FEM MODEL OF CONTINUOUS EXTRUSION OF TITANIUM IN DEFORM SOFTWARE

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Abstract
Continuous extrusion of metals using Conform™ machine [1] is a well-known process which has been used in industry for several decades as a technique for extrusion of soft metals (Al, Cu) and their alloys. New developments in continuous extrusion of metals include its use for high-strength materials and a utilization of its beneficial side effect, which is the microstructure refinement.

This work describes 3D FEM modelling of continuous extrusion of high-strength materials (titanium) using the finite element method software DEFORM-3D [2]. The model traces temperature and strain fields which are then compared to experimental data obtained from continuous extrusion of titanium stock. The temperature of the wheel, the temperature of the titanium feedstock and the circumferential speed of the wheel have substantial impact on the entire forming process. The goal is to find adequate boundary conditions to make the mathematical model fit the real-world process as much as possible and to allow its optimization.

Keywords finite element method, continuous extrusion, titanium, SPD, Conform™, Deform

1. INTRODUCTION
Continuous extrusion of titanium using the Conform™ process poses new requirements for the entire technology in contrast to the processing of standard materials (aluminium and copper alloys). The die materials are required to sustain multiple times higher mechanical stress at higher temperatures. Titanium feedstock is driven into the wheel groove at the angular speed of the wheel of \( \omega = 0.1 \text{ rad} \cdot \text{s}^{-1} \) and is carried by it for several seconds. Once it reaches the die chamber and hits the abutment, it undergoes shear deformation. Intensive heat transfer takes place between the titanium workpiece and the wheel (Fig. ).

In this study, the continuous extrusion of titanium was simulated using the FEM software DEFORM-3D. The model was implemented as a coupled heat-deformation problem. The important goal was to accurately measure real-world data and incorporate them into the FEM model. The results provide theoretical background for further development of the FEM model and for subsequent optimization of the forming process.
2. SIMULATION MODELS AND MEASUREMENT

Fig. 1 CONFORM simulation model

2.1. Heat Transfer Coefficient Between Titanium Feedstock and Wheel

The feedstock is induction heated prior to entering the equipment. It is then driven into the wheel groove and carried into the die chamber over a certain amount of time. It is clear that for the temperature field to be mapped, the heat transfer coefficient between the workpiece and the wheel must be known. An experiment was performed, where feedstock at 700°C was driven into the cold wheel groove and the decline in its temperature with time was measured. The measured data were compared with simulations for multiple heat transfer coefficient values. Fig. 1 shows the comparison between measured and computed curves. The next computation runs were performed with the value of 1000 W/m2K.

Fig. 1 Measured and computed temperature decreases
2.2. Average Temperature of the Wheel

The computation times can be reduced by using constant wheel temperature. As a result, the temperature field within the wheel need not be computed. The temperature within the groove exhibits a regular pattern given by the heat supply from the feedstock and by cooling while the groove is empty for the rest of the revolution. If the constant temperature is set equal to the average temperature of the groove surface, the heat balance can be achieved despite the periodic temperature changes. The CONFORM equipment records temperature at a point 12 mm below the wheel groove. By comparing the measured and computed temperature values, it is possible to find the surface temperature of the groove.

![Fig. 2 Measured and computed temperature at 12 mm depth beneath the wheel groove](image)

Fig. 2 shows the surface temperature of the wheel groove. The average temperature at the steady state is 143.7 °C. This temperature was used as the constant wheel temperature in the model.

2.3. Friction Coefficient Between Titanium and Chamber Die

The coefficient of friction between the workpiece and the chamber die was determined by tribometric measurement. At the temperature of $T = 350^\circ$C, the value of $\mu_f = 0.58$ was found. In order to validate the value, simulations were run with friction coefficients of $\mu_f = 0.2$ and $\mu_f = 0.7$ (Fig. 4 and Fig. 5). By comparing the simulated velocity field and the appearance of the workpiece section in the die chamber (Fig. 6), the friction coefficient value for further computation was found: $\mu_f = 0.6$. 

![computed temp. in 12mm depth](image)
![measured temp.1 in 12mm depth](image)
![measured temp.2 in 12mm depth](image)
![computed surface temperature](image)
2.4. Final FEM Model

The model of the process is shown in Fig. 6. Thanks to its plane symmetry, only one half of the equipment and feedstock were used for computation. The resulting strain-temperature field varying in time was analysed mathematically. At each iteration step, strain was computed, which was corrected with respect to temperature, until both strain and temperature fields changed.

In the deformation zone, titanium was considered to be plastic, whereas the other parts of the model were deemed rigid. The friction between the wheel and titanium plays a significant role in the mathematical model. Shear and Coulomb types of friction were tested in the model. The best results were achieved using Coulomb friction with \( \mu_f = 0.1 \) and a constant value with the compression separation criterion. In other cases considered, the contact between the titanium feedstock and the wheel was insufficient.

The temperature fields have only been examined within the titanium feedstock. The temperature of the wheel was set to a constant value 143.7°C (see section 2.2). The heat transfer coefficient between the titanium feedstock and the wheel was \( \alpha = 1000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \). The impact of the environment was neglected due to the rate of temperature changes.

About 80 000 elements were created in the titanium feedstock. The chamber die and its surroundings were fine meshed (Fig. 7).
3. SIMULATION RESULTS

The strain distribution within the titanium feedstock exiting the chamber die is uniform throughout, with equal values both on the section plane and on the surface (Fig. 8). The temperature field (Fig. 9) shows that heat is generated during forming. The strain rate distribution (Fig. 10) clearly shows that shear deformation of titanium takes place in the chamber die. The velocity field (Fig. 11) reveals that the velocity changes in the chamber die. It decreases locally due to an increase in the cross section area.
Fig. 8. Effective strain field within the workpiece

Fig. 9. Temperature field within the workpiece

Fig. 10. Effective strain rate field within the workpiece

Fig. 11. Total velocity field within the workpiece

Tab. 1 lists the corresponding calculated entry and exit temperatures of the titanium feedstock. It is evident that the exit temperature is not very sensitive to the entry temperature. Experimental data for the entry temperature of $T_{in} = 553^°C$ shows the exit temperature of $T_{out} = 450^°C$.

<table>
<thead>
<tr>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>510</td>
</tr>
<tr>
<td>450</td>
<td>494,5</td>
</tr>
<tr>
<td>350</td>
<td>486,5</td>
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4. CONCLUSIONS

The main goal of this study was to describe continuous extrusion of titanium by means of a mathematical model. The model was constructed in the FEM software DEFORM-3D. The outcome of the simulations is in good agreement with experimental results. The chamber die of the Conform™ machine was adapted for titanium forming.
The FEM model describes the forming process in the CONFORM device accurately. The model fits the measurement data and can be used for optimizing the existing technology and for estimating the process behaviour under non-standard conditions or for exploring the forming process in other materials. Further efforts will be take two directions. The first one is finding the optimum conditions for the process, particularly in relation to temperature and finding the dependence of grain size on the number of passes. The other is to obtain more test data, make the measurement in the actual CONFORM process more accurate and add the data to the FEM model to obtain better results.

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LITERATURE

[3] www.bwe.co.uk