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EXPERIMENTAL INVESTIGATIONS ON THE TRANSFORMATION-INDUCED PLASTICITY IN A HIGH TENSILE STEEL UNDER VARYING THERMO-MECHANICAL LOADING

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Abstract

Transformation-induced plasticity (TRIP) also known as transformation plasticity (TP) occurs during solid state phase transformation in the case of applied stress and may lead to irreversible macroscopic distortions in steel components after heat treatment. Particularly, in the context of cost-efficient hot forging, where heat treatment is integrated in the process chain, various complex stress states can occur during the cooling phase due to irregular part geometry, temperature gradients and local differences in the deformation history. Varying local temperature, unsteady stress state or even sudden unloading during the transformation can have a strong impact on the resulting TRIP strain. Thus prediction of the final distortions in hot formed steel components becomes challenging. For this reason process simulation based on the finite element (FE) method offers great opportunities for the accurate virtual process design, reducing time- as well as cost-intensive trial and error cycles. However, a realistic FE-simulation requires reliable mathematical models as well as detailed thermo-mechanical material data. In order to improve the modelling of the material behavior in a hot forging and quenching process, physical simulations for particular process-related time-force-temperature profiles have been carried out on a uniaxial thermo-mechanical testing machine. The relative dilatation of the steel specimens for several applied stresses as well as for the case of sudden unloading have been recorded and evaluated for both compressive and tensile loads. It has been shown that other process parameters (e. g. heating strategy) also have a significant influence on the resulting TRIP strains.

Key words: dilatation, transformation plasticity, backflow effect, high tensile steel, martensitic transformation

1. INTRODUCTION AND THEORY

Due to economic globalization, constantly rising energy costs and increasing competition in the metal forming industry, cost-efficient virtual design of single process steps or even of the whole process chains has been gaining importance in the recent years. Especially in the case of hot forging, the trial-and-error approach becomes very cost-intensive due to high material and tooling costs (Behrens et al., 2016). In order to counter the rising expenses and simultaneously meet high customer requirements, accurate computer-aided process design based on the FE methods has become an essential tool for process development in the field of metal forming (Vollrath, 2013).

Another technological trend in the field of steel forgings involves the integration of heat treatment into the forging process in order to save excessive energy input during the re-heating stage (Fischer et al., 2014). Quenching from the forging heat and subsequent annealing is one of the most energy-efficient possibilities to achieve outstanding mechanical properties of the forged parts. In the course of rapid cooling of the steel forgings, the undercooled austenite can decompose into different product phases. In addition to arising thermo-elasto-plastic strains, isotropic as well as deviatoric trans-

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formation related distortions may occur. The isotropic distortions are caused by the volume contraction due to the transformation of the lattice structure (e. g. from austenite to martensite). The transformation related deviatoric strains result from the plastic deformation at the phase boundary during the formation of the new phase. These strains coupled with the thermal and isotropic transformation distortions act as a driving force for residual thermal stresses and undesired dimensional changes in the final components (Somani et al., 2001).

In order to consider the coupled thermo-elasto-plastic-metallurgical material behavior in the FE-simulation, the total strain increment is usually decomposed into elastic (el), plastic (pl), thermal (th), isotropic transformation (tr) and transformation-induced plasticity (tp) components (Behrens & Schrödter, 2014):

$$d\varepsilon_{ij}^{total} = d\varepsilon_{ij}^{el} + d\varepsilon_{ij}^{pl} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{rp} \quad (1)$$

The current work is aimed at the experimental investigation of the transformation-induced plasticity (TRIP) phenomenon and the related irreversible macroscopic strains, which can occur during the solid state phase transformations in the steel forgings. In the case of martensitic transformation Magee (1966) has described it as an effect of a martensite formation in a preferred orientation relative to the applied stress. Transformation plasticity may occur even if the applied stress is less than the current yield stress of the weakest phase. It has been shown by several authors (e. g. Mahnken et al., 2009; Lütjens & Hunken, 2013; Leblond, 1989; Leblond et al., 1989) that besides the absolute value of the applied stress, its direction also contributes to the final magnitude of the TRIP strain. In addition, sudden unloading during the phase transformation may have a recovering or a so called backflow effect on the transformation plasticity, whereby a part of the already formed TRIP strain is formed back after a sudden unloading before the end of phase transformation (Fischer et al., 2000; Ahrens, 2003).

In order to clarify the interaction between the applied stresses and the resulting material behavior of the investigated steel, physical simulations for different thermo-mechanical loadings have been carried out. Dilatometric recordings were used to understand the influence of a non-constant stress state or an alternative heating strategy on the dimensional changes occurring during the martensitic transformation under an external or internal stress.

2. EXPERIMENTAL PROCEDURE

The investigated material was a common high tensile steel with the chemical composition presented in table 1.

Table 1. *Chemical composition of the investigated steel (in wt%)*

Steel grade	C	Si	Mn	P	S	Cr	Mo
DIN 42CrMo4	0.41	0.26	0.73	0.010	0.025	1.14	0.20

The investigated steel is commonly used for various hot forging applications due to its excellent hot formability and outstanding mechanical properties after the heat treatment. A typical high-temperature continuous cooling transformation diagram (HT-CCT) as reported by Nürnberger et al. (2010) is shown in figure 1. According to the HT-CCT diagram, the used steel has to be cooled from 1200 °C to 200°C at the most within 100 s in order to achieve a completely martensitic structure.

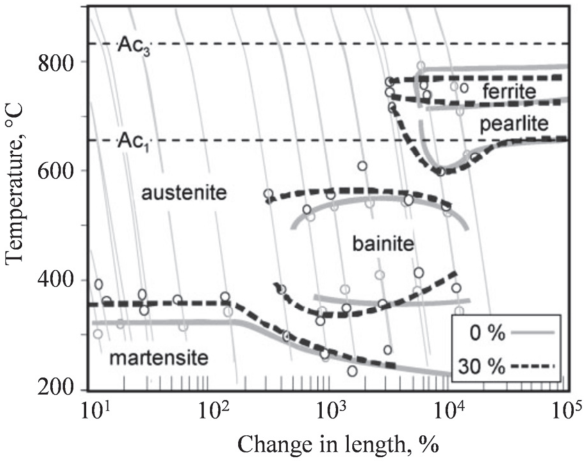

Fig. 1. *HT-CCT diagram recorded both for the undeformed (0%) and deformed (30%) material 42CrMo4 after soaking at 1200 °C (Nürnberger et al., 2010)*

A quenching-deformation dilatometer system DIL 805A/D+T (TA Instruments Inc.) was used in this study for thermo-mechanical physical simulations. Experimental investigations were carried out on the specific specimens consisting of three cylindrical segments threaded at the both flanges in order to make them suitable for both compression and tension tests. The measuring system of DIL 805A/D+T is located in a vacuum chamber in order to avoid undesired specimen oxidation and thus to prevent possible measurement errors. The experimental setup is schematically represented in figure 2a.

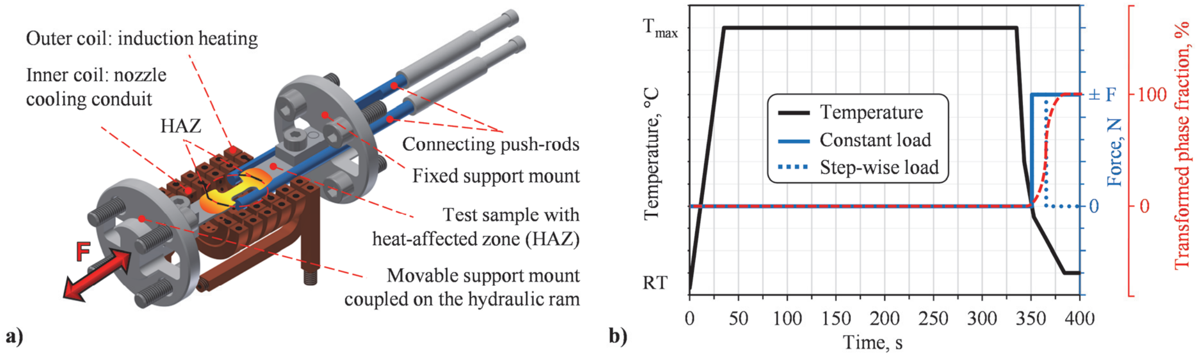

Fig. 2. a) Experimental setup for physical simulation of thermo-mechanical treatments (IFUM) and b) time-force-temperature profiles employed in this study

Temperature control is realized with the means of a double-layered coil and a type S thermocouple spot-welded in the middle of the heat-affected zone (HAZ). The outer coil layer is employed for induction heating and the inner one is used as a hollow nozzle cooling conduit. In order to achieve high cooling rates and avoid temperature gradients in the HAZ, helium gas was used as a cooling medium. Due to specific design of the measurement system, connecting push-rods are measuring longitudinal strains exactly in the middle segment of the specimen, which has a diameter of 5 mm and is 10 mm long.

2.1. Uniaxial tension-compression tests with constant load

With an aim to investigate the interaction between the emerging internal or external stresses and the resulting TRIP strain, several residual stress states were simulated by applying a constant uniaxial load on the specimens. The specimens were heated up from room temperature (RT) to the soaking temperature (T_{max}, 1200 °C) in 35 s followed by an isothermal soaking for 300 s and then cooled down to 100°C within 50 s according to a hot forging process of interest. An additional soaking temperature of 950 °C was studied, in order to investigate the effect of different heating strategies. The cooling rates for the temperature segments 950 °C – 600 °C, 1200 °C – 600 °C, 600 °C – 400 °C and 400 °C – 100 °C were -70 °C/s, -75 °C/s, -25 °C/s and -8 °C/s respectively. In the case of tension tests, a constant tension load "+F" was applied at the movable support mount just before the martensitic transformation in order to avoid plastic deformation of the hot austenite (figure 2b, blue continuous line). The same procedure has been performed for the compression tests employing a compression load "–F". Due to infinitesimal strains, the resulting stresses can be determined dividing the applied forces through the cross sectional area of the current specimen.

2.2. Uniaxial tension-compression tests with step-wise load

As discussed above, a non-constant stress may cause a backflow effect in the transformation plasticity, so that, a part of the already formed TRIP strain will be recovered. In order to study this effect for the investigated material, physical simulation tests with specific temperature-force profiles were performed on the DIL 805A/D+T system. The force has been applied shortly before the start of martensitic transformation and, in contrast to the constant load tests, has been taken away at 250 °C before the end of transformation for both compression and tension tests (figure 2b, blue dotted line). Dilatometric recordings were used to understand the correlation between state as well as direction of the applied stress and the amount of the backflow effect.

3. RESULTS AND DISCUSSION

3.1. Influence of applied stress on dilatation

In order to investigate the TRIP effect, dilatometric measurements have been done on the specimens heated up and cooled under several mechanical loads according to the strategy shown in figure 2b. Just before the martensitic transformation both tension and compression loads have been applied. The used loads amount to approx. 986 N, 1971 N as well as 2957 N and result into uniaxial stresses of 50 MPa, 100 MPa and 150 MPa respectively. The moderate stresses have been chosen in order to not exceed the yield stress of the undercooled austenite and thus to avoid undesired macroscopic plastic yielding.

Figure 3a shows the relative change in the specimen length ($\Delta L/L_0$, dilatation) at temperatures below 500 °C. Change in length of the specimens at 500 °C is set to null for a better illustration of the observed TRIP effects. The black continuous line shows specimen dilatation during the stress free experiment. It can be seen that the dilatation from 500 °C to 300 °C follows a linear course and represents linear thermal contraction of the metallic material. The upward surge in the dilatation at the temperatures below 300 °C results in the lattice transformation from bcc (austenite) to bct (martensite) configuration and the final change in the specimen length is equal to -0,17 % at 100 °C.

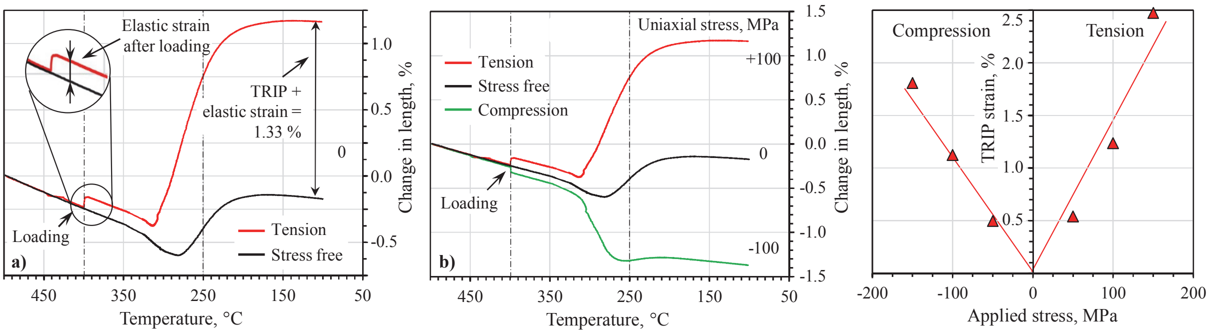

Fig. 3. *Longitudinal dilatations in the course of cooling from 1200 °C and subsequent martensitic transformation a) under a uniaxial tensile stress and b) those for compressive loading*

In the case of non-stress free experiments, small elastic strains of undercooled austenite were recorded at the moment of applying the load (400 °C). The elastic strains must be taken into consideration during the subsequent evaluation of the total TRIP-effect by subtracting them from the final dilatations. With the further decrease of specimen temperature, strains caused by phase transformation occur. In contrast to the stress free experiments, the applied stress slightly facilitates the martensitic transformation and thus the martensite start temperature rises up to 320 °C. This phenomenon is defined by the effect of an applied deviatoric stress and is in accordance with the literature (Åkerström, 2006; Şimşir, 2008). Further difference can be seen in the total dilatations of the specimens at 100 °C. Even though the applied tensile stress of 100 MPa lies below the global yield stress of the investigated material, microplasticity effects occur during the phase transformation leading to a relative length change of about 1.33 % (figure 3a, red line) as compared to the stress free experiments. A similar effect can be observed during the compression loading (figure 3b, green line). A change of 1.20 % in total dilatation was measured under a 100 MPa compression load as compared to the stress free test. In order to illustrate the significance of such a small strain for the residual stress state in the final steel component, it should be mentioned that a 1 % strain applied to a steel material with a Young modulus of 210 GPa will result into 2100 MPa stress assuming a pure elastic material behavior.

For more detailed study of the interactions between the applied stress and the resulting TRIP strain, recorded dilatations for all loading cases are presented in figure 4 as a function of the applied stress. The highest TRIP strain of 2.47% has been observed under a tensile stress of 150 MPa, whereas an equal compression stress (-150 MPa) lead to a TRIP strain of 1.81%. In general, TRIP effect for the investigated material is more pronounced under tensile stresses. This fact is also in accordance with the investigations of Ahrens (2003), Åkerström (2006), Şimşir (2008) for low alloyed steels. Decreasing the applied load will lead to a reduced TRIP strain, whereby the relationship between them can be described as nearly linear (figure 4, red trend lines).

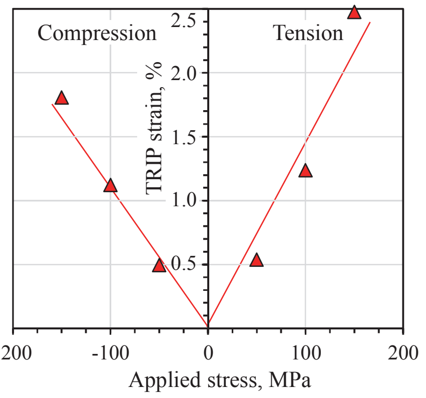

Fig. 4. *TRIP strains as a function of applied stress after cooling from 1200 °C*

3.2. Dilatation after sudden unloading or step-wise loading

Hot bulk metal forming can be characterized by unsteady time-, location- as well as temperature-dependent stress states inside the workpiece. In order to study the impact of unsteady stress states on the resulting transformation plasticity, step-wise loading or sudden unloading during the phase transformation can be physically simulated on thermo-mechanical testing machines. For this purpose, experimental tests according to figure 2b have been carried out on the DIL 805A/D+T machine. The specimen were heated up, cooled and set under a load at 500 °C as discussed above. In contrast to the prior investigations, the load has been taken away at 250 °C before the end of the phase transition. Resulted dilatometric measurements for both compressive and tensile uniaxial load of 986N (+/- 100 MPa) can be found in figure 5a.

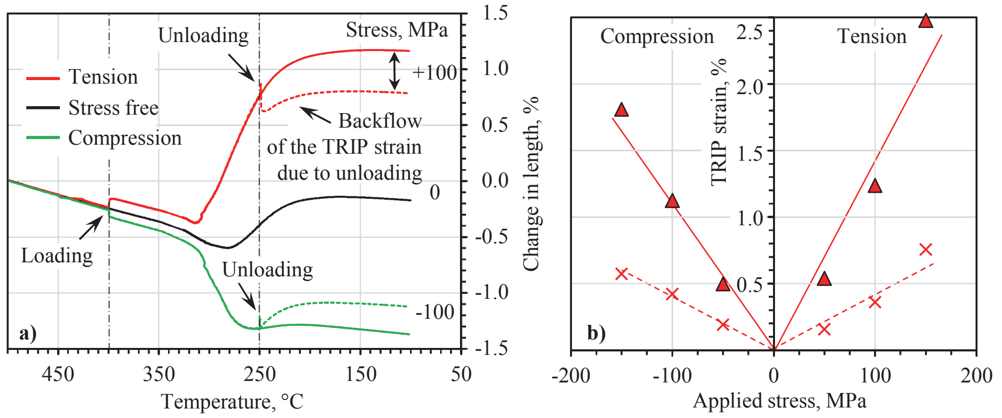

Fig. 5. *a) Longitudinal dilatations under a step-wise loading; b) TRIP (triangles) and backflow (crosses) strains as a function of applied stress*

Analog to the upward surge of the specimen length at the loading point (400 °C), the downward surge of the dilatometric curve at 250 °C is related to the elastic spring back after the unloading. The elastic strains due to unloading must be also considered during the evaluation of the final transformation plasticity. In the case of sudden unloading, it can be seen that the already formed TRIP strain is formed back and the final dilatation is not equal to the constant load case (figure 5a, dashed lines). It is due to the so-called backflow effect of the transformation plasticity, where a part of already formed TRIR strain is formed back after unloading before the end of the phase transformation (Wolff et al., 2007). In order to study the backflow effect related to the different internal stresses, physical simulation tests analog to the prior investigations but with a step-wise loading were performed on the investigated material. The resulting TP and backflow strains are shown in figure 5b as a function of applied stress. Similar to the absolute amount of the TRIP strain in the case of constant load tests, compressive stresses lead to a lower backflow strains. Hence, specimens tested under a compressive stresses of 50 MPa and 150 MPa resulting into 0.49 % and 1.81 % TRIP strain have shown a backflow dilatation of 0.19 % and 0.57 % respectively. Uniaxial tensile loads of 50 MPa, 100 MPa and 150 MPa with a subsequent unloading have resulted into 0.16 %, 0.36 % and 0.76 % backflow strains respectively. In principal, total amount of the backflow strain seems to be directly related to the absolute TRIP strain formed under the simulated stress and thus to the prior stress state history.

3.3. Influence of heating strategy

A number of dilatometric tests with a varying heating route were carried out, in order to study the influence of changing heating strategy, namely of different soaking temperatures, on the TRIP effect as discussed by Tschumak (2012). The specimens were heated up and cooled according to the similar temperature profile as presented in figure 2b. The only difference was that the soaking temperature has been changed from 1200 °C to 950 °C, which is in the lowest temperature range for hot forging processes. The recorded dilatations for both tensile and compressive loads resulting into uniaxial stresses of 100 MPa are shown in figure 6. As it can be seen, a higher soaking temperature leads to more pronounced transformation plasticity. According to Tschumak (2012) it can be explained as a grain size effect, where the grain growth is enhanced with a higher soaking time as well as temperature. Since the austenitisation at a lower soaking temperature (950 °C) leads to a lower total TP strain (0.87 %) compared to 1.24 % by the austenitisation temperature of 1200 °C, it can be stated that the austenitisation temperature indirectly impacts also the resulting backflow effect as well (0.22 % of backflow by 950 °C compared to 0.36 % backflow by 1200 °C).

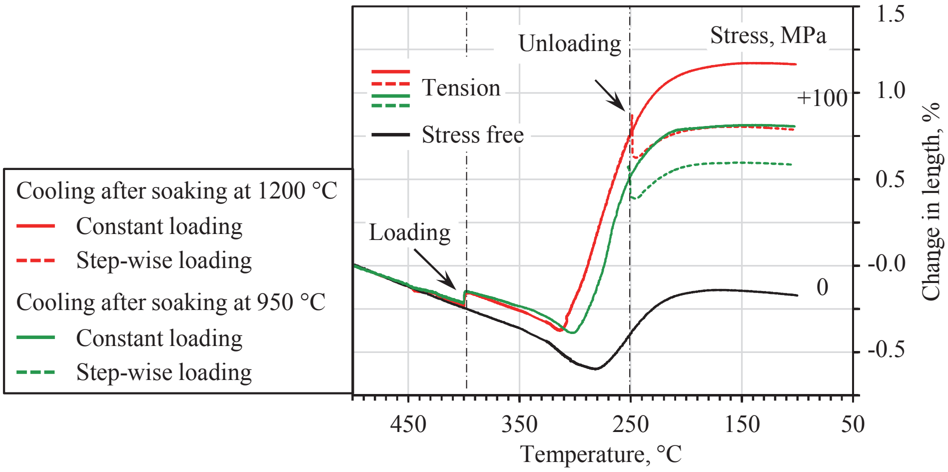

Fig. 6. *Longitudinal dilatations for tensile load after cooling from different soaking temperatures*

4. SUMMARY AND OUTLOOK

The impact of heating strategy, amount and direction of applied stress as well as unsteady stress states has been investigated by the means of thermo-mechanical physical simulation combined with the simultaneous dilatometric measurements. Figure 7 gives an overview on the resulting dilatations, which are presented as a function of applied stresses for both compression and tension tests involving the impact of different process parameters (e. g. soaking temperature, unsteady loading, etc.). In general, total TRIP strains are slightly more pronounced under tensile stresses as compared to the compression tests and seem to be in a nearly linear relation to the total value of the applied stress.

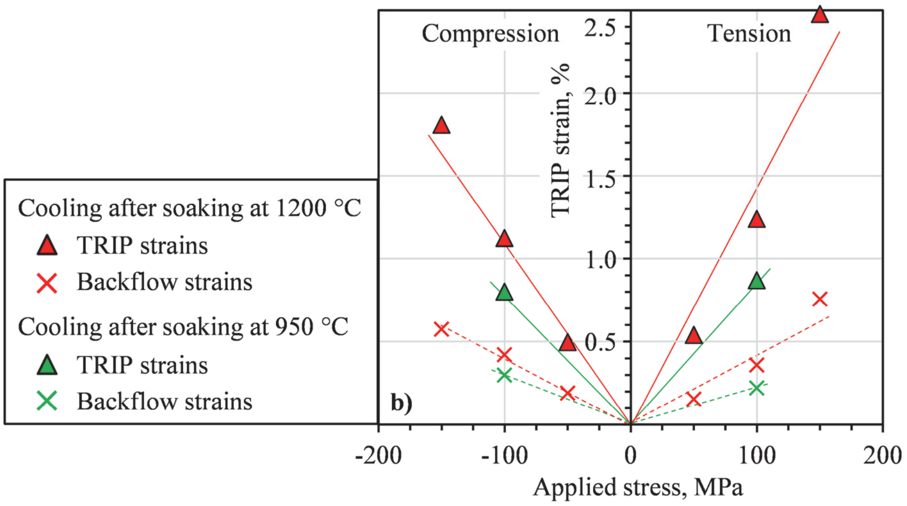

Fig. 7. *TRIP (triangles) as well as backflow (crosses) strains as a function of applied stress after cooling from different soaking temperatures*

Sudden unloading before the end of the austenite decomposition leads to a backflow effect of transformation plasticity as discussed by Wolff et al. (2007), whose total amount apparently correlates with the total amount of the already formed TRIP strain. Analog to the constant load tests, tensile stresses result into a higher propagation of the backflow effect as compared to the tests under compressive loads. A nearly linear relationship between the final dilatations and the applied stresses for both the constant and unsteady loading conditions was observed.

Furthermore, the influence of heating strategy was exemplarily studied by varying the austenitisation temperature before cooling. Due to the increasing tendency to combine several processing stages in the production chain of hot forged components, the initial soaking temperature or namely the initial microstructure before the cooling stage can significantly differ depending on the current process parameters and the location inside the workpiece. It has also been shown that for compressive as well as tensile stress of 100 MPa, the initial microstructure has a decisive influence on the resulting TRIP effect. Decreasing the soaking temperature correlates with a reduced TRIP effect, which is related to the finer grain size (Tschumak, 2012). However in the same work no dependence between the final TRIP strain and prior deformation of the stable austenite was found, which should lead to the grain refinement. According to Tschumak (2012), only the deformation of undercooled austenite had a considerable influence on the transformation plasticity. Hence, these interactions have to be studied in detail during the further investigations. Beside the influence of prior plastic deformation of the parent phase, in the further investigations the authors are aiming at a reverse numerical identification of the required material parameters from the experimental results presented in this work and a subsequent validation. For this purpose, transformation plasticity models involving a backstress tensor as discussed by Fischer et al. (2000) will be implemented in a commercial FE-solver (e. g. MSC.Marc), in order to perform a reverse numerical parameter identification.

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BADANIA DOŚWIADCZALNE INDUKOWANEJ PRZEMIANĄ PLASTYCZNOŚCI STALI O WYSOKIEJ WYTRZYMAŁOŚCI W WARUNKACH OBCIĄŻENIA TERMOMECHANICZNEGO

Streszczenie

Plastyczność indukowana przemianą (ang. TRansformation-Induced Plasticity - TRIP) występuje w czasie przemiany w stanie stałym w warunkach obciążenia naprężeniami i może prowadzić do nieodwracalnych makroskopowych deformacji elementów stalowych po obróbce cieplnej. Jest to szczególnie ważne w przypadku ekonomicznych procesów kucia, w których obróbka cieplna jest integralną częścią cyklu produkcyjnego. Przy skomplikowanych kształtach wyrobów powstają złożone stany naprężenia, gradienty temperatury i lokalne różnice w historii odkształcenia. Takie lokalne zmiany temperatury i niestacjonarne stany naprężenia, a nawet nagłe odciążenie w czasie przemiany, mogą mieć bardzo duży wpływ na odkształcenia spowodowane efektem TRIP. Dlatego możliwość przewidywania deformacji kształtowanych na gorąco elementów stalowych jest wyzwaniem dla naukowców. Symulacje metodą elementów skończonych (MES) stwarzają możliwość dokładnego wirtualnego projektowania procesu, pozwalając na skrócenie czasu i obniżenie kosztów związanych z doświadczalną metodą prób i błędów. Aby jednak uzyskać realistyczne wyniki symulacji MES potrzebny jest dokładny model matematyczny oraz prawidłowe dane termomechaniczne. Aby poprawić jakość modelowania zachowania się materiału w procesie kucia na gorąco i przyspieszonego chłodzenia, wykonano fizyczne symulacje na maszynie wytrzymałościowej przemysłowych cykli czas-siła-temperatura. Zmierzono względne odkształcenie dylatacyjne próbek dla różnych przyłożonych naprężeń, a także dla gwałtownego odciążenia próbki. Próby wykonano zarówno dla naprężeń ściskających jak i rozciągających. Analiza wyników wykazała, że poza wymienionymi powyżej parametrami także inne czynniki, takie jak np. strategia nagrzewania, mają wpływ na deformacje powstające w wyniku efektu TRIP.

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