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Model Predictive Control of the Punch Speed for Damage Reduction in Isothermal Hot Forming

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Abstract. Isothermal forging processes are typically used for near-net shaping of high-performance components such as turbine discs and blades. Recent developments have introduced isothermally forged titanium aluminides into commercial jet engines. Titanium aluminides are lightweight intermetallic compounds with excellent creep properties but very limited ductility. Their low workability requires isothermal forging at slow strain rates, which is typically kept constant in the process. This work explores the possibility of controlling the strain rate during the process using model predictive control, so that the process time is reduced while the microstructure transformation and the amount of damage introduced into the workpiece are controlled. The results of isothermal compression with friction show that both an acceleration of the process and a reduction of damage are possible using the suggested control strategy.

Introduction

In isothermal forging (IF), the dies and workpiece are held at the same elevated temperatures. The major benefits of IF are that near net-shape forgings are possible, which entail lower scrap rates and higher material yield. Also, the forging load is lower than in conventional forgings. However, IF requires expensive dies, intricate heating systems and a protective atmosphere for the dies. In addition, IF is a slow process with relatively low productivity. The ram speed is kept low enough to avoid material damage, but is typically not used as control variable. A controlled IF process would be desirable especially for expensive materials which allow for very low strain rates, to ensure faster processing with reproducible part quality.

Titanium aluminides (TiAl) of the second and third generation have been introduced recently as forged blades into civil aircraft in two- or three-shaft engines. The use of TiAl alloys with a density of approx. 3.9 g / cm^3 pursues the goal of replacing the heavy nickel-based superalloys currently used in the high-temperature range, thus achieving a drastic weight reduction. Forged blades are generally considered superior to cast blades [1]. Especially for highly loaded turbine components with very high rotational speeds such as the 'geared turbofan' [2], the necessary properties can only be achieved via a complex process chain, which includes isothermal die-forging as property-determining process.

TiAl blades are currently forged in two stages in the industry. First, the volume distribution necessary for the finish forging is achieved by lateral extrusion of a cylindrical preform, then the final forging is performed [3]. Due to the highly anisotropic and inhomogeneous deformation of two- and three-phase TiAl alloys, the forming is carried out in a narrow process window. In terms of temperature, the process window is limited towards lower temperatures by the disordering temperature of the phases and the mechanical strength of the dies. Towards higher temperatures, both the two-phase area $\alpha+\beta$ and the thermal load capacity of the dies set a limit. This results in a temperature window of ~100K. Since the microstructure development depends strongly on the temperature, all forming processes are carried out almost isothermally. For the common alloys of the third generation, dies are heated to temperatures of ~1200°C and the billets to temperatures between 1200 and 1350°C. However, the high process temperatures are not sufficient to shape the material at higher strain rates [4, 5]. As forging tool material, a particle-reinforced molybdenum-hafnium-carbon alloy (MHC) is typically used.

Despite the success achieved with isothermal forging, sustainability and cost issues persist. By reducing component costs, forged TiAl components could not only be increasingly used in aircraft turbines, but also in other applications, e.g. for helicopter turbines. Previous work by the authors of this paper put forward a new process design, which is based on pre-assembled die sets [6]. For smaller components, this process design allows for a cost advantage by reducing the idle time of the forging press. Another possibility to increase the rate of produced parts is to accelerate the isothermal forging process and to make the process adaptive to variations in the cast ingot material. So far, isothermal forging processes are conducted with a constant, very slow strain rate. The forging process of a turbine blade currently takes ~4-5 minutes for the production of the preform and for the final-forging each (cf. [7]). TiAl materials initially show a steep increase in yield stress during hot forming, but even at low degrees of deformation they reach a pronounced yield stress maximum and then show a steep yield stress drop. So far, the strong softening is not used to accelerate the forming processes after passing through the maximum load. If the softening in the workpiece could be used to accelerate the forming process, the process times could be significantly reduced. This paper investigates the possibility to accelerate the isothermal forging process by model predictive control (MPC) of the ram speed profile. An upsetting problem with friction is considered to introduce the basic method and study the feasibility of MPC of the isothermal forging process.

Materials and Methods

Material preparation. The material used in this study is a titanium aluminide alloy commercially known as TNB-V5 with a nominal composition Ti–45Al–5Nb–0.2B–0.2C (at.%). Isothermal compression tests were performed at temperatures of 1150-1250°C and at strain rates of 0.001–0.1s^{-1} using a deformation dilatometer. Gas-atomized powder with an average particle size of about 45 µm was consolidated by means of the field-assisted sintering technique (FAST), also known as spark plasma sintering (SPS), using an HP D10-SD machine (FCT Systeme GmbH, Germany). The sintering process was performed using graphite tools with a diameter of 40 mm. The graphite tool unit was filled with the powder. For technological reasons, a graphite film was placed between the powder and the die and punches. The sintering process was conducted in vacuum at a sintering temperature of 1250 °C for 4 minutes and under a compaction pressure of 35 MPa. Samples with dimensions Ø40 × 15 mm were produced. The deformation samples used in the compression tests (Ø5 × 8 mm) were cut from the SPSed specimens using electrical discharge machining.

Compression testing. Compression tests were carried out in vacuum of 10^{-4} mbar. Specimens were heated to testing temperature with a rate of 10 K/s, soaked for 5 min, and then upset under constant strain rate conditions to a strain of 0.9 (cf. Fig. 1).

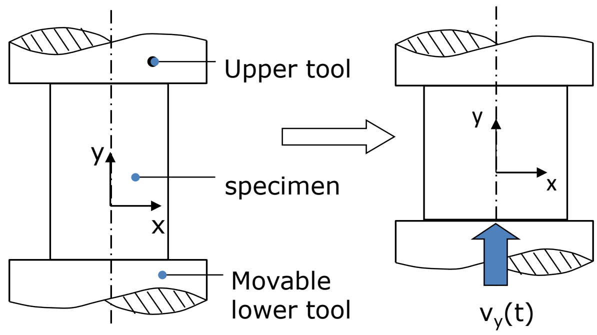

Fig. 1: Illustration of the compression test. $v_y(t)$ denotes the ram speed.

Each specimen was quenched immediately after upsetting. To determine the effect of forming on the microstructure and damage evolution, the compression samples were sectioned axially and prepared by means of standard metallographic techniques. The sample surfaces were treated by vibrational polishing. The sections were also analyzed using scanning electron microscopy.

Process model. A finite element process model was set up in ABAQUS, in which a cylindrical specimen is axially compressed with friction, in accordance with the dilatometer upsetting tests. The simulation is performed as axisymmetric model. The initial mesh is rectangular and has 260 elements, i.e. 13 by 20 in x- and y-direction. Axial symmetry and mirror symmetry are used to reduce the computational time. The initial specimen temperature is prescribed homogeneously inside the specimen according to the experimental conditions and evolves due to dissipation inside the workpiece and heat transfer. The material behavior is elastic-viscoplastic with a flow stress model and damage model as discussed below. The punch speed is controlled using the Python scripting by coupling ABAQUS to MATLAB.

Flow stress and microstructure model. The constitutive equations relating the flow stress with temperature, strain rate and strain are calibrated from the data of the hot compression tests. Based on the experimental results, a phenomenological flow stress model for hot deformation of the present alloy was established. The empirical equation proposed by Cingara & McQueen [8] was used for the flow curve up to the peak (Eq. 2), where C is a constant of the material which is weakly dependent on temperature and strain rate and determines the curvature of the flow curve up to the peak. The effects of strain rate and temperature on flow stress and microstructure can be integrated into the model using the Zener Hollomon parameter, cf. (Eq. 1), where is the strain rate, Q_w is the apparent activation energy for hot deformation, R is the universal gas constant and T is the deformation temperature. Details of the model are described in recent research of the authors [9]. A JMAK-type recrystallization model is used to describe the conversion of the microstructure from the initial into the worked state, Eq. (3). No distinction between individual phases is made in this work.

Table 1: Model equations for the TNB-V5 alloy.

Zener Hollomon Parameter	$Z = \dot{\varepsilon} \cdot \exp\left(\frac{Q_w}{RT}\right)$ (1)
Strain hardening	$\sigma_{(0,1)}(\varepsilon) = \sigma_p \left[\frac{\varepsilon}{\varepsilon_p} \exp\left(1 - \frac{\varepsilon}{\varepsilon_p}\right)\right]^C$ (2)
Flow stress	$\sigma_Y = \begin{cases} \sigma_0 & \text{if } \varepsilon < \varepsilon_{cr} \\ (1-X)\sigma_0 + X\sigma_1 & \text{if } \varepsilon \geq \varepsilon_{cr} \end{cases}$ (3)
Softening kinetics	$\dot{X} = \frac{kq(1-X)}{\varepsilon_{ss} - \varepsilon_{\mathrm{cr}}} \left(\frac{\varepsilon - \varepsilon_{\mathrm{cr}}}{\varepsilon_{ss} - \varepsilon_{\mathrm{cr}}}\right)^{q-1}, \quad \varepsilon \geq \varepsilon_{cr}$ (4)
Damage	$\dot{D} = D \frac{\dot{\varepsilon}\sqrt{d}}{\mathrm{K_{IC}} f^{\frac{1}{3}}} \left(a\left(\frac{4}{27} - \frac{\mathrm{J_3}^2}{\mathrm{J_2}^3}\right) + b \frac{\mathrm{J_3}}{\mathrm{J_2}^{\frac{3}{2}}} + c \left\| \frac{I_1}{\sqrt{\mathrm{J_2}}} \right\| \right)$ (5)

A model for damage evolution in hot working has been applied in the current study. The model is being developed in the collaborative research project Transregio 188, with steel as primary area of application. The model is based on the evolution equation put forward by Horstmeyer et al. [10], who developed a model based on the fracture toughness, Eq. (5). Coupling to microstructural features such a grain size d is possible through the explicit dependence of the evolution of the damage variable D on d as well as on the volume of potential failure sites, *f*. The dependence on stress state is taken into account via the term in the brackets, which takes into account the stress triaxiality by the ratio of the first invariant of the Cauchy stress tensor, $I_1=\sigma_1+\sigma_2+\sigma_3$ and the square root of the second invariant of the stress deviator, J_2. The other terms contain ratios of the third and second invariant of the stress deviator, J_3 and J_2, which account for the dependence of damage evolution on the Lode angle.

Model parameter identification. The parameters of the flow stress model as well as the damage model were determined by inverse methods. For the calibration of the material model, all available flow curves were used and the optimization problem

$$\begin{cases} F(\boldsymbol{\theta}) = \sum_{T_i}\sum_{\dot{\varepsilon}_j}\sum_{\varepsilon_k}\left(\sigma^{(\exp)}\left(T_i,\dot{\varepsilon}_j,\varepsilon_k\right) - \sigma^{(\mathrm{sim})}\left(T_i,\dot{\varepsilon}_j,\varepsilon_k,\boldsymbol{\theta}\right)\right)^2 \\ \boldsymbol{\theta}^* = \arg\min F(\boldsymbol{\theta}) \end{cases} \tag{6}$$

was solved using the Levenberg-Marquardt algorithm. The parameter identification of the damage model was based on the void fraction obtained from scanning electron microscopic evaluation of the specimens that showed damage. More details on parameter identification are reported in previous work [9].

Optimal control of the punch speed. To obtain a reference trajectory for model predictive control, first an optimal control problem for the punch velocity is solved. The control input of the process is the punch velocity $v_y(t)$, which determines the evolution of the variables responsible for damage evolution according to Eq. (5). With the plastic strain rate and the stress state in the specimen, the damage variable D can be computed everywhere in the specimen. The problem can be stated as follows:

$$\left.\begin{array}{l} \min\limits_{v_y(t)} t_1 \\ \int_0^{t_1} v_y(t)dt = \Delta h = const. \\ \max\limits_{v_y(t)} D(t,\Omega) < D_{cr} \;\; \forall t \in [0;t_1] \\ X(t_1,\Omega) > 0.95 \end{array}\right\} \tag{7}$$

The problem is hence to minimize the process time t_1, which is necessary to form the specimen to a height reduction of Δh, while keeping the damage variable D smaller than a critical value and recrystallization above 95% at the outer radius of the workpiece, given by the domain Ω. This position of the specimen develops the largest circumferential tensile stresses and it is thus sufficient to enforce the control constraint in this region only. In order to simplify the problem, the velocity function is represented in the following way: initially, a constant ram speed is used, which corresponds to a strain rate of 0.01/s. In each control interval, a new constant ram speed $v^*(i)$ is sought by minimization. The parameters defining the profile are set by the optimizer, which is implemented in MATLAB. The simulation results are processed using python scripts in ABAQUS and read into the optimizer.

Model predictive control of the punch speed. To control the punch speed in the deformation process, an MPC problem is solved for the control region. The state of the specimen is given by its current value of X and D. The system state is summarized in the state vector $\boldsymbol{x}$. The total time is split into control intervals. In each interval i, a punch velocity $v(i)$ is sought that minimizes

$$\min J\left(\boldsymbol{x}(n), v(\cdot)\right) = \sum_{k=0}^{N-1} \ell\left(\boldsymbol{x}_{v*}(k), v*(k)\right) \quad (8)$$

where

$$\ell\left(x_v(k), v(k)\right) = \left\|\boldsymbol{x}(k) - \boldsymbol{x}*(k)\right\|^2 + \lambda\left\|v(k) - v*(k)\right\|^2 \quad (9)$$

is a measure of the distance between the system state ($\mathbf{x}^*$) and control (v^*) and the reference state in terms of the Euclidean norm. $\lambda \geq 0$ is a parameter that penalizes the control. The MPC problem is solved in MATLAB and yields the control sequence $v(i)$, i=0..N.

Results and Discussion

The controlled process runs under step-wise variation of the punch velocity. As can be seen in Fig. 2, the required forming pressure is subject to oscillations due to the harsh variations in punch speed. However, the process terminates ~25% earlier than a process performed at constant ram speed.

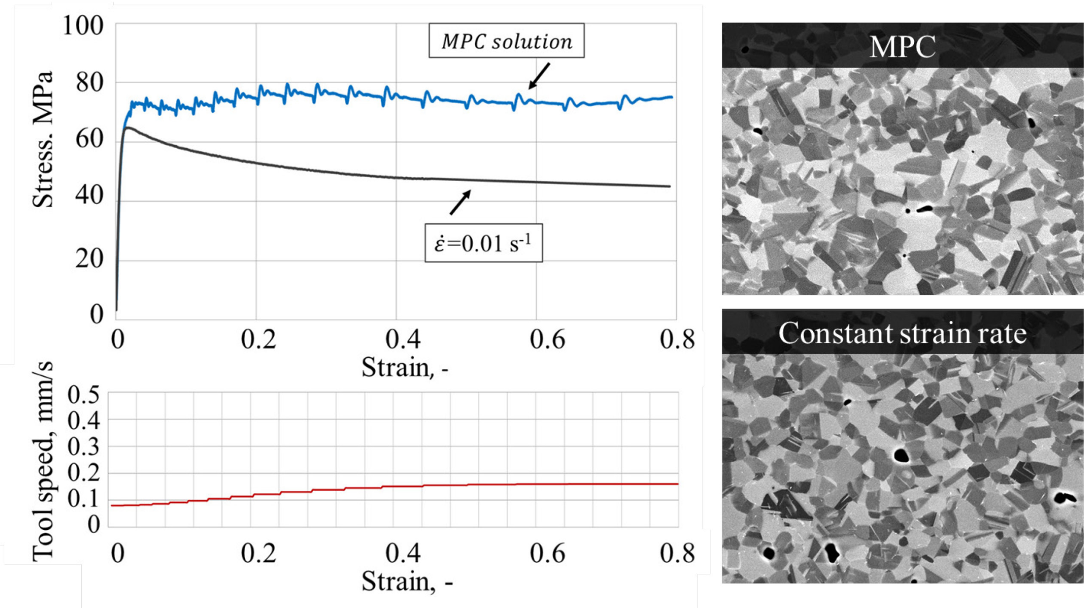

Fig. 2: Results of the compression test with constant and MPC ram speed.

The specimens which were tested at constant strain rate were sectioned and analyzed by SEM to reveal damage in the microstructure. The material produced by SPS was also investigated to analyze possible defects in the initial microstructure. The SEM analysis of the initial state shows a dense, defect-free microstructure consisting of three phases, α_2, β_0 and γ. After compression testing, damage in the form of voids is found in the specimens deformed at constant strain rate at the outer surface of the specimen where barreling and hence tensile stresses are largest.

The second compression test was performed with the velocity profile obtained by MPC. The SEM micrographs of the deformed specimen show a fine-grained, fully transformed microstructure. Damage was reduced compared to the constant strain rate, but not entirely avoided.

The MPC solution reduces the process time and damage compared to the test which is performed at constant strain rate. Obviously the damage model is not accurate enough to predict the onset of damage yet, so that the optimization yields a reference state and an MPC solution which still causes damage. However, compared to the constant strain rate process, which has not been subject to optimization, damage has been reduced. This shows that the optimal control and MPC approach allow for accelerating the process after an initial time in which the specimen has little damage tolerance. Due to barreling, tensile stresses occur towards the end of the compression test, which require further attention, i.e., the improvement of the damage model used in this work. In a real forged component, more complex stress states will arise, and it may become more difficult to accelerate the process, since the material volume with an unfavorable stress state, possibly in combination with a lower temperature, will determine the maximum forming speed.

Summary

In this work, possibilities of speeding up isothermal forging by increasing the punch velocity during cylindrical compression were analyzed. The following conclusions can be drawn:

- Optimal control and MPC solution show that the velocity can be ramped up to almost twice the initial speed, yielding a time saving of 25%.
- Damage at the outer surface where barreling and tensile stresses are largest can be reduced compared to the specimen deformed at constant speed.
- The result shows that a constant strain rate is far from an optimal process time and has a larger probability of inducing damage.
- A more accurate damage model is needed to control the process. Also, the variance in initial microstructure and processing conditions need further attention.

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