Transformation Induced Plasticity (TRIP) of SAE 52100 Steel during Martensitic and Bainitic Transformations

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ABSTRACT

Transformation induced plasticity (TRIP) of SAE 52100 steel during quenching is investigated both experimentally and theoretically. TRIP parameter (K) is determined experimentally for both martensitic and bainitic transformations by using the stressed dilatometry technique. A new method for extraction of for an incomplete transformation is suggested for the martensitic transformation. Theoretical calculations using well-established models for the TRIP effect and the results from the literature are used for the justification of the results of this work. The results for bainitic transformation is found to be in good agreement with both the literature and theoretical calculations using Leblond`s model. On the other hand, experimentally determined value is found to be significantly different from the literature. Nevertheless, it is still in reasonable agreement with the calculations using Leblond`s model.

INTRODUCTION

Transformation Plasticity (TP) or Transformation Induced Plasticity (TRIP) is a significantly increased plasticity during a phase change [1]. TRIP is currently explained by the competition of Greenwood and Johnson [2] and Magee [3] mechanisms depending on thermo-mechanical loading conditions. The extensive review of the TRIP effect can be found elsewhere [4].

Transformation plasticity is an important phenomenon which usually has a strong impact on the predicted distortion and residual stresses by heat treatment simulations. For low quench intensities (small components, low heat extraction rates), TRIP is the sole mechanism leading to distortion of the components [5]. For example, in the work of Acht et al. [6], it is clearly demonstrated that TRIP is the major cause of change in the angle of conicity of gas-nozzle field quenched conical bearing rings made from DIN 100Cr6 steel. Moreover, in many cases, TRIP is also reported to be a good stress relaxation mechanism [7, 8].

Neglecting the TRIP effect might lead to significant errors in heat treatment simulations; in some cases,

even the sign of the stress (tension or compression) cannot be predicted correctly [7]. Moreover, the suggestion of Bhadeshia et al. [8] to design and produce low martensitic transformation temperature steels to reduce welding residual stresses; can be regarded as an efficient way of exploiting the importance of the stress relaxation effect of the TRIP phenomenon.

Owing to its importance in the prediction of heat treatment and welding distortion as well as residual stresses, there exist many models for modeling of the thermomechanical behavior of steels undergoing phase transformations including TRIP effect. Earlier material models in the field [9-12] date back to 1980`s. Although most of these models suggested until now today are usually capable of predicting the TRIP strain accurate enough, the determination of those TRIP model`s parameters is still a challenge [13]. Experimental determination of TRIP model parameters requires stressed dilatometers or physical simulators, which are not widely available. Even in the presence of high-quality equipment, the determination of TRIP model parameters is still a challenging task. The inelastic deformation is quite small and its accurate measurement requires both

careful experimentation and high precision equipment.

In this study, the TRIP constant was determined by using a deformation dilatometer. The results were justified by comparing them with the literature and with the theoretical calculations. The difference between the results of this experimental study and the here presented theoretical calculation is negligible. On the other hand, the differences are considerable when the here presented results are compared to the results of Dalgic et. al. [14] which used a different testing equipment.

THEORY

The Effect of Stress on Phase Transformations

The effect of stress on phase transformation can be summarized in two main parts: first, it changes transformation kinetics and second it causes generation of irreversible permanent strain, namely, transformation plasticity. This second effect can be active even when the material is exposed to stresses that are smaller than the yield strength of the parent phase at a given temperature [15-18].

During thermal treatments, the material is subjected to fluctuating thermal and transformation stresses due to the temperature gradient and phase transformations. These fluctuating stresses can change critical transformation temperatures or phase transformation kinetics. In other words, they may accelerate or retard the transformation of austenite into the product phases.

The effect of stress on transformation kinetics of martensite has been extensively investigated [8, 18-22]. The critical temperature for martensitic transformation, Ms, may vary with the type of stress applied to the material.

Stress state applied on the material can be decomposed into two parts as deviatoric stress and hydrostatic pressure. It is known that positive hydrostatic pressure may lower the Ms, whereas uniaxial stresses increase Ms. Hydrostatic pressure confronts to the transformation dilation of martensite, so Ms is expected to be lowered. On the other hand, an increase of Ms by deviatoric stresses can be explained by the interaction of shear components of global stress state with displacive transformation strains [18, 19, 23, 24].

In the case of diffusional transformations, hydrostatic pressure also retards the transformation by confronting the associated volumetric expansion. On the contrary, transfor-

mation rate is accelerated by uniaxial stresses, which increase the number of nucleation sites by increasing the fraction of internal defects and the free volume needed for diffusional transformations [18, 21, 25, 26].

Transformation Induced Plasticity

Transformation (induced) plasticity (TRIP) is a deformation mechanism that is known to cause a permanent irreversible deformation during a phase transformation. Greenwood and Johnson [2], Magee [3] and later Leblond [11] have developed models for TRIP. In uniaxial loading, the evolution of TRIP strain ($\varepsilon^{tp}(P)$) is often described by the Equation (1):

$$\varepsilon^{tp}(P) = K \cdot \sigma \cdot f(P) \tag{1}$$

Where K is the transformation plasticity parameter, σ is the applied stress, and f(P) is known as the progress of transformation plasticity or scaling function which expresses the dependency of transformation plasticity strain on the fraction transformed (P). Progress of transformation plasticity f(P) must satisfy f(0) = 0 and f(1) = 1. The transformation plasticity strain at the completion of the transformation (P = 1) is referred as the extent of transformation plasticity (ε^{tp}).

Experimental determination of K and f(P) requires stressed dilatometry tests conducted at different stress levels. Independent of f(P), K parameter can be determined by conducting constructing a plot of the extent of TRIP (ε^{tp}) vs. applied stress (σ). The slope of the regression line with a constant intercept of 0 yields the TRIP parameter K. After determination of K, f(P) can be determined from the same experiments by calculating the evolution of TRIP strain according to Equation 2 and determining a phenomenological function that fits all tests reasonably.

$$\varepsilon^{tp}(P) = \varepsilon(\sigma, P) - \varepsilon(\sigma = 0, P) \tag{2}$$

Both K and f(P) can also be treated theoretically according to the theory of micromechanics and phase transformation kinetics. There are different suggestions for f(p), which are reviewed in Fischer et al. [4].

There are several models published in the literature about the calculation of transformation plasticity parameter (K) which can be generalized in the form of Equation (2) [2, 11, 27, 28]:

$$K = C\left(\frac{\Delta V}{V}\right)\left(\frac{1}{\sigma_y^a}\right) \tag{3}$$

Table 1. The chemical composition of SAE 52100 steel used in this study.

	C	Cr	Si	Mn	Al	Cu	Mo	Ni	O	P
wt. (%)	0.99	1.43	0.24	0.36	0.017	0.1	0.02	0.06	5e-5	0.016

Figure 1. Temperature program for the tests for bainitic transformation.
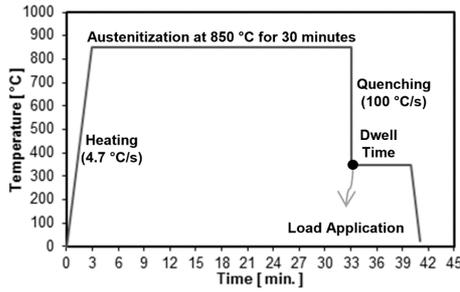

Figure 2. Temperature program for the test for martensitic transformation.

Where, C is a geometrical constant whereas; $\Delta V/V$ and σ_y^a are the dilatation due to phase transformation and the yield strength of the parent phase, respectively. Different models can be obtained by changing multiplier C between 0.66 and 0.83, given in Equation (3).

In order to calculate K with these models, volume change and yield strength of austenite must be known a priori as a function of temperature. Equation (4), which was determined experimentally in a former study [29], is used for the calculation of yield strength of austenite (in MPa).

$$\sigma_y^a (T) = -0.3211T + 294.44;\ 25\,^{\circ}\mathrm{C} \leq \mathrm{T} \leq 850\,^{\circ}\mathrm{C} \quad (4)$$

The material is assumed to experience isotropic volume changes during phase transformations and the relative change in volume ($\Delta V/V$) was calculated from the relative length ($\Delta L/L$) change in the dilatometry tests according to Equation 5.

$$\left(\frac{\Delta V}{V} \right) = 3 \left(\frac{\Delta L}{L} \right) \quad (5)$$

EXPERIMENTAL PROCEDURE

The material used in this study was SAE 52100 (DIN/EN 100Cr6, JIS-SUJ2) bearing steel and the chemical composition of this steel is given in Table 1.

The tests are conducted on a thermo-mechanical testing unit (DIL-805 A/D/T, Baehr-Thermoanalysis GmbH) which was used as a stressed dilatometer. The system employs inductive heating, He/N$_2$ gas quenching and it is also capable of applying simultaneously a uniaxial compressive force up to 20 kN. Both thermal and mechanical systems are controlled through a closed-loop control system. The experiments were performed under a vacuum of 5×10^{-4} mbar to prevent oxidation and the specimen is quenched with He gas.

Specimens with lengths of 10 mm and diameters of 5 mm were extracted from 6000 mm long as-cast and rolled 100Cr6 steel rods with a diameter of 37 mm. SAE 52100 steel rods were sliced down to 10 mm long slices. Then, each sli-
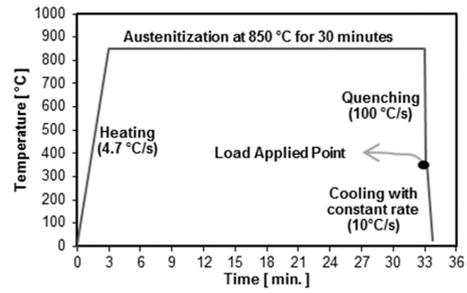
ce was spheroidized in an atmosphere controlled furnace at 790 °C for 14 hours to obtain a homogenous microstructure. After this, specimens are extracted by electrical discharge machining (EDM) from the half radius in order to eliminate the effect of core segregation.

A representative temperature program for the bainitic transformation is presented in Figure 1. First, the specimen is austenitized at 850 °C for 30 minutes and subsequently cooled down from 850 °C to 350 °C at 100 °C/s. Then, a short dwell of 1.5 is imposed for the stabilization of temperature. After this, the specimen was loaded immediately with various compressive stresses (0, 5, 20, 40 and 50 MPa). The stress on specimen was held constant until the end of isothermal dwell until the completion of transformation. It should be noted that the stresses imposed to the specimens were always below the yield strength of austenite at a temperature of 350 °C, which is 178 MPa. Each test is repeated at least 2 times to ensure the reproducibility of the results.

A representative temperature program for TRIP test of martensitic phase transformation is shown in Figure 2. The first step in the temperature program is identical to the TRIP tests of bainitic phase transformation: First, the specimen is austenitized and then cooled down to 350 °C at 100 °C/s at which various compressive stresses are applied. In the next step, the specimen is cooled down to the room temperature (25 °C) at 10 °C/s, while the load on the specimen is held constant during cooling. The stresses imposed on the specimens were always below the yield strength of austenite at temperature of 350 °C. Various compressive loads applied on specimens as 0, 5, 50 and 100 MPa.

In order to investigate the effect of stress on bainitic phase transformation, applied stress and temperature were held constant during the test until phase transformation was completed. Therefore, K can be simply determined independent of the choice of f(P) as f(P) must be 1 at the end of the transformation. On the other hand, the treatment of tests for martensite requires a more complicated treatment: The stressed-dilatometer used in this study cannot be used in subzero temperatures, but the martensitic transformation is not completed at room temperature for this steel as
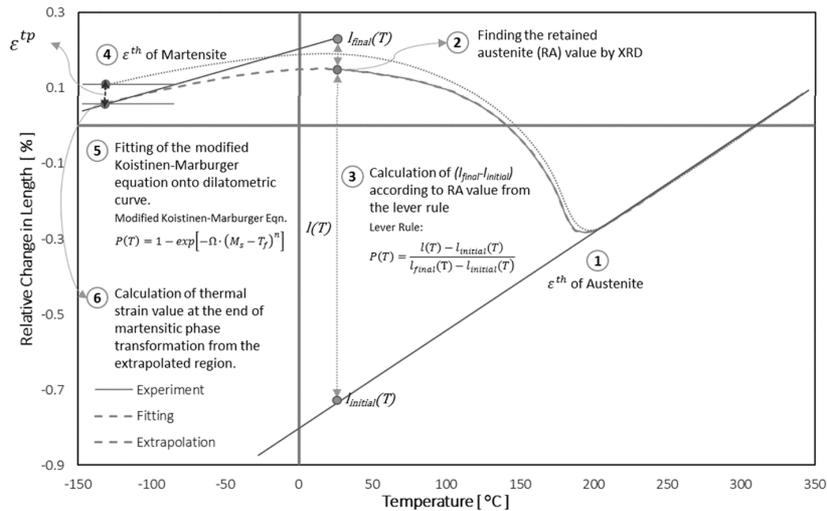
Figure 3. Temperature program for the test for martensitic transformation

its M_f determined as -94 °C in a former study [30]. Hence, the extent of TRIP (ε^{tp}) cannot be directly determined from room temperature tests. Therefore, it is not possible to determine TRIP parameter (K) by from ε^{tp} vs. σ plots.

In this study, a new method is developed to calculate the extent of plasticity from incomplete transformation curves of stressed dilatometer experiments. The method involves the fitting of a kinetic equation for martensitic function to available data and extrapolating the thermal strain of martensite until the completion of transformation. Extrapolated thermal strain for martensite is then used to calculate ε^{tp}. The procedure is summarized in Figure 3.

Modified Koistinen-Marburger equation was selected as the kinetic function

$$P(T) = 1 - \exp\left[-\Omega\left(M_s - T\right)^n\right] \quad (6)$$

Where P(T) is the proportion of martensite transformed at a given temperature, M_s is the martensite start temperature, Ω is transformation rate constant, n is the under-

cooling exponent. The values for transformation rate constant, Ω, and exponent n are obtained from the former study [30], and M_s is determined as a function of stress. In order to fit the modified equation onto the dilatometric curve, phase fraction of martensite must be known. It can be calculated by applying lever rule on the dilatometric curve, which is given in Equation 7.

$$P(T) = \frac{L(T) - L_{initial}\left(T\right)}{L_{final}\left(T\right) - L_{initial}\left(T\right)} \quad (7)$$

where, $l(T)$, $l_{initial}(T)$ and $l_{final}(T)$ are the thermal strains of austenite-martensite mixture, austenite and martensite, respectively.

Thermal strain of austenite was calculated by fitting line onto austenite region of the dilatation curve. On the other hand, thermal strain for martensite was formerly determined in [30] by subzero quenching experiments and XRD retained austenite measurements.

Finally, modified Koistinen-Marburger equation was fitted onto the dilatometric curve, which had been converted into values of fraction of martensite by the lever rule.
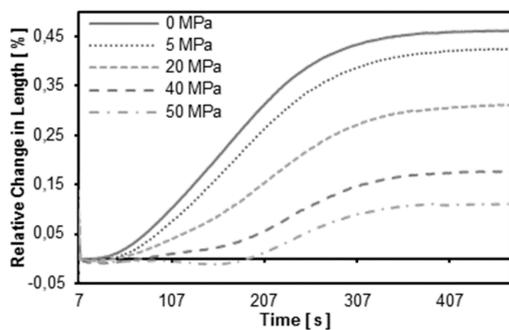

Figure 4. Relative length change vs. Time plot for the tests conducted at different stress levels for the bainitic transformation. Curves clearly indicate the presence of TRIP together with some changes in the transformation kinetics.
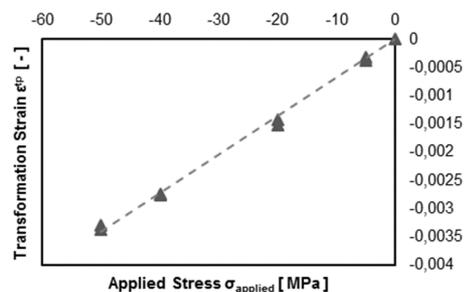

Figure 5. The extent of plasticity (εtp) vs. applied stress (σ) curve for bainitic transformation at 350°C. Kbainite is determined as 6.82·10-5 MPa-1 from the slope of the regression line.
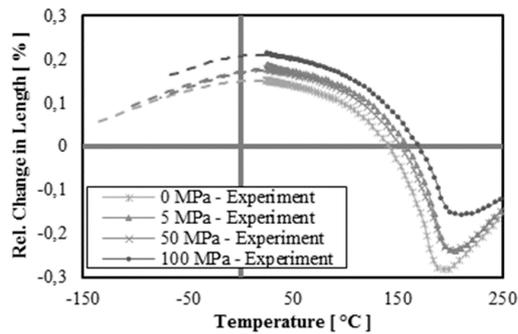
Figure 6. Relative length change vs. Temperature plots and fits Modified Koistinen-Marburger model for the tests conducted at different stress levels for the martensitic transformation. Aside from TRIP, an increase in Ms and Mf temperatures is observed with increasing stress.

Figure 7. The extent of plasticity (εtp) vs. applied stress (σ) curve for bainitic transformation at 350°C. Kbainite is determined as $6.82 \cdot 10^{-5}$ MPa-1 from the slope of the regression line..

Then, martensitic phase transformations were extrapolated up to $P(M_f)=1$ to calculate thermal strain of martensite at the end of transformation, which is the extent of plasticity (ε^{tp}). Calculated ε^{tp} values are used similar to experimentally determined ones to construct a plot to determine the TRIP parameter.

RESULTS AND DISCUSSION

The dilatation curves for the tests conducted for bainitic transformation at 350°C under different compressive stresses are presented in Figure 2. The results show a decrease in the axial strain as the imposed stress increases. As the applied stress is lower than the yield strength of the soft phase, this additional plastic deformation is related to TRIP. The tests also indicate some changes in transformation kinetics but the focus of this study is TRIP and those effects are left out of the scope for the sake of brevity.

The extent of TRIP for bainitic transformation is straightforwardly calculated according to Equation 2 at the end of transformation and plotted against the applied stress in Figure 5. A regression line is fitted to the data and K for bainitic transformation is determined from the slope of the regression line as $6.82 \cdot 10^{-5}$ MPa^{-1}. The result is quite close to the result [28] in the literature for the same steel at the same temperature, which reports K = $7.24 \cdot 10^{-5}$ MPa^{-1}. Theoretical calculation of K according to Leblond model (C=2/3 in Equation 3) yields K = $5.08 \cdot 10^{-5}$ MPa^{-1} which is also reasonably close to experimentally determined value. Thus, it can be concluded that the result lies in line with both the literature and the theory.

The dilatation curves for the tests conducted for martensitic under different compressive stresses are presented in Figure 6. The figure also shows the fitted modified K-M fittings to the experimental data and the extrapolated dilatation curves to the completion of transformation. Similar to results of the bainitic transformation, the presence of TRIP is evident as the dilatation curves shift up as the mag-
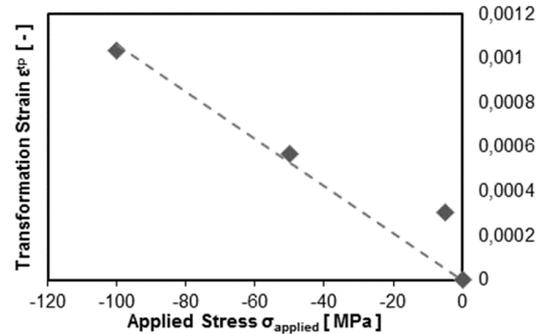
nitude of the applied stress increases, which result in a net difference in length at the end of quenching. Besides TRIP effect, the results also show an increase in M_s temperature as the stress increases, which is also expected according to the theory. Extrapolated curves also indicate the same behavior in M_f again as expected. However, those effects are left out of the scope of this article for the sake of brevity.

Figure 7 presents ε^{tp} vs. σ plot constructed using the ε^{tp} value from the extrapolated curves in Figure 6. The TRIP parameter is determined as $1.06 \cdot 10^{-5}$ MPa^{-1} from the slope, which is considerably smaller than K = $5.42 \cdot 10^{-5}$ MPa^{-1} reported in the literature [28]. On the other hand, a theoretical calculation based on Leblond model yields an average value of K = $1.18 \cdot 10^{-5}$ MPa^{-1} in the transformation range. Despite the large difference with the literature, the experimentally determined value is quite close to the value estimated by Leblond model.

CONCLUSION

In this study, TRIP constant (K) was calculated for bainite and martensite phases of SAE 52100 steel by stressed dilatometry experiments. A new method is suggested for determination of K for martensitic transformation for steel steels having subzero M_f temperature. The results are justified with the literature and the theoretical model of Leblond.

Both experimental and theoretical calculations for bainitic transformation are in good agreement with the literature. On the other hand, for the martensitic transformation, the result is close to the theoretical calculations using the Leblond model but interestingly, it is significantly different from the results from the literature. This might be due to the difference in experimental conditions such as chemical composition of steel used in experiments, austenitization conditions, loading conditions and instruments used or due to the difference in the method used for the numerical analysis of experiment results.

ACKNOWLEDGMENTS

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