

## **INVESTIGATION AND NUMERICAL MODELLING OF EXTRUSION TOOL LIFE TIME**

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### **Abstract**

The extrusion process is used to produce aluminium and copper profiles. The tools are typically made of hot-work tool steels and subject to high cyclic thermal and mechanical loadings. Due to the local appearing high temperatures which can reach up to 580 °C within the die for aluminium extrusion additionally creep-fatigue damage occurs.

The final goal of the current activities is the numerical description of the entire extrusion process regarding mechanical and thermal loads during a real life pressing cycle and the coupled fatigue and creep damage. Process data are provided by an extrusion company, whilst the steel vendor makes all necessary material data available.

The simulation of the heat treatment and the resulting state of a die used is the basis for the subsequent modelling of the cyclic loads during the press cycles. The material behaviour is described by a visco-plastic model and damage is predicted using an incremental life time rule.

The resulting life time is comparable to typical ones in the extrusion industry. Also the location of maximum damage agree well with observed cracks in withdrawn dies.

### **Keywords**

Hot work tool steel, extrusion, numerical simulation, heat treatment, life time prediction.

## INTRODUCTION

As the mechanical and thermal stresses are very high during the extrusion process the die material must fulfill several requirements:

- High thermal stability to avoid tempering effects
- High thermal conductivity to avoid heat accumulation within the die
- Wear resistant against abrasive materials to be extruded
- ...

Chromium-molybdenum-vanadium-alloyed hot work tool steels meet all these requirements. Two representative die materials are the Böhler grades W300IB and W400VMR with the chemical composition given in table 1.

Material	Mat.num.	C [%]	Si [%]	Mn [%]	Cr [%]	Mo [%]	V [%]
W300IB	1.2343	0.38	1.1	0.40	5.0	1.3	0.40
W400VMR	~1.2343	0.36	0.2	0.25	5.0	1.3	0.45

Table 1 – Chemical composition of W300IB and W400VMR

Fig. 1 shows a dropped out die for aluminium extrusion made of W400VMR used at Alcan, Sierre. The diameter of the tool is roughly 700 mm. As the process temperatures are in the order of the tempering temperature softening may occur and additional to the thermo-mechanical loadings plastification and creep damage appear. Cracks in the bridges depicted in the right image of figure 1 eventually lead to the elimination of the die.

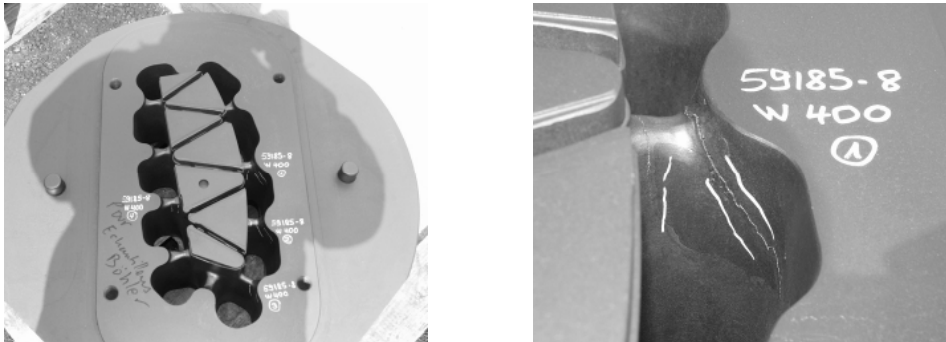
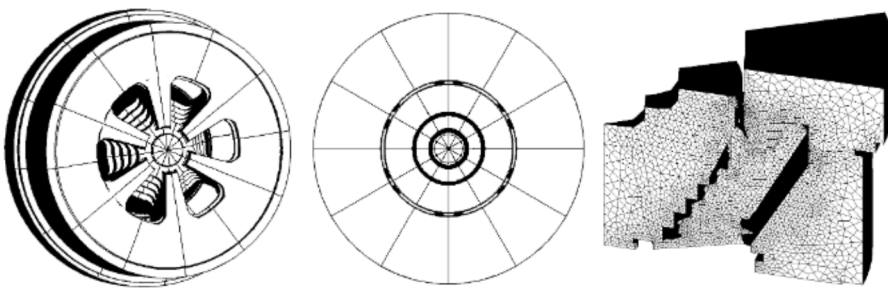


Figure 1 – Extrusion tool made of hot work tool steel W400VMR

In order to optimize the selection and shape of the material as well as the extrusion process itself several numerical simulation models have been combined. The simulation of the heat treatment yields results about phase distribution, residual stresses, distortion and hardness. This information together with process data provided by the extrusion company is the basis for the subsequent life time prediction model.

## **COMPUTATIONAL MODEL**

For the sake of simplicity an extrusion die for tubes with a symmetry of  $30^\circ$  is considered for the simulations (fig. 2). The computational model consisting of 50 000 elements is depicted in the right image of fig. 2.

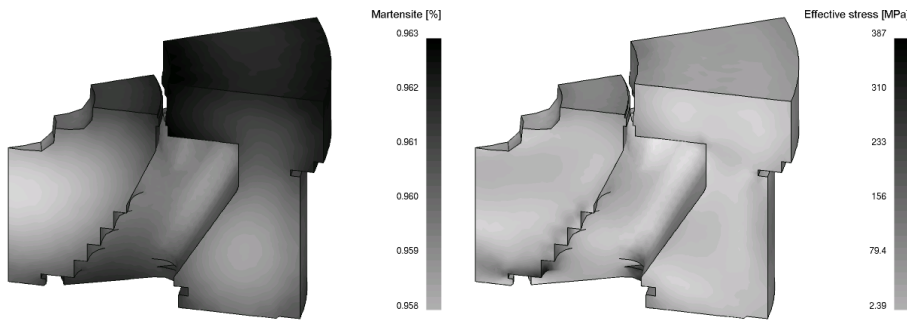


**Figure 2** – Computational Model

## **HEAT TREATMENT SIMULATION**

To predict the life time of tools, the accurate knowledge of the initial state after heat treatment is of particular importance. Hence the phase distribution (volume fraction of phases) and residual stresses have been analysed by means of the finite element method. The calculations were carried out using the FE-programme DEFORM™ HT. Details about the used models for transformation can be found in [1].

The heat treatment was performed in a vacuum furnace with gas quenching. The austenitization temperature was  $1030^\circ\text{C}$  for W300 IB and the quenching parameters for nitrogen 3 bar were used. After hardening about 96 % volume fraction of martensite and 4 % volume fraction of retained austenite can be determined from the calculation (fig. 3). From previous studies it is known, that the phase distributions can be predicted very well [1].



**Figure 3** - Volume fraction of martensite and von Mises stress after hardening

To calculate residual stresses, the transformation kinetics and the flow curves of each phase must be known as well as the temperature-dependent elastic and thermo-physical material properties. The maximum effective stresses (von Mises equivalent stress) after hardening appear at exposed positions on the die as it can be seen in figure 3. During tempering the retained austenite dissociates and the tetragonal martensite is transformed into tempered martensite. The residual stresses within the die are substantially lowered and equilibrate across the tool.

## PROCESS SIMULATION AND LIFETIME PREDICTION

### Constitutive Model

The material behavior is described by a visco-plastic model according to Chaboche [2], where the total strain  $\varepsilon$  is taken to be composed of elastic  $\varepsilon_e$ , thermal  $\varepsilon_{th}$  as well as inelastic  $\varepsilon_{in}$  parts. 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 [3, 4]. The influence of the thermo-mechanical history on the current stress-strain behavior can be described with internal (non-measurable) variables, beside the measurable (external) variables of deformation, time, temperature and stress [5]. The evolution equations for the internal variables are given by flow and hardening rules, which are described in detail in [4].

All material properties needed in the constitutive model are temperature-dependent and have been determined for temperatures in the range of 470 – 590 °C with 30 °C temperature steps.

## Lifetime prediction

Cyclically loaded structures suffer a fatigue failure. Fatigue lifetime means in a macroscopic model the initiation of a macro-crack (typically a fraction of millimeter). Time incremental lifetime rules (Sermage et al. [5]; Yeh and Krempl [6]) evaluate the total damage in each time increment and, thus, can be applied 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 subroutine 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:

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

where  $\sigma_{eq}$  is the Mises equivalent stress calculated from the applied stress deviator,  $\dot{\epsilon}$  the inelastic Mises equivalent strain-rate,  $\dot{\epsilon}_{in}$  the inelastic strain rate tensor and  $\dot{\epsilon}_0$  is a normalisation constant [4]. The material parameters  $A$  and  $m_l$  describe the stress-dependence of the lifetime behaviour and have been determined from low-cycle-fatigue (LCF) tests with strain rate of  $10^{-3} \text{ s}^{-1}$  without hold-times and on the basis of the third cycle. The parameter  $n_l$  describes the time-dependence of the lifetime: for rate-independent behaviour  $n_l$  is equal to 1,  $n_l$  equal to 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 [4].

The cycles-to-failure  $N_f$  of the LCF experiments have been determined at 2% stress drop in tension and have been calculated by the formula

$$N_f \approx \frac{1}{(\Delta D)_3} \quad (2),$$

where  $(\Delta D)_3$  is the lifetime consumption within the third cycle.

## Model of cyclic die loads

The initial state of the tool (distribution of phases and residual stresses) before usage is obtained by the heat treatment simulation. The resulting phase distribution (tempered martensite in the present case) designates the material properties of the die to be used in the simulation of the extrusion process. Additionally the accurate knowledge of the unsteady local thermal and mechanical loading within one cycle on the die is needed to predict damage. Hence the thermo-mechanical load of the die during extrusion of a billet has been analysed by means of the finite element method by Alcan, Sierre, where the die was assigned a rigid behavior. The output of these simulations was the time-dependent temperature boundary condition on the contact surfaces billet-die during on cycle in the steady state regime. Due to missing stress boundary conditions, the time-dependent pressure conditions normal to the contact surfaces billet-die were assumed as 100 MPa.

For the calculation of the cyclic temperature and stress evolution in the die, FEM calculations have been conducted with an elastic die, using Abaqus™ Standard. The necessary contact conditions (friction, interface heat transfer coefficient) between the extrusion tools and the boundary conditions (convection coefficient, emissivity) have been described using existing data. The time increment had to be chosen relatively small (0.25 s) in order to handle large stress and thus damage gradients with time. Within each extrusion cycle that consists of a press time of 300 s and a loading time of 300 s, both the heat of the billet and the applied radial stresses have been defined by the above described boundary condition at the contact surface billet-die. Fig. 4 displays both the stress distribution and the temperature at the end of the third extrusion cycle. The maximum temperature (about 540 °C) appears near the contact area billet-die, and the maximum von Mises equivalent stress of 730 MPa is also located in this area.

For the chosen extrusion examples, the simulations led to maximum lifetime consumption in the region of relatively high both temperature and equivalent stresses (Fig. 5). Especially for more complicated shaped dies like the one in fig. 1 the areas exhibiting highest temperatures and maximum stress do not coincide. However, the largest accumulated damage occurs in regions with disadvantageous overlapping of creep and fatigue (i. e. maximum overlapping temperature and equivalent stress loading). Fig. 6 depicts the lifetime consumption evolution with time for 3 extrusion cycles. The calculated cycles-to-failure of the die are approximately 10,000 which seem reasonable in comparison to real lifetime of aluminium extrusion dies. This must also be judged regarding the fact that no measured stress data were available to be used as boundary conditions as mentioned above.

Despite the different geometries of the real die (fig. 1) and the one used for the simulation (fig. 2) it is obvious that the maximum damage occurs in the bridges for both cases.

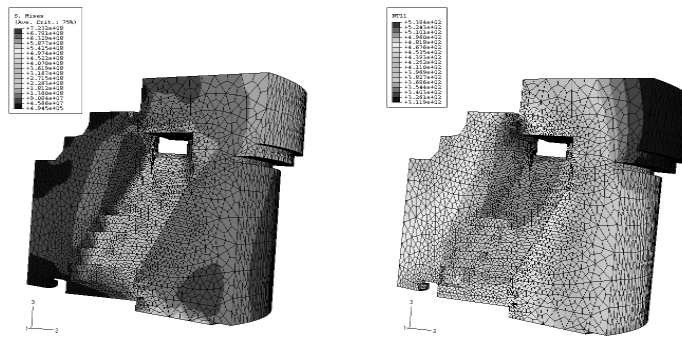


Figure 4 – Von Mises stress and temperature at the end of the 3<sup>rd</sup> press cycle

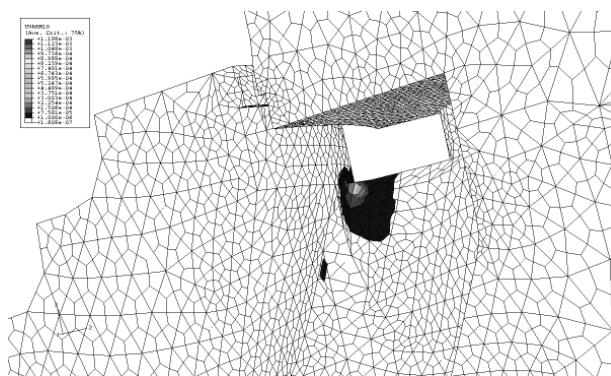


Figure 5 – Damage distribution at the end of the 3<sup>rd</sup> press cycle

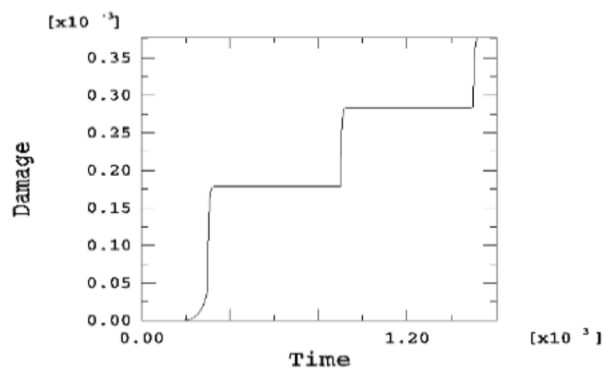


Figure 6 – Lifetime consumption of element with maximum damage

## CONCLUSION AND OUTLOOK

The simulation of heat treatment of a die made of hot work tool steel used for aluminum extrusion was presented. The resulting phase distribution within the die determines the material properties utilized in the subsequent simulation of cyclic die loads. Applying unsteady local thermal and mechanical loadings yield damage of the die. This damage and finally the number of cycles-to-failure of the tool can be predicted by the used time incremental lifetime rule. The location of maximum damage agrees well with the position of cracks observed in withdrawn dies provided by the extrusion company. The determination of material parameter used in the life time rule is in progress for other steel grades. Comparing the predicted life times using different steel grades may eventually help the customer to select the optimal material for its process.

As the process conditions during the extrusion cycles are not exactly known in a next step Gleeble™ experiments using defined thermal and mechanical loads will be performed to obtain a thorough verification of the lifetime prediction model.

Currently the heat treatment simulation is done using DEFORM™ HT, whilst the lifetime prediction rule is implemented as an user subroutine in Abaqus™. In future it is planned to perform all simulations in DEFORM™ HT.

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