XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON THE FATIGUE LIFE OF HOT WORK TOOL STEEL X38CRMOV5-3 UNDER FORGING PROCESS CONDITIONS

B.-A. BEHRENS, T. HADIFI

Institute of Forming Technology and Machines
Leibniz University Hannover
30823 Garbsen, Germany
e-mail: hadifi@ifum.uni-hannover.de, www.ifum.uni-hannover.de

Key words: Cyclic Plasticity, Thermo-Mechanical Fatigue, Hot Work Tool Steel

Abstract. Hot forging dies experience during service excessive cyclic thermo-mechanical, tribological as well as chemical loads. These loads occur in a repeated manner and may cause premature fatigue failure of the forming tools and thus lead to an interruption of the production process. Die failures due to fatigue crack initiation constitute about 25 % of all failure types. The initiation and propagation of fatigue cracks can mainly be ascribed to high cyclic thermal and mechanical loads exerted on the tool material. Thus the hot work tool steel in service should combine a high red hardness with the ability to withstand heat checking at a high abrasion resistance. One of the most commonly used hot work tool steels for manufacturing high quality tools for hot forming operations like forging and casting is AISI H13 (X38CrMoV5-3), which also provides these properties.

The numerical simulation based on the finite element method (FEM) has so far become an indispensable tool for the design and optimisation of hot forging processes. So far FE based process simulations are limited to obtaining accurate results related to the formability of the workpiece material and the necessary press force. Tool related aspects like the prediction of the tool life quantity and the estimation of abrasive wear is so far limited to cold forming tools. Due to the complex thermo-mechanical phenomena occurring in the interface layer between workpiece and forming tool it was so far not possible to give a reliable estimation on the tool life as current modelling approaches do not capture relevant influences in order to describe forging die fatigue and damage mechanisms in a realistic manner. For the prediction of the maximum cycles until fatigue failure it is still a common approach to resort to strain amplitude based models which neither take into account the transient temperature evolution nor the triaxiality of the local stress state. It is obvious that hot work tool steel materials need a more sophisticated modelling as severe thermo-mechanical loads are prevailing.

In order to make a reliable estimation on the tool life quantity of forging dies it is therefore necessary to use advanced and sophisticated material models.

1 INTRODUCTION

Due to high temperatures and forming forces, which arise in forging processes, dies undergo high thermal and mechanical loads. These loads have a major impact on the fatigue life of the dies and thus can lead to fatigue crack initiation on the surface. Thermo-mechanical fatigue represents, along with abrasive wear, the most frequent cause for forging tool failure [1]. Fatigue cracks arise in areas which are subjected to cyclic deformations caused by excessive mechanical loads. Plastic deformations combined with thermal cycling on the die surface lead to material fatigue and thus to crack initiation.

According to the theory of fracture mechanics, the fatigue crack is followed by a crack propagation which finally leads to a catastrophic failure of the tool. In hot forging industry, this failure type generally appears after less than 20,000 produced parts [10, 2, 5], whereas the frequency of occurrence basically depends on the forming process in use.

The low tool life quantities and the appearance of cracks in the die notches is a clear sign for low cycle fatigue [5, 11]. The crack nucleation process of LCF cracks is preceded by a crack free phase. Beginning from the 1st cycle structural changes occur in the loaded material, which alter the mechanical material properties. This can be ascribed to the changes in the dislocation density and their agglomeration, which lead to creation of slip bands. The protruding slip bands and the imperfection of the surface are the main causes for crack nucleation [12]. The further propagation of this crack constitutes the second phase (stable phase), where the crack grows with each load cycle. This phase is followed by an increasing crack growth rate, which finally leads to a total fracture [4]. The duration of each phase generally depends on the thermo-mechanical service load during forging, tool design as well as on the die material properties.

So far the FEA-based determination of the number of forging cycles until crack initiation as a result of material fatigue cold forging dies has been done for cold forging dies [3, 4]. It can be noted that only few experimental investigations have been carried out under process conditions typical for forging processes on common hot work tool steels [6]. In previous works the thermo-mechanical fatigue behaviour of hot work steels has been considered in a simplified way. Besides Oudin and Rezai-Aria [6, 7] Sjostrom [8] carried out strain-controlled fatigue testes with the hot work steel X38CrMoV5-1, while the specimens were simultaneously loaded thermally and mechanically. Stress controlled fatigue tests on the same steel grade were carried out by Berti and Monti [9] in order to characterise its thermo-mechanical fatigue behaviour. Within the framework of their experimental investigation the specimens were cyclically heated and cooled at a high speed, whereas plastic strains, as they appear in low cycle fatigue, were not considered.

In order understand the fatigue behaviour hot work tool steels the X38CrMoV5-3 was investigated under conditions typical for hot forging. For this cyclic In-Phase thermo-mechanical fatigue tests were carried out to reproduce the severe situation, when form filling is at hand and the hot workpiece material is in full contact with the die’s surface. During this moment the high inner pressure induces tensile stresses in the die cavity and is exposed to drastic temperature rise, which entails a local softening of the die material. The data was then used to fit the parameter values of a general material model which offers the possibility to describe isotropic and kinematic softening/hardening phenomena in dependence of the temperature. Due to the varying temperature in the specimen owing to the induction heating process it was necessary to model the whole fatigue test including the heating-cooling phases and the mechanical cycling. Based on numerical simulation and the adjusted model parameters it is possible to predict cyclic stresses and strains in the material, which may cause a premature fatigue failure. Based on the fitted material model and process simulations quantitative estimations on the tool life quantity of hot forging dies can be given.

2 MATERIAL BEHAVIOUR MODELLING

A fundamental part of a finite element simulation of fatigue phenomena is the accurate mathematical description of the material behaviour under cyclic thermo mechanical loads. In order to model the elasto-plastic deformation behaviour of metallic materials in most cases one resorts to macroscopic or phenomenological material models. Amongst others, one demand to material models is to reproduce the experimentally observed cyclic material behaviour e.g. yielding, cyclic hardening and softening in a correct manner. Classically, deformation behaviour of metallic materials is described by means of an elastoplastic material model based on the assumptions of Hooke for elastic strains and v. Mises respectively Prandtl-Reuss for plastic strains. For an estimation of the life expectancy of mechanical components based on numerical modelling it is crucial to reproduce both, shape and position of the stabilised stress-strain hysteresis curve. To achieve an accurate description of the stress response of cyclically loaded materials it is of paramount importance to resort to material models which are able to capture the evolution of the cyclic stress phenomena, e.g. kinematic and isotropic hardening and softening.

In the past few decades numerous material models have been developed to account for such phenomena, which are also very well reported in literature. Based on the pioneering research works of Armstrong and Frederick, who proposed a nonlinear kinematic hardening rule, Chaboche has introduced a model which is able to model the elasto-viscoplastic deformation behaviour of metals under isothermal conditions [13, 14], which was extended in further works [15, 16]. The extended material model links the isotropic hardening rule to a kinematic evolution law in order to reproduce deformation phenomena like mean stress relaxation and creep [17, 18]. The following chapter will describe this model in more detail.

Viscoplastic material model according to Chaboche

The material model according to Chaboche is, as aforementioned, a phenomenological approach. As soon as a material is exposed to cyclic loading additional variables are needed to fully describe the transient and stationary material response.

$$\sigma = k + R + \underline{\underline{X}} + \sigma_{\mathrm{v}}$$

The variable k stands for the initial yield stress of the material, whereas tensor R accounts for the evolution of the isotropic hardening and softening behaviour during plastic reversal. The second order tensor $\underline{\underline{X}}$ describes the long term behaviour of the material under cyclic elasto-plastic loading. Kinematic hardening or softening can be seen as a motion of the yield surface in the stress space depending on the accumulated plastic strain $p = \int |\,\mathrm{d}\varepsilon_p\,|$. The variable σ_v accounts for viscous effects in the material. It relates the rate of deformation to the stress and effectively to the relaxation and hardening phenomena.

Isotropic hardening variable R

The evolution of the isotropic hardening variable R is directly linked to introduced plastic deformation p, which stabilises at a value Q after a certain number of loading cycles. The mathematical formulation for such behaviour is as follows:

$$R = Q(1 - \exp(-\mathrm{b}\,\varepsilon_p))$$

which can be schematically visualised according to figure 1.

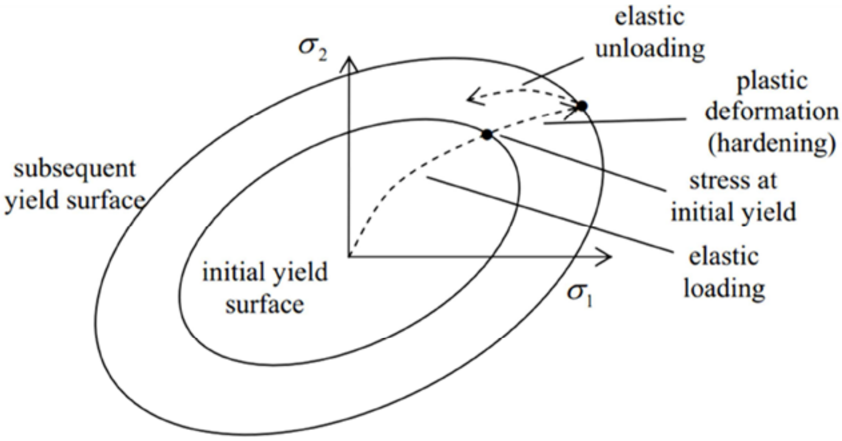

Figure 1: Size change of the yield surface with increasing plastic deformation due to isotropic hardening.

The parameters b and Q are temperature dependent and can be determined from cyclic isothermal compressive/tensile tests. The total value of R can be determined from the difference of the maximum stress at the first cycle and the maximum stress at stabilisation.

<u>Kinematic hardening tensor $\underline{\underline{X}}$</u>

With the help of the kinematic hardening/softening terms in the Chaboche material model it is possible to model the Bauschinger effect, which turns up regularly when metallic materials are exposed to alternating compressive and tensile loads. This phenomenon is related to the evolution of the mean stress with increasing cumulative plastic strain. This behaviour can be illustrated as a translation of the yield surface in the stress space (figure 2)

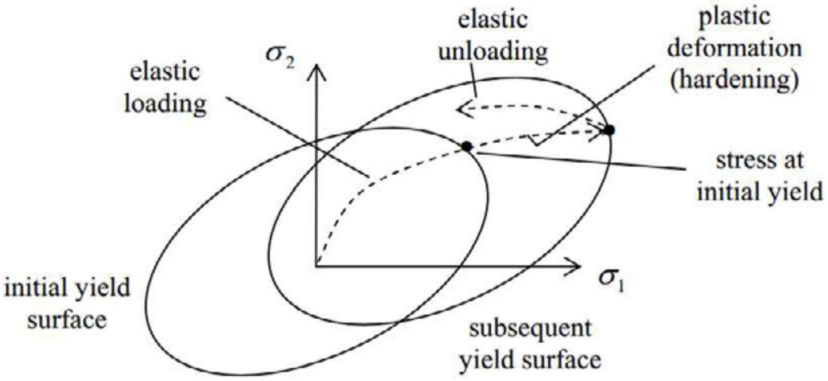

Figure 2: Translation of the yield surface due to kinematic hardening/softening

In most cases metals respond to cyclic loads exceeding the yield limit with a combined kinematic and isotropic hardening/softening behaviour as illustrated in figure 3.

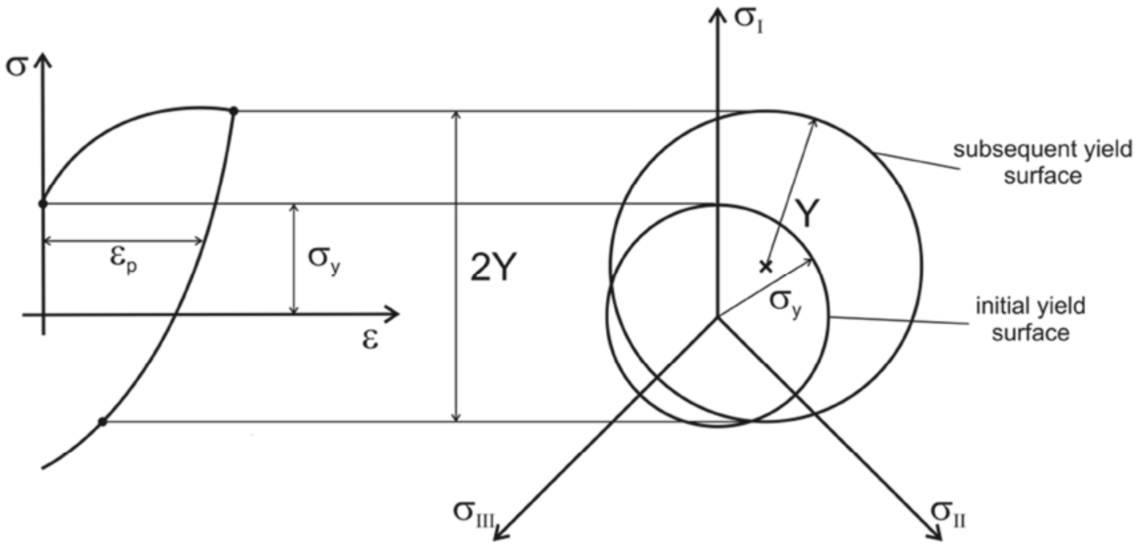

Figure 3: Shrinkage and growth of the yield surface with increasing plastic deformation.

Most commercial multi-purpose FEA systems provide similar material models for numerical simulations. A very essential aspect of using phenomenological material models is determining necessary material specific parameter values. This is primarily done in undertaking experimental investigations in order to characterise the material under analysis based on low cycle fatigue (LCF) and thermo-mechanical fatigue (TMF) tests [19, 20, 21], which have been carried out within the scope of this work.

3 EXPERIMENTAL PROCEDURES

Owing to the high temperatures of up to 1250 degC and the high forces during forming, hot work tool steels are subjected to a combination of thermal and mechanical loads, which constitute their main life limiting aspect. In order to facilitate a realistic estimation on the life expectancy it is necessary to describe the cyclic material behaviour of the tool material under forging conditions. Strain-controlled thermo-mechanical fatigue tests are a very essential means to analyse the cyclic stress response and determine necessary parameter values for both, the constitutive relationship and the damage model. In practice three types of thermo-mechanical fatigue tests exist which are classically used for material characterisation. N the one hand isothermal low cycle fatigue tests are used to investigate the fatigue and material behaviour at constant temperature. In these tests the specimen is heated up to the desired temperature and exposed to a cyclic mechanical load until material failure. On the other hand if varying temperatures are dominating so-called in-phase (IP) and out-of-phase (OP) thermo-mechanical fatigue tests are carried out. Both tests have in common that besides the mechanical load also the temperature is varied in a controlled manner. In IP-TMF tests the peak stress occurs at the same time when the temperature is on its maximum, whereas in OP-TMF tests the specimen experiences the highest tensile load at the moment when the temperature is minimal [22]. An illustration of the stress-strain behaviour during both types of loading is given in figure 4.

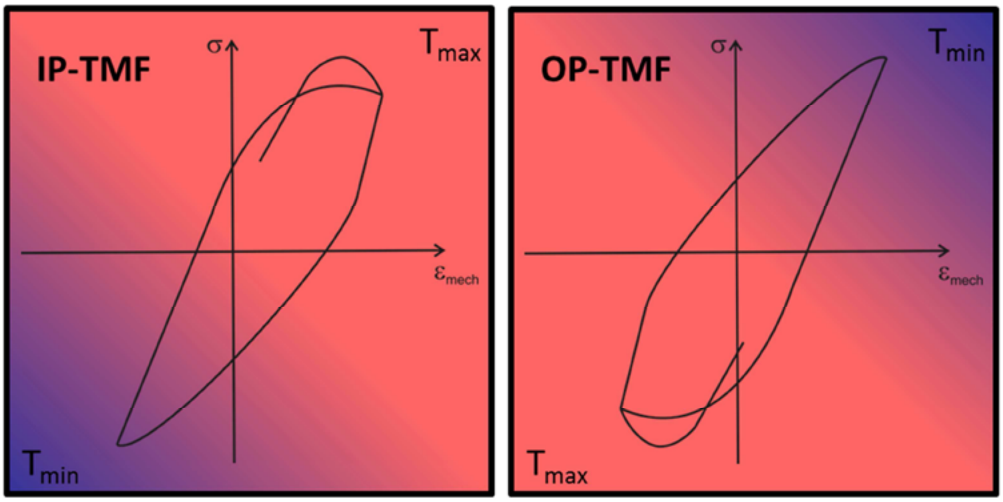

Figure 4: Load and temperature phasing in IP-TMF (left) and OP-TMF (right)

During one process cycle surfaces of forging dies typically undergo a combination of the highest thermal and mechanical load simultaneously, when full form filling is obtained. After unloading and removal of the workpiece, the mechanical and thermal loads reach their minimum during the lubrication and cooling stage. This situation can be easily reproduced with IP-TMF tests. For this strain-controlled in-phase thermo-mechanical fatigue tests were carried out for the conventional hot work tool steel X38CrMoV5-3 (54 HRC) on a servo-hydraulic testing machine with integrated induction heating and controlled specimen cooling facility (figure 5).

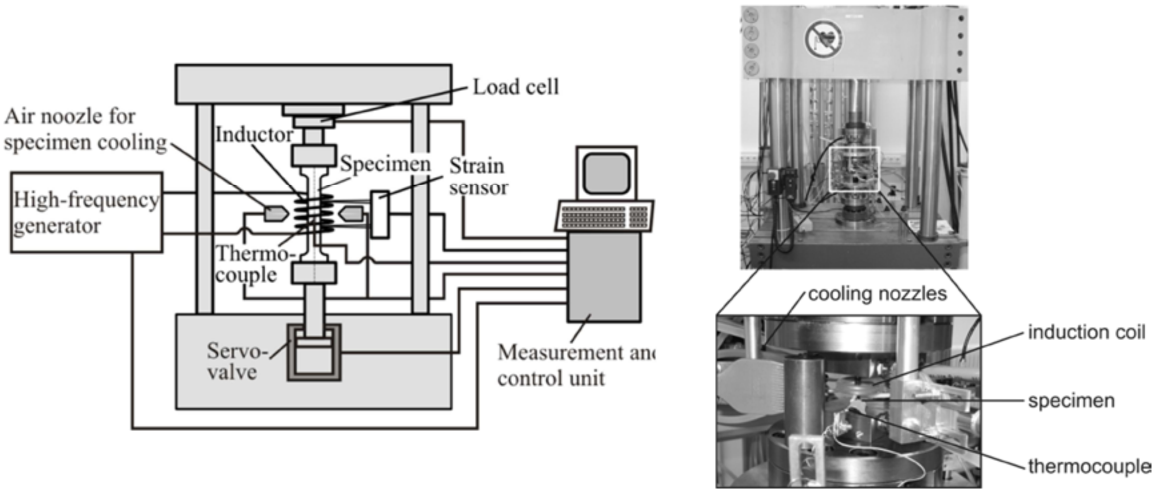

Figure 5: left: schematic drawing of test rig for TMF tests, right: real test rig used for TMF tests

Typically, the surface temperature of hot forging dies ranges within one forming cycle in critical tool regions are found to be between 200°C and 600°C [23], which has also been used as the temperature range for the cyclic tests. A process time of t = 11 s was chosen, where the specimen is heated up with a rate of 300 K/s. The mechanical load is applied simultaneously to the thermal load, such that they have their maxima at the same time. After loading, the specimen is cooled down to 200°C and unloaded at the same time. The strain and temperature course for one cycle can be seen in figure 6, left. These cyclic fatigue tests were carried out with the strain amplitudes of 0.35%, 0.4%, 0.45%, 0.5% and 0.55% in order to obtain the strain-number curve for the hot work tool steel under analysis under conditions typical for forging. Figure 6, right shows the stress strain hysteresis after 10, 100 and 1000 cycles.

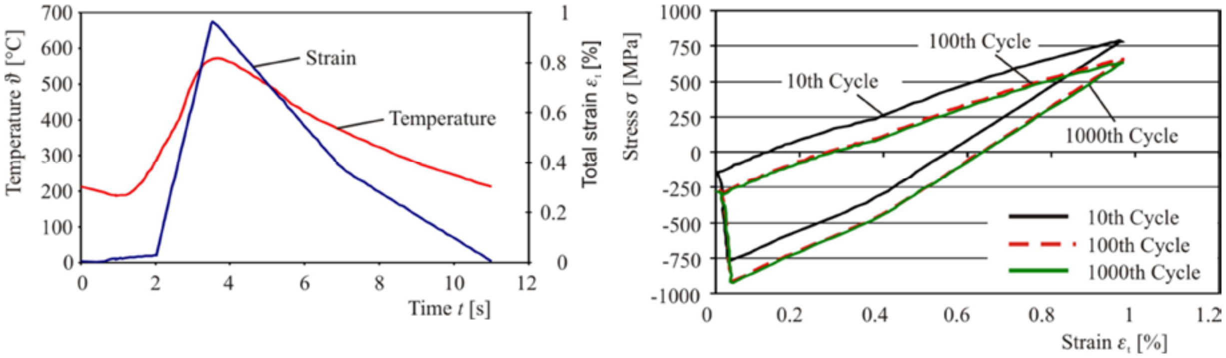

Figure 6: left: strain and temperature profile for one cycle from the service-like in-phase TMF tests, right: stress-strain hysteresis curves after 10, 100, 1000 cycles

It is obvious that transient effects take place in the first 100 loading cycles which also can be identified from the evolution of the stress amplitude over loading cycles (figure 7).

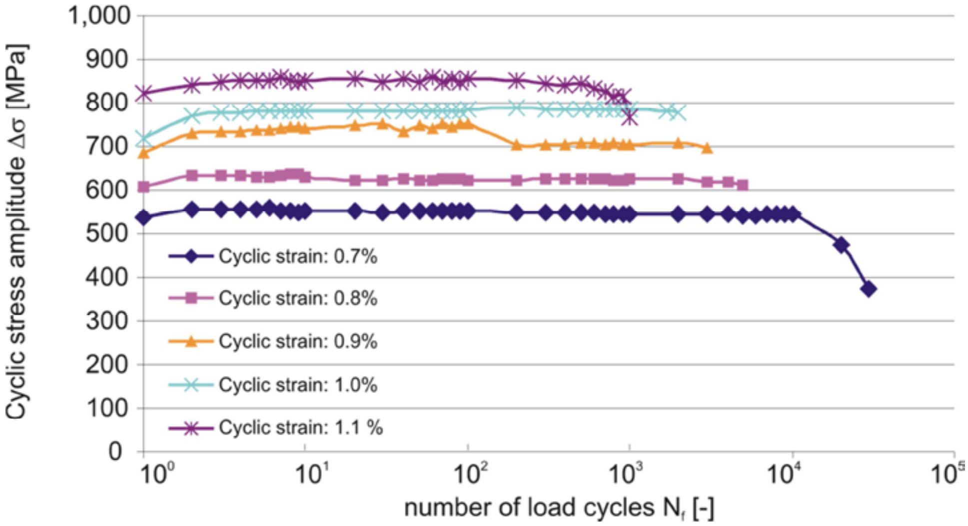

Figure 7: Cyclic stress amplitude from IP-TMF tests for different strain amplitudes

For all strain amplitudes a clear isotropic hardening after the first few cycles can be identified, which is followed by a stationary state until fatigue fracture. This behaviour has been numerically reproduced with numerical simulation

4 SIMULATION

The TMF tests carried within the scope of this work with the use of induction heating. This type of heating is always used if contact-less heating of the specimen is desired. The specimen is located within an induction coil through which an AC current is supplied at a high frequency, which induces an alternating electromagnetic field. This field induces so-called eddy currents in metallic parts which are not connected to the electric circuit. As the induced currents are deflected towards the boundary of the specimen due to the skin effect, one can observe a direct resistive heating that region. The eddy currents are flowing against the ohmic resistance of the material, which is the main source of heat energy generation. In addition to that, ferromagnetic materials benefit from the hysteresis effect, which is an additional source of heat energy generation. The rest of the specimen is consequently heated by heat conduction which depends highly on the material properties in use. It is obvious that a non-uniform temperature distribution in the specimen's gauge length is dominating. Both, the fatigue properties and the deformation behaviour show a high dependence on the instantaneous temperature. In order to account for this influence in the parameter identification, the fatigue test is holistically modelled including the inductive heating, the cooling stage and the cyclic tensile loads.

Amongst all commercial FEA packages used for modelling induction heating processes, LS-DYNA offers the most advantages. Classically, electromagnetic simulations can only be realised, when the surrounding air is discretised with a mesh with coincides with the coil and the specimen mesh. In the case of fatigue tests, the geometry of the specimen is ever changing due to the tensile load exerted on it. This would result in an air mesh distortion, which may entail numerical instabilities and can lead to inaccurate results or even to an abnormal end of the computation. The FEA package LS-DYNA offers the possibility to couple the Finite-Element-Method (FEM) to the Boundary-Element-Method (BEM) for the numerical description of such processes [24]. With this software it is thus not necessary to consider the air mesh in coupled electro-magnetic-thermo-mechanical simulation as the transport of the magnetic field is taken into account by so-called fundamental solution of integral equations. Based on thermal (thermal conductivity λ, specific heat capacity c_p, coefficient of thermal expansion α) and electromagnetic material properties (relative permeability μ_r, temperature dependent electric resistivity ρ) taken from literature it was possible to determine the locally differing transient temperature distribution in the material under analysis. The simulation of the induction heating phase can be seen in figure 8. The duration of the heating and the cooling phase has been chosen according to the real tests to have maximum comparability.

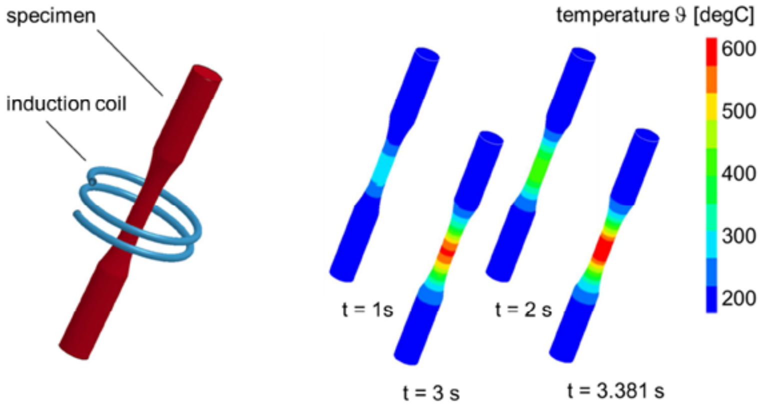

Figure 8: left: Simulation model of the induction heating, right: temperature increase over time

The determination of the temperature dependent material parameters were carried based on computational optimisation. Within the framework of this research work the FEA package LS-DYNA has been used in combination with the material *MAT_188, which can account for the hardening and softening phenomena associated to thermo-mechanical cyclic loading. The course of the temperature over time in the specimen (heating-cooling) has been taken as a boundary condition over each mechanical cycle. The simulation model of the mechanical loading phases has been parameterised and made available to the optimisation software LS-OPT. LS-OPT automatically detects predefined parameters in LS-DYNA input decks to, where the user sets the range where the algorithm can vary the parameter values. The objective of the optimisation is to minimize the mismatch between the computed and experimental force-displacement curve. Within LS-OPT a meta-model based optimization strategy with domain reduction using the newly developed curve matching metric which is based on the Partial Curve Mapping (PCM) of the experimental curve on the computed one has been chosen [25]. For a more detailed description of the fundamental theory the reader is referred to the manual of the software and related publications.

The optimisation based parameter fitting has been carried out for the strain amplitudes, which were used in the tests ($\Delta\varepsilon$= 0.35%, 0.4%, 0.45%, 0.5% and 0.55%). The next figure 9 shows a comparison of the computed and the experimental stress amplitude evolution for a strain amplitude of $\Delta\varepsilon = 0.55$ %. It can be clearly seen, that the material model is able to reproduce the real material behaviour under service-like conditions. After a certain number of cycles a stationary region can be identified

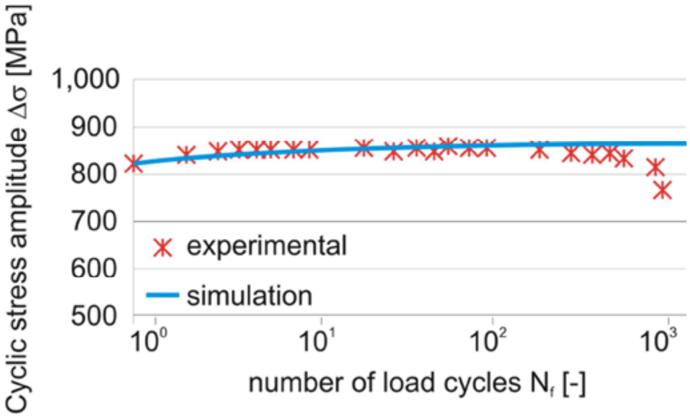

Figure 9: Computed and measured stress amplitude evolution for cyclic strain amplitude $\Delta\varepsilon = 0.55$ %

5 SUMMARY & CONCLUSION

The present work deals with the prediction of the cyclic material behaviour of a common hot work tool steel under conditions typical for hot forging. For this in-phase thermo-mechanical fatigue tests have been carried out to reproduce the load situation in the die cavity, where the highest temperature and the highest mechanical load appear simultaneously. These tests were performed to understand the characteristic fatigue behaviour of the steel and to provide the test data for FEA based simulations. A Chaboche-type material model available in the nonlinear FEA solver LS-DYNA has been used to reproduce the material's behaviour in the tests. The adjustment of the material parameter has been done with the help of FEA based optimisation, using a FEA model of the real fatigue test including the inductive heating, the forced cooling and the cyclic tensile loads. Based on this approach a very agreement between simulation and experiment has been achieved. This material model can be used to predict the fatigue of hot forging tools under service loads in the design stage of a hot forging process.

It is planned to carry out further thermo-mechanical tests and microstructure investigations on the hot work tool steel to allow for a more elaborate analysis of the fatigue behaviour. Besides isothermal LCF tests, the material will be subject to TMF tests at higher temperatures and strain amplitudes to cover the whole load regime typical for hot forging.

REFERENCES

[1] E. Doege, B.-A. Behrens: Handbuch Umformtechnik, Springer Verlag Berlin, 2nd Edition, 2010.

[2] E. Haibach: Betriebsfestigkeit: Verfahren und Daten zur Bauteilberechnung, 3rd Edition, Springer-Verlag, Berlin, 2006

[3] T. Pedersen: Numerical modelling of cyclic plasticity and fatigue damage in cold-forging tools, International Journal of Mechanical Sciences 42, pp. 799-818, 2000

[4] M. Meidert: Beitrag zur deterministischen Lebensdauerabschätzung von Werkzeugen der Kaltmassivumformung, Dr.-Ing. Thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg, 2006.

[5] M. Knörr: Auslegung von Massivumformprozessen gegen Versagen durch Ermüdung, Dr.-Ing. Thesis, Hannover, 1995.

[6] A. Oudin, F. Rezai-Aria: Temperature dependence of thermo-mechanical fatigue behaviour of a martensitic 5 % chromium steel, EUROMAT 2000 Advances in Mechanical Behaviour, Plasticity and Damage, Vol. 2, pp.1053-1058, 2000.

[7] F. Rezai-Aria, A. Oudin, S. Jean, B. Miquel, P. Lamesle: An investigation of thermal and thermo-mechanical fatigue of X38CrMoV5 (AISI H11) tool steel, 21st International Die Casting Congress & Exposition, pp. 353-360, 2001.

[8] J. Sjostrom, J. Bergstrom: Evaluation of the cyclic behaviour during high temperature fatigue of hot work tool steels, 6th international tooling conference, Karlstad University, Sweden, 2002.

[9] G. A Berti, M. Monti: Thermo-mechanical fatigue life assessment of hot forging die steel, Fatigue & fracture of engineering materials & structures, Vol. 28, pp. 1025-1034, 2005.

[10] Heinemeyer, D.: Gesenkschäden und Einflussgrößen der Standmenge, Industrieanzeiger 100, 68-70, 1978

[11] Lange, K.; Knörr, M.; Altan, T.: A Fatigue Analysis Concept to Avoid Failure of Forging Tooling. Proc. 27th Plenary Meeting of the International Cold Forging Group (ICFG), Padua 1994

[12] Richard, H.A.: Bruchvorhersagen bei überlagerten Normal- und Schubbeanspruchungen sowie reiner Schubbelastung von Rissen. Habil. Schrift, Univ. Kaiserslautern 1984

[13] Panhans, S.; Kreißig, R.; Meinel, S.: Identifikation der Materialparameter eines viskoplastischen Materialmodells vom Überspannungstyp für den Einsatzstahl 20MoCrS4, Technische Mechanik, Band 24, Heft 2, 105-115, 2004

[14] Panhans, S.: Ein viskoplastisches Materialmodell mit nichtquadratischer Fließfunktion, Dissertation, Technische Universität Chemnitz, 2006

[15] Chaboche, J.-L.; Rousselier, G.: On the Plastic and Viscoplastic Constitutive Equations, Part I: Rules Developed with Internal Variable Concept. J. Press. Vess. Techn. ASME 105, 153-158, 1983

[16] Chaboche, J.-L.; Rousselier, G.: On the Plastic and Viscoplastic Constitutive Equations, Part II: Application of Internal Variable Concept to the 316 Stainless Steel. J. Press. Vess. Techn. ASME 105, 159-164, 1983

[17] Chaboche, J. L.; Nouailhas, D.: Constitutive Modeling of Ratchetting effects – Part I: Experimental Facts and Properties of the Classical Models, Journal of Eng. Mat. And Technology, Vol. 111, 383-392, 1989

[18] Chaboche, J. L.; Nouailhas, D.: Constitutive Modeling of Ratchetting effects – Part II: Possibilities of Some Additional Kinematic Rules, Journal of Eng. Mat. And Technology, Vol. 111, 409-416, 1989

[19] Roos, E.; Föhl, J; Rauch, M.: Moderne Materialprüfung, Wechselwirkungen-Jahrbuch aus Lehre und Forschung, Universität Stuttgart, 2003

[20] Schemmel, J.; Beschreibung des Verformungs-, Festigkeits, und Schädigungsverhaltens von Komponenten im Kriechbereich unter instationärer Belastung mit einem elastisch-viskoplastischen Werkstoffmodell, Dissertation, Universität Stuttgart, 2003

[21] Döring, R.; Hoffmeyer, J.; Vormwald, M.; Seeger, T.: Verformungsverhalten und rechnerische Abschätzung der Ermüdung-lebensdauer metallischer Werkstoffe unter mehrachsig nichtproportionaler Beanspruchung, Mat.-wiss. u. Werkstofftechnik 33, 280-288, Wiley-VCH Verlag GmbH, 2002

[22] Peter Hähner, Ernst Affeldt, Tilmann Beck, Hellmuth Klingelhöffer, Malcolm Loveday, Claudia Rinaldi, Validated Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing, http://www.tmf-workshop.bam.de/en/tmf_media/eur22281en.pdf

[23] Stute-Schlamme, W.: Konstruktion und thermomechanisches Verhalten rotationssymmetrischer Schmiedegesenke, Dr.-Ing. Dissertation, Technische Universitat Hannover, 1981

[24] P. L'Eplattenier, G. Cook, C. Ashcraft, M. Burger, J. Imbert, M. Worswick: Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical-Thermal-Electromagnetic Simulations, steel research international, Volume 80, Issue 5, pages 351–358, May, 2009

[25] K. Witowski, M. Feucht, N. Stander, An Effective Curve Matching Metric for Parameter Identification using Partial Mapping, 8th European LS-DYNA Users Conference, Strasbourg, 2011