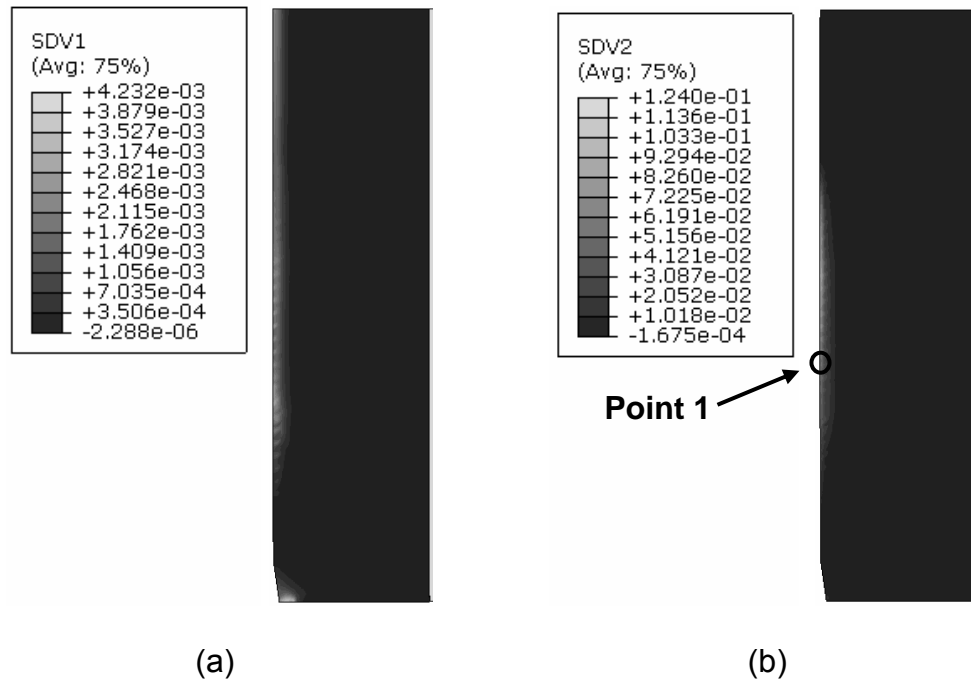


Figure 3: Results for the coupled calculations without (6986 cycles) (a) and with consideration of triaxiality (1355 cycles to failure) (b) performed with ABAQUS Standard v.6.8 and Z-Mat v.8.3.5.

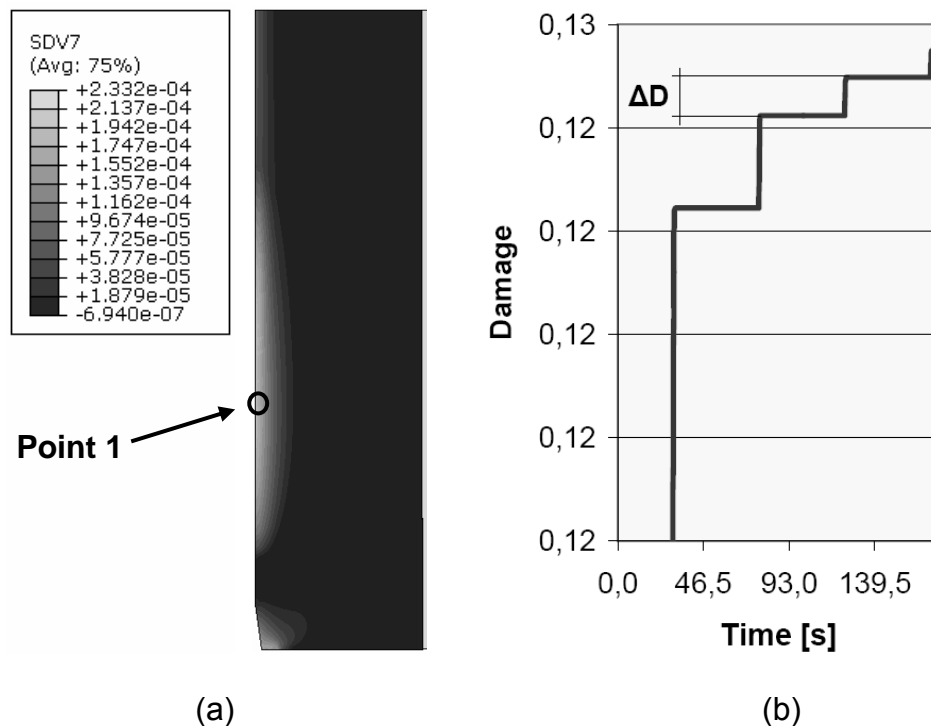


Figure 4: Accumulated inelastic strain in the liner (a) and lifetime consumption (b) of a considered node (Point 1) in the most damaged area at the inner liner wall according to the coupled calculation with consideration of triaxiality (Figure 3b).

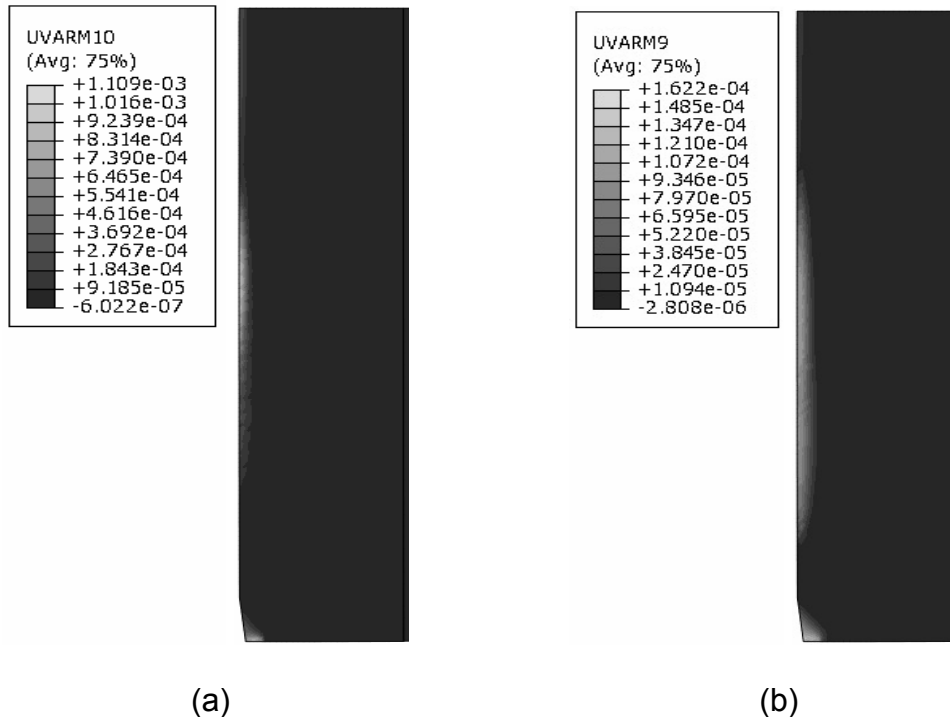


Figure 5: Results for the uncoupled calculations of damage with consideration of triaxiality (failure after 3886 cycles) (a) and accumulated inelastic strain in the liner (b).

## Conclusions

A lifetime rule for complex multi-axial loading, based on a Chaboche type model for creep-fatigue interaction was presented. The lifetime of the liner made of austenitic hot work tool steel during copper extrusion was predicted. The extrusion process was simulated by axisymmetric finite element method in order to get both temperature and radial stress boundary conditions for a subsequent cyclic simulation of temperature and stress evolution in the container. In the environment of Abaqus and ZMat, the applied elastic-viscoplastic constitutive model fed a time incremental lifetime rule. With this procedure, the lifetime to failure can be predicted realistically.

The critical regions of tools are generally edges, diminutions and areas under high thermal and/or mechanical loads, respectively. Damage initiation takes place at these critical regions, which are the source of component failure. The largest accumulated damage was calculated for regions that exhibit maximum overlapping temperature and equivalent stress loading. Constitutive coupling of elastic-viscoplastic materials behaviour as well as the consideration of triaxiality in the lifetime rule led to a considerable reduction of cycles to failure, which could be based on compressive stress components in the liner.

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