Rheinisch-Westfälische Technische Hochschule Aachen
Institut für Bildsame Formgebung

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Hauptseminar

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Durchgeführt in der Abteilung Werkstoffmodellierung
im WS 2013/14

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2 Foundations

2.1 Open-die forging

Open-die forging is the oldest forging process and can be used to create a variety of final forms. It is an incremental, highly flexible metal forming process. The process typically involves two dies of simple geometry moving towards one another and thus forming the work piece. Open-die forging processes can be separated into four categories: upsetting, stretch forging, punching and hollow forging. This work, however, will focus on a stretch forging process.[DB07]

The incremental and flexible nature of open-die forging makes it suitable primarily to the manufacturing of small lot sizes or for the forming of parts that cannot be produced by other processes due to power and force limitations of these processes. Its primary use is in the preparation of cast ingots for further machining. By open-die forging, cavities from the casting process can be rectified and the needed material properties can be reached.[DHK+11]

2.2 Finite element method

The finite element method is a method to model, beside others, continuum mechanics of solid work pieces. The work piece is separated into discrete parts, called elements, which are themselves geometrically defined by nodes. While these nodes hold coordinates as information, the elements hold temperatures, stresses etc. Using material properties such as flow curves, friction, thermal conductivity and emissivity, the system's reaction to thermal and mechanical external loads can be calculated.

Due to the non-linear nature of the resulting equation system, only very simple models can be calculated analytically while most must be approximated numerically. Besides matters of usability, the numerical approach is the most important difference between available software packages. These are spread across a wide spectrum from academic systems with large freedom for the user to easy-to-use specialized tools for certain uses.

3 Model process

This work deals with modeling of an open die forging process with multiple passes. The material used is a common stainless steel. The process parameters are orientated on a plan for forging a block with four passes given by the forging simulation software ForgeBase. Important process parameters, besides the flow curves, are for example the material data, the height reduction during every pass, the movement of the die, meaning the kinematics, the process temperature, etc. The detailed process conditions are discussed in the following chapters.

3.1 Material data

The material used is a 1.4301 (X5CrNiMo18-10) stainless steel. It is an austenitic steel which contains high quantities of the alloying elements chrome and nickel 3.1. Therefore it is non-corrosive, acid- and heat-resistant. The field of application is widely spread and reaches from the automotive industry up to the chemical industry [(DE08].

The chemical composition (in weight-%) of the material is as follows [met14]:

Table 3.1: Chemical composition of 1.4301

C[%]	Cr[%]	Ni[%]	Si[%]	Mn[%]	P[%]	S[%]	N[%]
max 0,07	17,00-19,50	8,00-10,50	max 1,00	max. 2,00	max 0,045	max 0,03	max 0,11

For the input in a simulation model the thermal material data is crucial, containing are the temperature depending thermal conductivity, the spec. heat capacity and the Young´s modul, see Figure 3.1, 3.2, 3.3.

It is necessary that the data describes the whole temperature range of the process. Further parameters are set constant and are pictured in 3.2.

Table 3.2: Constant process parameters (reference temperature 20°C)

Poison	0,3	-
Thermal expansion	0,000012	[1/K]
Emissivity	0,7	-
Heat transfer coeff.	4,5	[W/(m²K)]
Friction coeff.	0,4	-
Dissipation	0,9	%

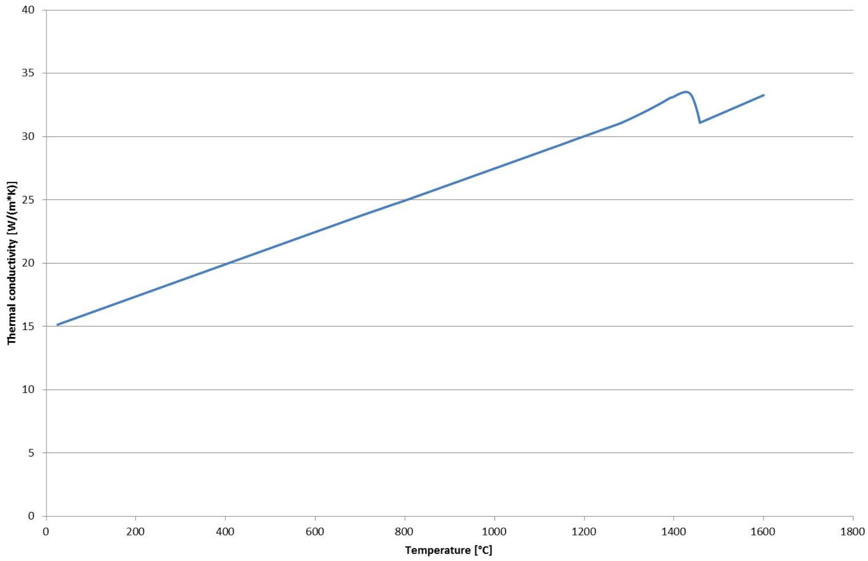

Figure 3.1: Thermal conductivity of 1.4301

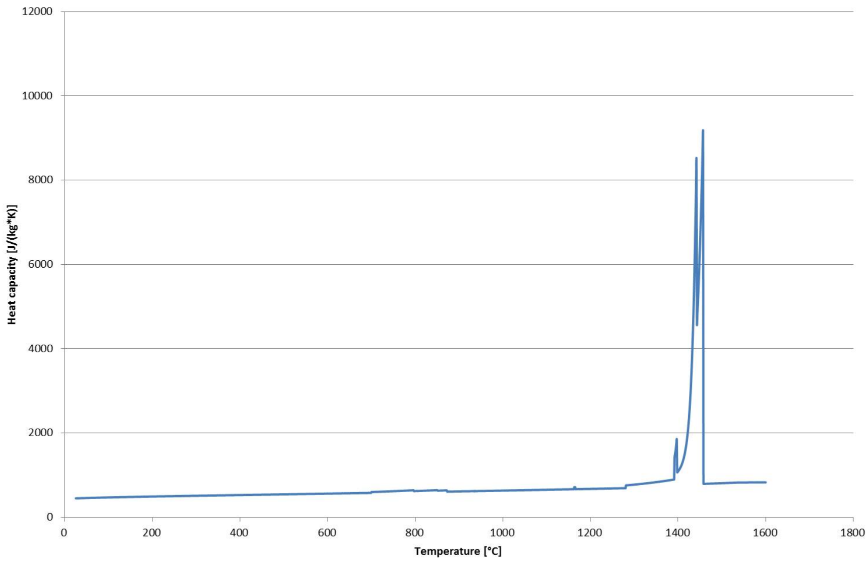

Figure 3.2: Heat capacity of 1.4301

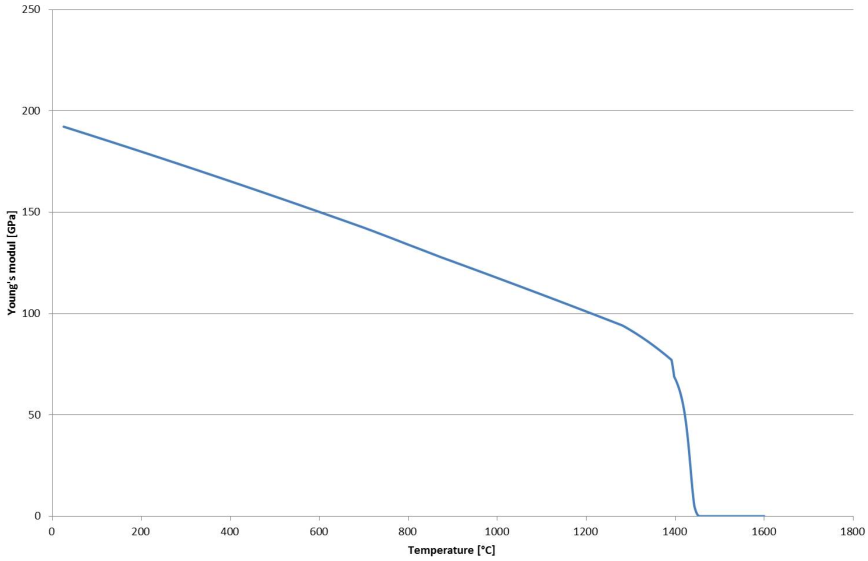

Figure 3.3: Young's modul of 1.4301

3.2 Forging plan (ForgeBase)

The settings of the forging simulation are based on the calculation of the forging software ForgeBase 3.3. The simulations are done for a four passes process on a block (workpiece - WP) with the dimensions of 150mm in height as well as in width and 600mm in length. However, only 400mm of the length are forged. The rest is provided for the manipulator to hold and move the WP. The WP is set as a plastic solid and is meshed with a brick mesh with 12544 elements. The upper and lower dies are set as rigid object. The manipulator is set up as a spring with a stiffness of 175 N/mm and the maximum clamping force of 222,4 kN. For detailed dimensions of the upper and lower die, as of the manipulator see **??**.

The passes in the simulation vary in height reduction and bite ratio. Between the passes the WP is rotated in positive and negative direction with 90° rotation angle. There are two models of movement. On the one hand the bottom die is fixed, though the top die moves with a speed of 80mm/s (Simufact). On the other hand the top and the bottom die move with a speed of 40mm/s (DEFORM; PEP/LARSTRAN).

Moreover, the heat treatment before and during the process is of great importance. Before the first pass starts, the WP gets heated up to 1200°C for 2 hours. It is vital, that the WP does have a homogeneous distribution. During the forging passes, heat is

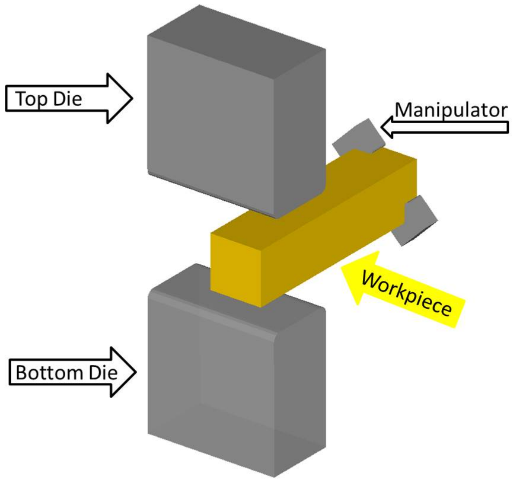

Figure 3.4: Illustration of the process setup from DEFORM

Table 3.3: Forging plan from ForgeBase

Pass Nr.	Reduction [mm]	Height 1 [mm]	Width 1 [mm]	Height 2 [mm]	Width 2 [mm]	Rotation [°]	Bite width [mm]
0	0	150	150	150	150	0	0
1	28	122	162	122	162	0	105
2	30	132	132	132	132	90	85
3	25	107	143	107	143	-90	92
4	27	116	116	116	116	90	75

getting lost by the effects of emission and the heat transfers to the dies. Because of that, a second heat is necessary between the second and the third pass. The WP is heated up again to 1200°C within 1 hour. After the last pass the WP cools down upon air to room temperature.

4 Previous work

The described process has previously been investigated using Simufact.forming from simufact engineering gmbh. *Zusammenfassung Ergebnisse Yuwei*

5 Material modeling

This chapter deals with the concept of material modeling based on semi-empirical equations. At first there will be a short overview of the mechanisms of recovery and recrystallization and after that a review of common models describing the evolution of microstructure during hot forming and a way to integrate them into common FEM-software.

5.1 Recovery and recrystallization

The flow stress is highly dependent on microstructural softening and hardening mechanism during forming. In addition, these mechanisms are influenced by the temperature, strain rate and strain.

During hot forming, defects are generated within the crystal lattice. According to Gottstein [Got07] the defects can be distinguished respecting their dimensions. Especially one dimensional defects called dislocations, are the carriers of plastic deformation and therefore crucial for hot working. During hot deformation the density of dislocations rises and hence the resistance of the material to deformation rises too. At a certain point the stored energy in the material is high enough to induce dynamic recovery (DRV) or dynamic recrystallization (DRX). These mechanisms cause softening of the material.

DRV leads to equilibrium between hardening and softening. However DRX leads to a softened material. The effects of DRV and DRX can be well seen in the warm flow curve behavior, see 5.1.

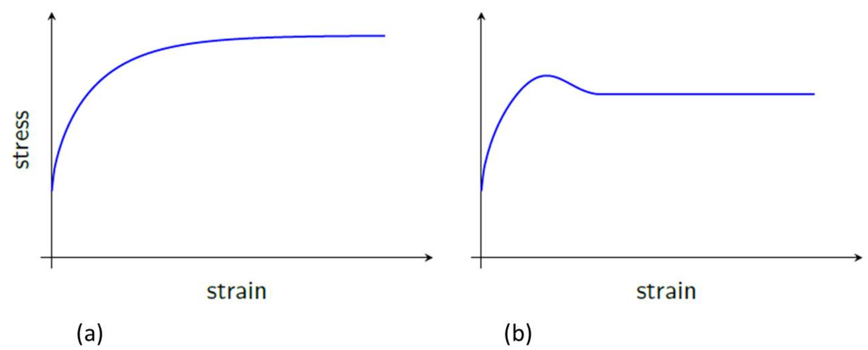

Figure 5.1: Warm flow curves when recovery (a) or recrystallization (b) is predominant [Loh10]

The softening effect of DRV and therefore the reduced level of stress with increasing strain is based on the rearrangement and annihilation of dislocations [Gottstein]. During DRX new grains are built and grow at spots with low specific energy. Both effects lead to a totally refined microstructure.

After hot forming, remaining dislocations can still store a great amount of energy. This energy can be enough to cause static recovery (SRV) or static recrystallization (SRX). These processes take place during heat treatment after warm forming. The softening effects are the same as in DRV or DRX. The driving force drops during SRV and SRX and only when there is enough energy stored, SRV and SRX lead to a fully refined microstructure.

After or parallel to SRV and SRX, grain growth (GG) can take place. The driving force is the reduction of stored energy. During grain growth the nucleated grains grow by using up the old grain structure.

5.2 gives a short summary about the recovery, recrystallization and grain growth mechanisms during warm forming.

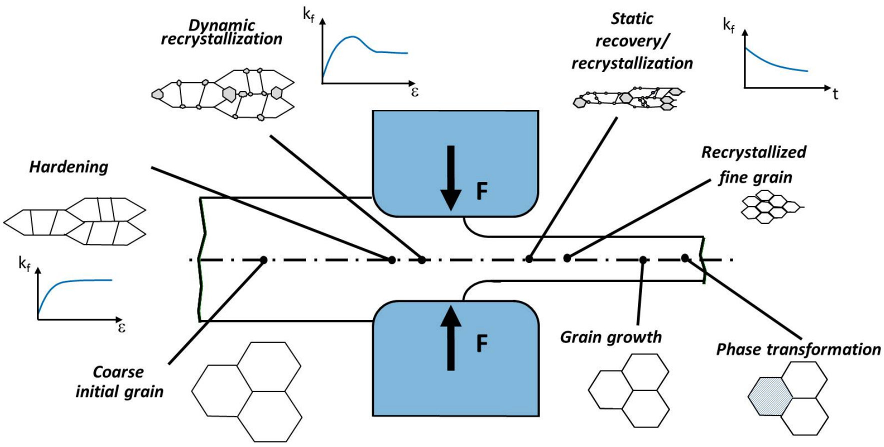

Figure 5.2: Recovery and recrystallization mechanisms during warm forming

The flow curves 5.3 are essential for the determination of the recrystallization kinetics and the fraction of recrystallized material. Therefore it is the basis for the creation of a microstructure model. At the IBF, flow curves are determined by isothermal compression tests at cylindrical specimens with an eight to diameter ratio of 1,5. For the 1.4301 tests have been carried out at temperatures ranging from $900 - 1250°C$ and strain rates of $0,05 - 100s^{-1}$ 5.3.

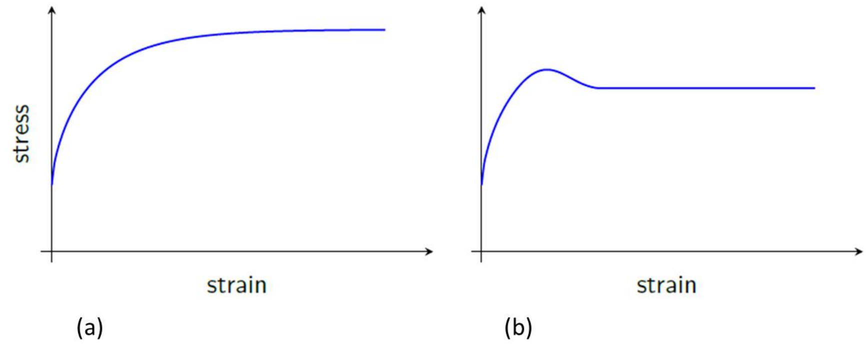

Figure 5.3: Determined flow curves of 1.4301 (temperature range: 900-1250°C)

For the semi empirical material model given by Deghan Manshadi [?] the special strain values are of great importance. These strain states are seen in 5.4. There is the peak strain ε_p, the strain of steady state ε_{ss}, and not seen in 5.4 the critical strain ε_c which is located at 60% of the peak strain. The stresses at these characteristic points are also of importance.

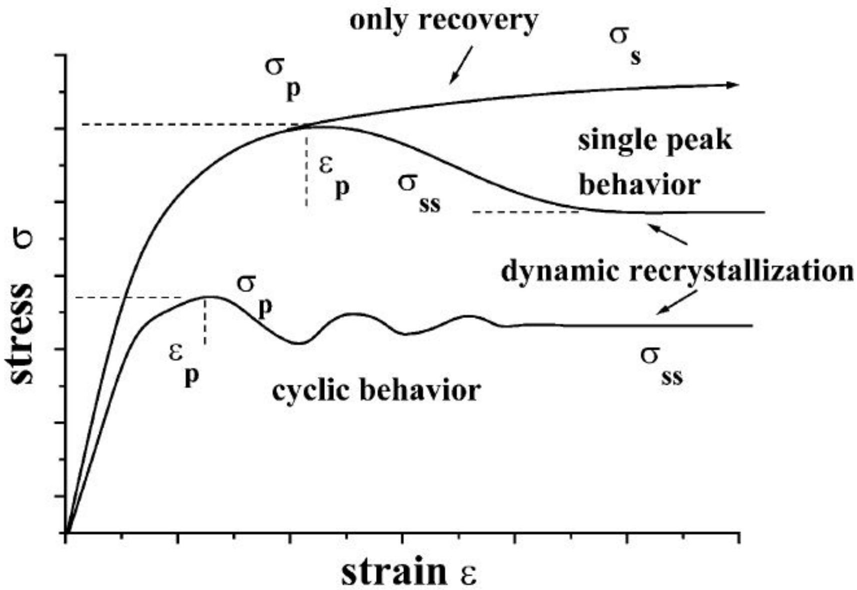

Figure 5.4: Warm flow curves with characteristic stress and strain points [MJJ03]

They can also be calculated by:

$$\varepsilon_p = 3,6 \cdot 10^{-3} d_0^0 \cdot Z^{0,15} \tag{5.1}$$

$$\varepsilon_c = 0,6 \cdot \varepsilon_p \tag{5.2}$$

$$\varepsilon_{ss} = 0,00598 \cdot d_0^0 \cdot Z^{0,1536} \tag{5.3}$$

5.2 Semi emprirical material models

For the prediction of microstructural evolution semi-empirical models are used for many years. Lohmar and Karhausen gave a detailed overlook over the common models used in warm forming [Loh10][F.94].

The JMAK-equation is a way to calculate the fraction of recrystallization X 5.5 for the different recrystallization mechanisms DRX and SRX. In this work the equation for the calculation of DRX and SRX published by Dehgan Manshadi is used [ARP08].

$$X = 1 - exp\left(log\,(1 - 0,95) \cdot \left(\frac{\varepsilon_{eff} - \varepsilon_c}{\varepsilon_x}\right)^{1,3}\right) \tag{5.4}$$

$$X = 1 - exp\left(log\,(1 - 0,5) \cdot \left(\frac{t_{SRX}}{t_{50}}\right)^{1,1}\right) \tag{5.5}$$

Where t_{50} is the time where 50% recrystallization took place 5.5:

$$t_{50} = 8 \cdot 10^{-9} \varepsilon^{-1,5} \cdot Z^{-0,42} exp\left(\frac{375000}{R \cdot T}\right) \tag{5.6}$$

A lot of these models relate the stress behavior to the strain rate $\dot{\varepsilon}$ and the Temperature T. A popular way to describe this is given by the Zener-Hollomon parameter Z [CH44]:

$$Z = \varepsilon \cdot exp\left(\frac{Q}{R \cdot T}\right) \tag{5.7}$$

These equations lead to the determination of the grain size d_{DRX} and d_{SRX} [ARP08]:

$$d_{DRX} = 5916 \cdot Z^{-0,1748} \tag{5.8}$$

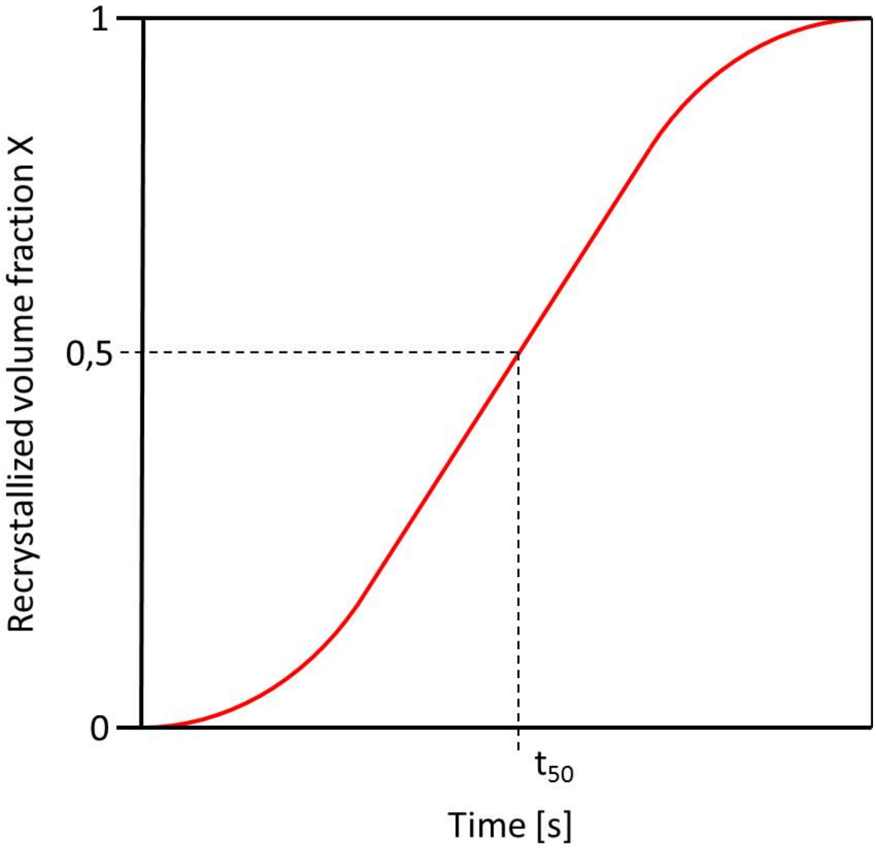

Figure 5.5: Fraction of recrysrallization X

$$d_{SRX} = 4,7 \cdot 10^2 \cdot \varphi_{SRX^{-1}} \cdot 100^{0,3} \cdot Z^{-0,1} \tag{5.9}$$

6 Validation

For the modelling of the described process, different software packages are available. Besides DEFORM3D, both FORGE from Transvalor, Mougins, France, and a combination of PEP (Pre- and Postprocessing Environment for Programmers) developed at IBF and LARSTRAN from LASSO Ingenieurgesellschaft mbH, Leinfelden, Germany have been used to validate the results. The packages differ in their ease of use and freedom in modelling. A comparison of both usability and results will be made here.

6.1 FORGE

FORGE, specifically FORGE3D, from Transvalor is a FEM software package catering primarily to industrial users. This can be seen in the easier to use and rather polished user interface. FORGE, like most packages, is split into a preprocessing tool, an equation system solver, and a postprocessing tool.

As a product for industrial customers, FORGE implements a fairly easy to use concept and various functions for simplifying the definition of die movement and kinematics. It provides predefined so-called Presses which, based on a few values such as initial height, final height, number of blows etc., create a basic kinematic for an open die forging process. While this provides an easy way to get results for simple processes, it makes the setup of specific, more advanced processes rather difficult.

While it is possible to define custom presses and use these to model die kinematics, this function is hardly documented in freely available documents such as FORGE's online help system. This, however, leads to defining kinematics via basic linear and rotational movement operations in cases that do not meet the predefined standard processes. Especially in academic surroundings, where processes vary widely, the combination of undocumented functions to define presses and limited freedom to access and modify the process in-process makes adequate process definition difficult.

Similar to the definition of kinematics and movements is the adaption of the available material data for FORGE. While an extensive material data base is available, import of new material data is not well documented. It is, however, possible to derive the data structure from exported files.

In FORGE, the process has been modelled symetrically with symmetry in the x-y and x-z planes. Apart from this, the model represents the real process in matters of die kinematics and work piece movement. That is, the die only moves in z direction while the work piece moves and rotates underneath it.

6.1.1 Forging Forces

The resulting forging forces acting on the dies are shown in diagrams 6.1 and 6.2 for passes 1 and 2 and passes 3 and 4 respectively. As is expected, the force required for forging rises with each blow. This can be explained by hardening mechanisms due to the introduced strain. The last blow of each pass requiring less force is due to the smaller bite length in the last blow. In general, forging forces between 1.5MN and 2.0MN seem realistic.

The diagram shows for pass 2 that a problem occurred in modelling. The peaks for the 2nd through 5th blow follow each other immediately, displaying a lack of waiting time in between. A closer examination of this will be seen below.

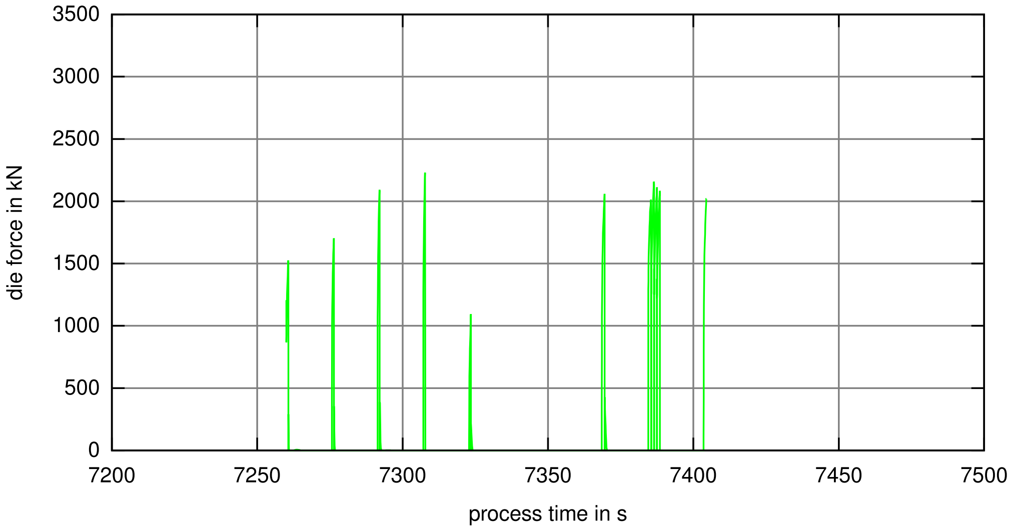

Figure 6.1: Forging forces for passes 1 and 2 as calculated by FORGE3D

6.1.2 Strain

The effective strain in the core of the work piece after pass 4 is shown in diagram 6.3. A minimum value of 1.4 and a maximum value of 2.1 hint to a decent forging of the core.

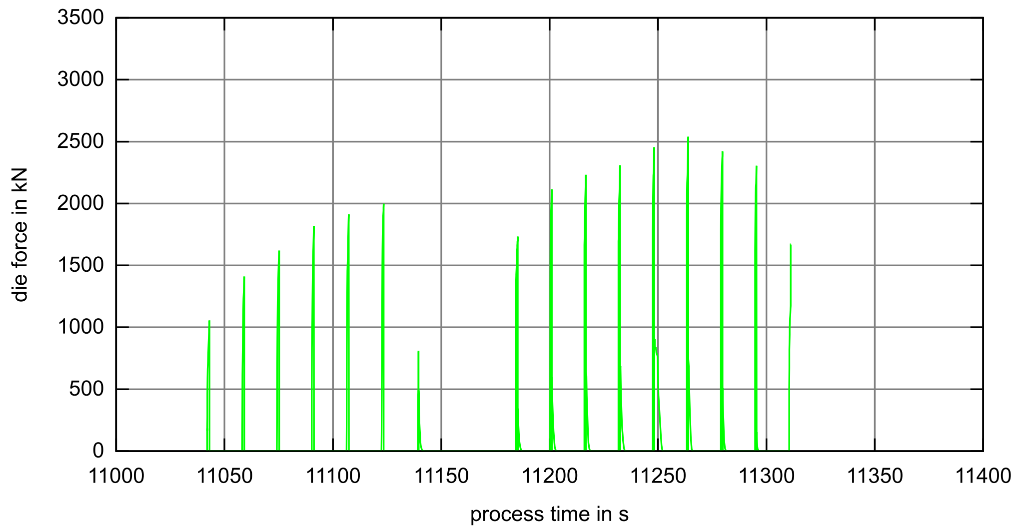

Figure 6.2: Forging forces for passes 3 and 4 as calculated by FORGE3D

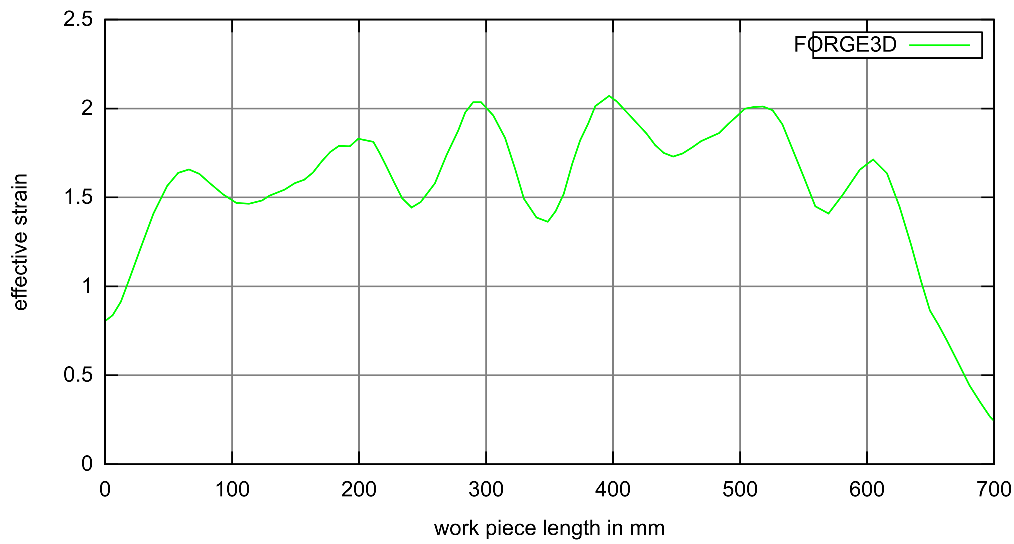

Figure 6.3: Effective strain in the core of the work piece after stroke 4 as calculated by FORGE3D

6.1.3 Temperature

The temperature distribution in the core of the work piece after a cooling period of 120min is shown in diagram 6.4. Here, expectations are met as well by a low temperature at the head of the work piece, a fairly even distribution along its length and a rise in temperature at the end, which has not had any contact with the die.

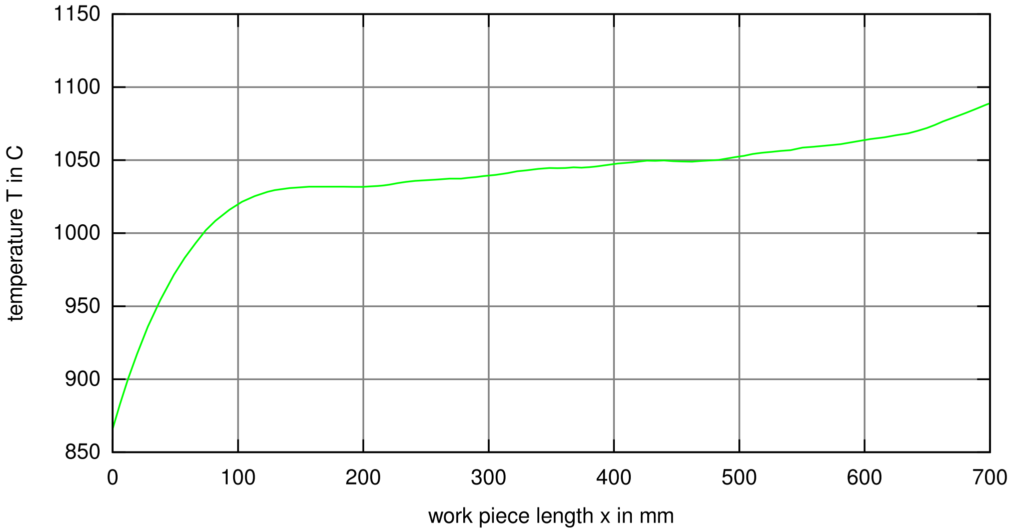

Figure 6.4: Temperature distribution along the core after cooling as calculated by FORGE3D

Diagram 6.5 shows the temperature devolution of a node 100mm from the head of the work piece in its core. All stages of the process can clearly be seen here.

6.2 PEP/LARSTRAN

PEP/LARSTRAN is a combination of one pre- and postprocessing tool (PEP) and one solver (LARSTRAN). Both have been developed in an academic surrounding and accordingly provide more access to process variables during processing. On the other hand, a deeper understanding of FEM is necessary to use the system since values such as time step length and mesh element edge length are not calculated automatically but rather have to be input by the user.

Kinematics control is done via a so-called model program. Here, die movements, changes in die speed and other process variables are defined to happen at a given time step. While other systems provide the concept of manipulators which exert a certain restore

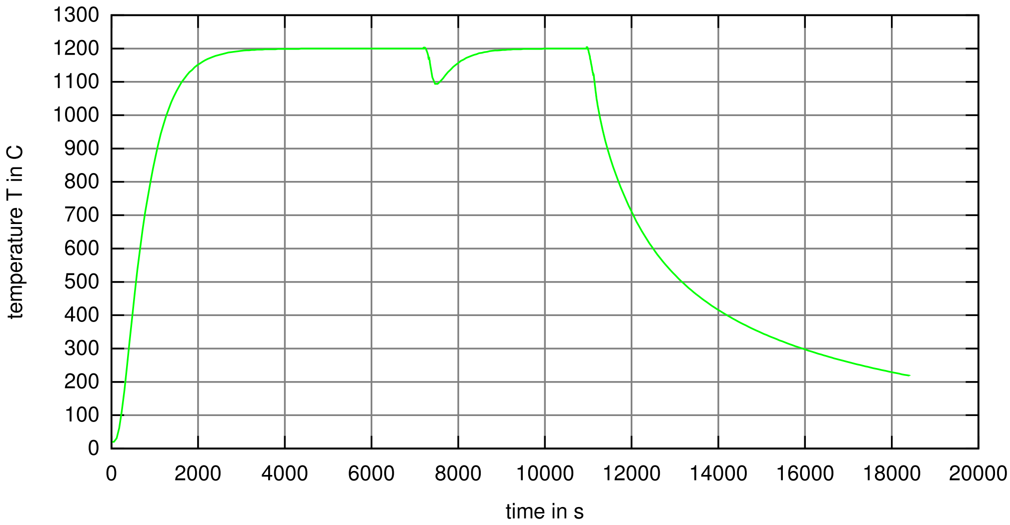

Figure 6.5: Temperature devolution of a point 100mm from the head in the core of the work piece as calculated by FORGE3D

force on the die to prevent unrealistic work piece movement due to singular die contact, PEP/LARSTRAN does not allow for such possibilities. Similar functionality has been achieved by defining a fixing of the work piece based on the number of contact nodes, but certain differences can still arise.

PEP/LARSTRAN die kinematics are based exclusively on the movement of the dies instead of the work piece. Since the concept of model programs does not allow for the definition of die movement according to the current work piece situation, however, it is not possible to even run one forging pass without stopping it and modifying the die movements. Moreover, the systems allows for only one ambient temperature, which means that each heating and cooling process and a combination of two forging passes have to be simulated separately and ambient temperature modified manually.

6.2.1 Forging Forces

6.2.2 Strain

6.2.3 Temperature Distribution

7 Summary

8 Outlook

List of Figures

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