EXPERIMENTAL AND NUMERICAL INVESTIGATION OF DYNAMIC TRANSFORMATION INDUCED PLASTICITY DURING HOT FORMING

[1]Bernd-Arno BEHRENS, [1]Johanna UHE, [1]Hendrik WESTER, [1]Christoph KOCK, [1]Norman HEIMES

[1]Institute of Forming Technology and Machines, Leibniz University Hannover, Garbsen, Germany, EU, behrens@ifum.uni-hannover.de, uhe@ifum.uni-hannover.de, wester@ifum.uni-hannover.de, kock@ifum.uni-hannover.de, correspondence: heimes@ifum.uni-hannover.de

https://doi.org/10.37904/metal.2023.4639

Abstract

Hot forging processes are influenced by numerous thermo-mechanical-metallurgical material phenomena, which interact strongly. In particular, the strains due to transformation-induced plasticity (TRIP) occurring during the forming process have a considerable influence on the distortion and residual stresses of the components. As TRIP strains are anisotropic they depend on the orientation and magnitude of the stress states superimposed to the phase transformation during cooling. By numerical modelling the impact of the TRIP effect can be analysed and taken into account during process design. However, required material data are poorly accessible to non-existent in literature. Therefore, this work focuses on the determination of characteristic values of TRIP for the material AISI 52100 considering dynamic effects. Tests were performed using hollow specimens which were thermo-mechanically loaded. An external stress was applied shortly before the start of the transformation and, in the case of reversible transformation plasticity, selectively released during the transformation phase. In this way, it was possible to determine phase-specific as well as load-dependent reversible transformation plasticity effects. The determined values for TRIP effect with and without backstress were transferred to a FE simulation and successfully validated with an experimental comparison. The material models and subroutines created are now to be validated on the basis of experimental forging tests by comparing distortion and residual stresses.

Keywords: Hot forging, FE-simulation, phase transformation, transformation-induced plasticity, AISI 52100

1. INTRODUCTION

The use of forging processes has proven to be a highly advantageous technology for the production of intricate and highly loaded components [1]. By heating the billet to temperatures of up to 1,250 °C, the yield stress decreases, resulting in higher strains and lower forming forces andallows for the production of complex parts. Additionally, the forging process generates a refined microstructure in the material, which enhances the strength and durability of the final part. However, designing a hot forming process is a challenging task due to the interaction of multiple influencing parameters [2]. The interaction between mechanical, thermal, and metallurgical phenomena significantly affect the final properties depending on the process parameters and the chemical composition of the used material. For this reason, hot forming processes are often designed using the finite element (FE) method. By using suitable material models, different effects and interactions in the coupled thermo-mechanical-metallurgical process can be taken into account. Behrens et al. used the additive strain decomposition method to take into account mechanical, thermal, and metallurgical effects by considering the five parameters of elastic, plastic, thermal, transformation-related, and transformation plasticity strains separately and then summing them up to the total strain increment [2,3]. The transformation-related strains are volumetric strains that a polymorphic material undergoes due to phase transformations, such as austenite transforming into microstructural constituents like ferrite, pearlite, bainite, or martensite. Anisotropic transformation strains occur when phase transformations are superimposed with a mechanical stress. This effect is described by the transformation plasticity strains. Material parameters for calculating transformation-induced plasticity (TRIP) are difficult to obtain. Moreover, there are few standards and norms for characterising these material phenomena and the recording of such material data requires special test equipment. Currently, there are only guidelines for determining phase transformation times, like ASTM A1033 [4], which provide a reasonable guideline for designing heat treatment routes. However, these tests can only be used to determine the transformation times and the resulting amount of phase fractions transformed. The transformation-related strains and transformation plasticity, which are crucial for optimising forging processes with regard to the development of distortion and residual stresses, cannot be calculated based on data derived from these tests. Therefore, this work focuses on the experimental determination of characteristic values of TRIP for the material AISI 52100 under consideration of dynamic effects. Based on experimtal data the different backstress parameters ${c_{ph}}^{tp}$ were calculated to consider the dynamic TRIP effect in the numerical simulation. Finally, numerical simulations of the experimental tests were performed to analyse the influence of the backstress parameter on the predicted strains.

2. MATERIAL AND METHODS

In this study, the steel alloy AISI 52100 was examined, which is commonly used in hot forging processes for the production of roller bearing rings or high-loaded components. The experiments were carried out using the thermal-mechanical physical simulation system Gleeble 3800-GTC with a low-force testing setup, as depicted in **Figure 1(a)**. The apparatus allows for precise force measurement up to 20 kN via a load cell.

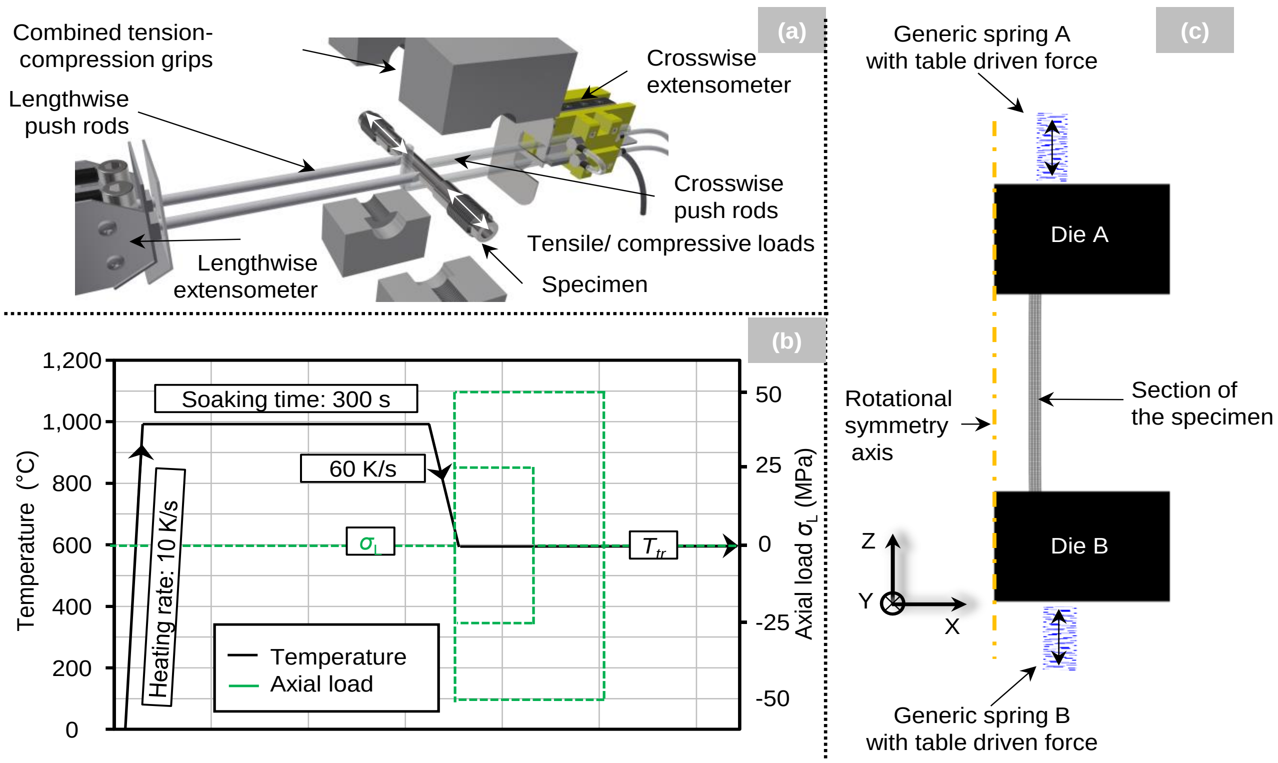

Figure 1 (a) Gleeble 3800-GTC setup for characterisation of TRIP effect, **(b)** test procedure with regard to temperature and superimposed load, **(c)** Schematic representation of the simulation model of the characterisation tests

A thin-walled hollow specimen was used to achieve high cooling rates from the austenitising temperature to the test temperature in order to avoid premature phase transformation. Cooling was achieved with nitrogen from the inside through the borehole. The outer diameter of the specimen in the gauge area is 8 mm, where the inner diameter is 6 mm. The length of the gauge area is 18 mm. A detailed describtion of the specimen design is given in [3]. During testing, strain measurement was conducted using two extensometers, a lengthwise and a crosswise extensometer, as depicted in **Figure 1(a)**. The specimen was clamped in custom-made grips using M12 threads, which allowed both tensile and compressive loads to be applied. The lengthwise extensometer was a HZT071 type full-bridged strain gauged design transducer from DSI Inc. with a resolution of ±2 µm, while the crosswise extensometer was a linear variable differential transducer based dilatometer type 39018 from DSI Inc. with a resolution of ±0.4 µm. Both extensometer were designed to be used continuously at specimen temperatures between 10 °C and 1,200 °C. The used temperature and axial loading sequences of the tests are shown in **Figure 1(b)**. First, the specimen is heated from room temperature to the austenitisation temperature of 1,000 °C at a heating rate of 10 K/s. This temperature is maintained for a soaking time of 300 s to ensure complete and homogeneous austenisation. Subsequently, the specimens are cooled down with a cooling rate of 60 K/s to the test temperature of 600 °C. The test temperature of 600 °C was chosen to achieve a pearlitic phase transformation. The test temperature is kept constant afterwards until the end of the test. With the reaching of the test temperature a compressive or tensile load is axially applied to the specimen. The duration of stress application were determined from the time temperature transformation diagram so that approx. 50 % of the pearlitic phase transformation is completed. At the end of the holding time, the specimens are abruptly unloaded. However, the temperature is kept constant until the phase transformation is completely finished. During the tests, the loads ±25 MPa for 50 s and ±50 MPa for 95 s were investigated. A numerical model of the tests was created in Simufact.Forming v16 heat treatment module to calibrate and verify TRIP related material coefficients determined from experimental data. To simulate the effects of transformation-related strains and transformation plasticity, the experimental temperature profiles displayed in **Figure 1(b)** were employed as boundary conditions. The design of the model is shown in **Figure 1(c)**. Only the central section of the specimen with a measuring length of 18 mm was modelled using rotational symmetry with 332 quad-elements of MSC.Marc-Type 10. The auxiliary modelling dies A and B were used to apply the tensile or compressive loads and were tied to the specimen, with movements in the x- and z-direction allowed without friction. The tensile or compressive loads were modelled by the generic springs A and B to which table-driven force profiles were assigned. As the forces used in this study were in the elastic range of the steel, only elastic material parameters were required for the simulations, which were taken from a previous work of the authors [3]. In previous studies, the transformation plasticity in the diffusion-controlled phase transformations for AISI 52100 was determined experimentally and the required ${K_{\mathrm{ph}}}^{\mathrm{tp}}$ for the numerical calculation was calculated according to [3, 5]. In contrast to the experiments shown in this paper, the load was applied over the complete phase transformation. The coefficient ${K_{\mathrm{ph}}}^{\mathrm{tp}}$ is a proportionality factor describing the ratio between transformation plasticity strain and the superimposed stress [6]. For the modelling of the reversible transformation plasticity, the model is used analogously to [3], which is, however, now supplemented by the backstress parameter ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ in adaptation to Tanaka et al. [7].

$$\mathrm{d}\varepsilon_{\mathrm{ij}}^{\mathrm{tp}} = \frac{3}{2} K_{\mathrm{ph}}^{\mathrm{tp}} \frac{\mathrm{df}(\xi_{\mathrm{ph}})}{\mathrm{d}\xi_{\mathrm{ph}}} \mathrm{d}\xi_{\mathrm{ph}} \left(S_{\mathrm{ij}} - X_{\mathrm{ij}}\right)$$

$$\mathrm{f}(\xi_{\mathrm{ph}}) = \xi_{\mathrm{ph}}\left(1 - \ln(\xi_{\mathrm{ph}})\right) \; ; X_{\mathrm{ij}} = {c_{\mathrm{ph}}}^{\mathrm{tp}} \varepsilon_{\mathrm{ij}}^{\mathrm{tp}} \quad (1)$$

The essential component of the instantaneous increment of phase ph $\mathrm{d}\xi_{\mathrm{ph}}$ and the stress deviator S_{ij} is already calculated by the FE solver and provided to the model. Within equation (1), a backstress parameter of ${K_{\mathrm{ph}}}^{\mathrm{tp}} = 7.7 * 10^{-5} MPa^{-1}$ for compressive loads and ${K_{\mathrm{ph}}}^{\mathrm{tp}} = 12.46 * 10^{-5} MPa^{-1}$ for tensile loads is used for the pearlitic phase transformation at 600 °C, so only ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ need to be fitted based on the experiments. The ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ parameters for compression and tension are fitted to the tests with the highest load of ±50 MPa and their quality is evaluated on the tests with a superimposed load of ±25 MPa.

3. RESULTS AND DISCCUSION

The experimental results are shown in **Figure 2** for AISI 52100 and the isothermal transformation at 600 °C with dynamic loading as well as constant loading. Data for constant loading were taken from previous work [3]. Lengthwise strain curves show the same behaviour up to unloading **Figure 2(a)**. With the onset of unloading, the backstress effect becomes visible. Under tensile loading, the effect of reversible strain is more pronounced than under compressive loading. At a constant tensile stress of +50 MPa, a lengthwise transformation plasticity of $\varepsilon_{\mathrm{tp,l}} = 0.6\ \%$ is determined, whereas the dynamic loading results in a lengthwise transformation plasticity of $\varepsilon_{tp,l} = -0.38\ \%$. A negative lengthwise strain of $\varepsilon_{\mathrm{tp,l}} = -0.5\ \%$ was measured for the constant compressive load of -50 MPa and a lengthwise strain of $\varepsilon_{\mathrm{tp,l}} = -0.33\ \%$ for dynamic loading. This resulted in a backstress effect of $\varepsilon_{\mathrm{tp,back}} = 0.22\ \%$ for a tensile load of 50 MPa and $\varepsilon_{\mathrm{tp,back}} = 0.17\ \%$ under compressive load. For the tensile and compressive loads of ±25 MPa, the backstress effect is more clearly pronounced for tension than for compression. According to the volume constancy of the transformation plasticity it is noticeable that tensile loads result in a diameter decrease, whereas specimens subjected to compressive loads show an increase in diameter. The measurement of the cross strains at +50 MPa and -25 MPa are unusable due to slipping of the measuring system. At -50 MPa a slight backstress effect of about $\varepsilon_{\mathrm{tp,back}} = -0.04\ \%$ can be observed. At +25 MPa the effect is more visible and measure $\varepsilon_{\mathrm{tp,back}} = -0.09\ \%$. The comparison of the tests with constant and dynamic loading shows that the backstress effect is more noticeable in the lengthwise direction than in the crosswise direction. In addition, the backstress effect is greater for tensile loads than for compressive loads, which is also confirmed by the studies presented in [8,9].

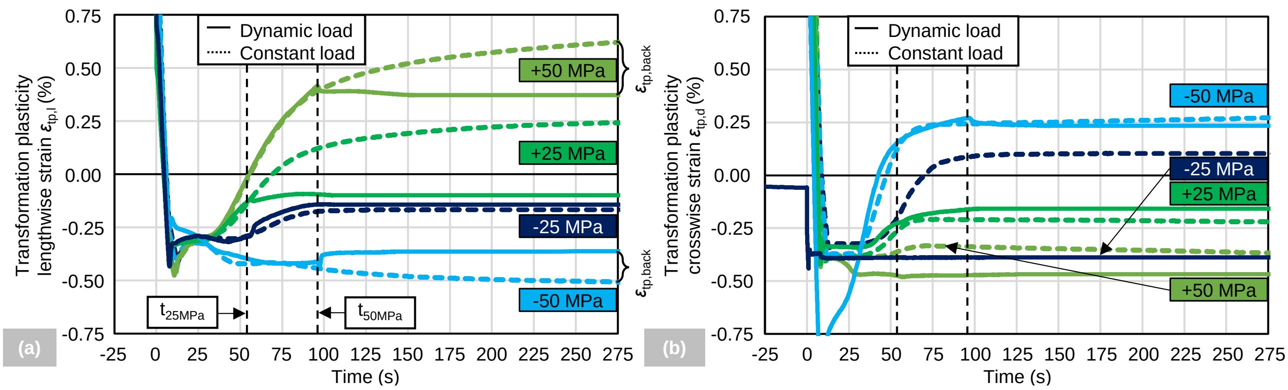

Figure 2 Development of (a) lengthwise strain, (b) crosswise strain under constant and dynamic superimposed loads

For the numerical analysis of the dynamic tests, the boundary conditions from the tests were implemented in the described FE model by modifying the spring specifications. The ${K_{\mathrm{ph}}}^{\mathrm{tp}}$ values for AISI 52100 determined by Behrens et al. were used for the simulation [3]. In order to be able to take the back stress effect into account numerically, the ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ factors were fitted to the strain curves in the lengthwise direction optainied from the test with loads of +50 MPa and -50 MPa. A ${c_{\mathrm{ph}}}^{\mathrm{tp}} = 1{,}000\ MPa$ was determined for the tensile load and ${c_{\mathrm{ph}}}^{\mathrm{tp}} = 125\ MPa$ for the compressive load. The numerically calculated strain curves are shown in **Figure 3(a)** in the lengthwise direction in relation to the experiments. For +50 MPa and for -50 MPa, the same strain as in the experiment is obtained and the time of unloading is also well reproduced. During the loading phase, the course at -50 MPa corresponds to the experimental course, whereas slight deviations at +50 MPa are present. The tests at ±25 MPa were also simulated with the determined ${c_{\mathrm{ph}}}^{\mathrm{tp}}$-parameters. With the chosen ${c_{\mathrm{ph}}}^{\mathrm{tp}}$-parameters the backstress effect under tensile load was overestimated while for compressive load the backstress effect was underestimated. The development of the cross strains is plotted in **Figure 3(b)**. A comparison can only be made with the curves of -50 MPa and +25 MPa, due to mentioned slipping of measuring systen occured during the tests with +50 MPa and -25 MPa. At -50 MPa the amount of strain is calculated well, but a clear deviation is noticeable during the loading phase. The cross strain for +25 MPa is underestimated in the same way as for the lengthwise strain. All calculated cross strains, show stronger deviations during the loading phase. The deviations are due to the changed kinematics of the phase transformation. As shown by Behrens et al., a tensile or compressive load accelerates the phase transformation. Therefore, the cross strain in the experiment increases much faster than in the simulation. In order to treat this effect numerically, it would be necessary to consider the effect of an accelerated phase transformation due to superimposed loads in the ttt diagram. For this, data such as transformation start and end times or martensite start and end temperatures as a function of stress have to be taken into account [3].

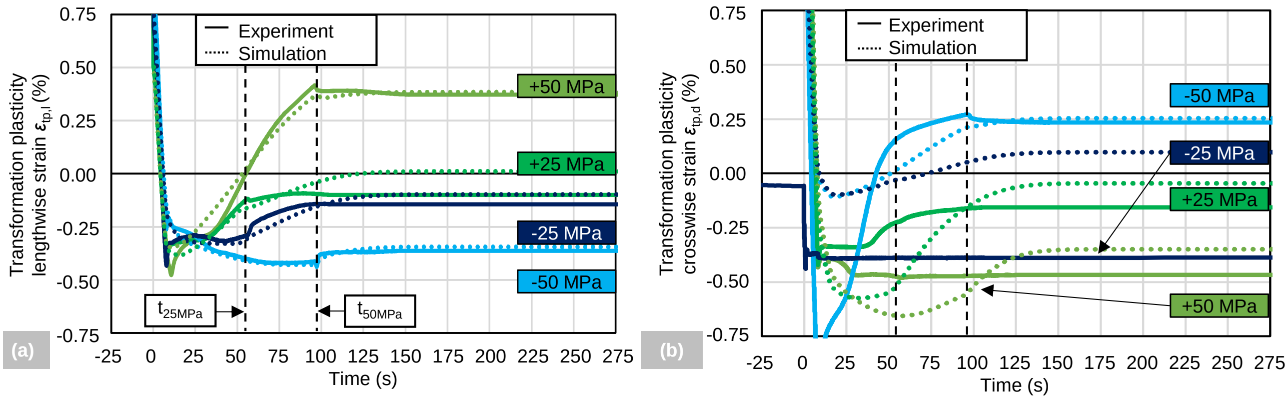

Figure 3 Comparison of the experimental and numerical calculated (a) lengthwise strain, (b) crosswise strain

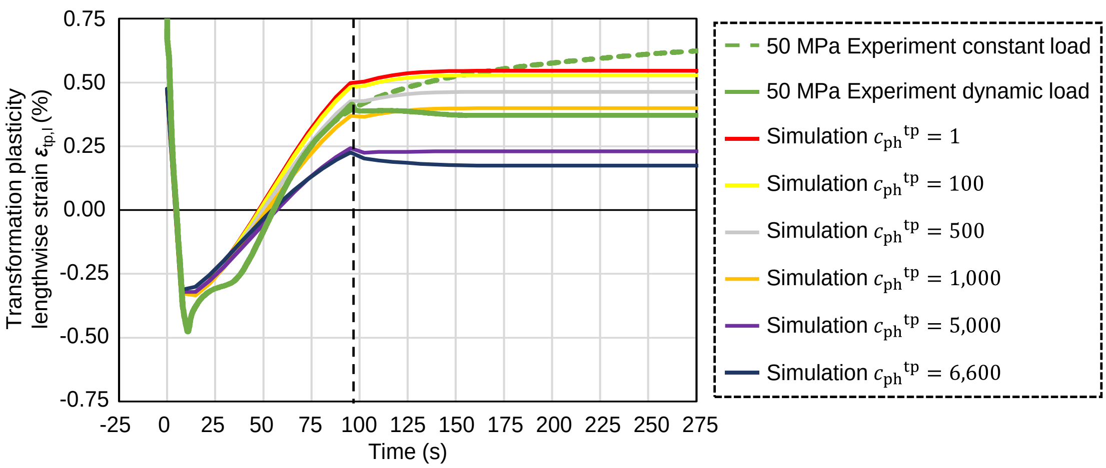

Figure 4 Influence of different c_{ph}^{tp}-factors on the lengthwise strain for a constant K_{ph}^{tp}-factor

As shown, by fitting the c_{ph}^{tp}-factor, the strain curves with a superimposed load of ±50 MPa could be calculated with good agreement to the experimental results. However, tests with a superimposed load of ±25 MPa show deviations between experimental und numerical calculated strains. **Figure 4** shows the influence for different c_{ph}^{tp}-factors on the strain curves for a superimposed load of +50 MPa. The resulting strain curves indicate that a reduction of the deviation by only varying the c_{ph}^{tp}-factor cannot be achieved without at the same time leading to deviations in the curves for loads of ±50 MPa. As the c_{ph}^{tp}- factor increases, the strain decreases. Besides influencing the strain development after unloading, the c_{ph}^{tp}-factor also influences the strain development during the loading phase. The results show that, in addition to the c_{ph}^{tp}-factors, the c_{ph}^{tp}-factor must also be recalculated if dynamic loads are taken into account. In this context. Wolf et al. provide an approximate calculation pre-layer for the residual stress parameters c_{ph}^{tp} and K_{ph}^{tp} which can be used as a starting value for the optimisation [10].

4. CONCLUSION

In this work, dynamic tensile and compressive loads were applied during a pearlitic phase transformation to investigate the TRIP effect for the bearing steel AISI 51200. The experimental tests were performed on a Gleeble 3800-GTC, using two extensometers to measure longitudinal and cross strains. A backstress effect of $\varepsilon_{\mathrm{tp,back}} = 0.22\ \%$ strain was determined under tensile load and $\varepsilon_{\mathrm{tp,back}} = 0.17\ \%$ for compression load. The tests were afterwards numerically depicted using FE simulations and the backstress factor ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ was fitted. For a load of ±50 MPa, the backstress effect could be represented numerically with sufficient accuracy. However, a reduced load of ±25 MPa leads to deviations. The deviations are due to the fact that the ${K_{\mathrm{ph}}}^{\mathrm{tp}}$-factors used were calculated for tests with constant loads [3]. Thus, to model constant and dynamic load effects both backstress parameters ${c_{\mathrm{ph}}}^{\mathrm{tp}}$ and ${K_{\mathrm{ph}}}^{\mathrm{tp}}$ need to be modified. After joint fitting, these material parameters can be used and transferred to numerical analysis of forging processes. In this way, the prediction of distortion can be improved there.

ACKNOWLEDGEMENTS

This study was funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) - 212963651 (BE 1691/142-2). The authors gratefully acknowledge the German Research Foundation for their financial support of his project.

REFERENCES

[1] SEMIATIN, S. L., et al. *Introduction to Forming and Forging Processes*. Metals Handbook: Volume 14, Forming and Forging. Ohio, USA, 1988.

[2] BEHRENS, B.-A., SCHROEDER, J., BRANDS, D., BRUNOTTE, K., WESTER, H., SCHEUNEMANN, L., UEBING, S., KOCK, C. Experimental and Numerical Investigations of the Development of Residual Stresses in Thermo-Mechanically Processed Cr-Alloyed Steel 1.3505. *Metals.* 2019, vol. 9, p. 480.

[3] BEHRENS, B.-A., BRUNOTTE, K., WESTER, H., KOCK, C. Methodology to Investigate the Transformation Plasticity for Numerical Modelling of Hot Forging Processes. *Key Engineering Materials.* 2022, pp. 547-558.

[4] A01 COMMITTEE, et al. Practice for Quantitative Measurement and Reporting of Hypoeutectoid Carbon and Low-Alloy Steel Phase Transformations. ASTM International: West Conshohocken, PA, USA, 2018.

[5] LEBLOND, J.-B., DEVAUX, J., DEVAUX, J.C. Mathematical modelling of transformation plasticity in steels I: Case of ideal-plastic phases. *International journal of plasticity*. 1989, vol. 6, pp. 551-572.

[6] VIDEAU, J.-C., CAILLETAUD, G., PINEAU, A. Experimental study of the transformation-induced plasticity in a Cr-Ni-Mo-Al-Ti steel. *Le Journal de Physique IV*. 1996, vol. 6. C1, pp. 465-474.

[7] TANAKA, K., TERASAKI, T., GOTO, S., ANTRETTER, T., FISCHER, F., CAILLETAUD, G. Effect of back stress evolution due to martensitic transformation on iso-volume fraction lines in a Cr-Ni-Mo-Al-Ti maraging steel, *Mat. Sc. Eng*. 2003, A 341, pp. 189-196.

[8] ŞIMŞIR, C. 3D *finite element simulation of steel quenching in order to determine the microstructure and residual stresses.* 2008. Dissertation. Middle East Technical University.

[9] AHRENS, U. *Beanspruchungsabhängiges Umwandlungsverhalten und Umwandlungsplastizität niedrig legierter Stähle mit unterschiedlich hohen Kohlenstoffgehalten*. 2003. Dissertation. University of Paderborn.

[10] WOLFF, M., BOEHM, M., DALGIC, M., LOEWISCH, G., LYSENKO, N., RATH, J. Parameter identification for a TRIP model with backstress. *Computational materials science*. 2006, vol. 37, no. 1-2, pp. 37-41.