Effects of Martensitic Phase Transformation on Advancing Cracks in Austenitic Steel

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1 Abstract

This paper is based on a constitutive model for an austenitic stainless steel. Previous research in this particular field include investigations of the transformation zones at a crack tip of a stationary crack [4]. Moving on, it would be interesting to consider the transformation toughening related to the martensitic formation. This is the topic of this paper, where propagating cracks are analyzed by exploiting a cohesive zone model.

The phase transformation model [6] is implemented in FORTRAN code. It is utilized in ABAQUS as a user-material subroutine. The cohesive zone model, previously discussed in [7], is also implemented in FORTRAN code as a user-element subroutine. The goal is to capture the effects of the phase transformation, and how it alters the crack tip behavior. A special cohesive zone model which takes the phase transformation in adjacent continuum elements into account is also developed.

Results are presented for different temperatures when the phase transformation is switched on and off. Some simulations are also carried out with an altered cohesive zone model and compared to the regular model.

Looking at the results, comparing a bilinear law and a trapezoidal TS-law (traction-separation law), there are clear differences with martensite present and with a crack propagating without phase transformation. The biggest differences occur at low temperature when significant amounts of phase transformation take place. Also altering the cohesive zone model can give additional effects.

2 Introduction

In the article published by Hallberg in 2007 [6], a constitutive model for martensite transformation in austenitic stainless steel is derived. In a subsequent article, also by Hallberg, from 2011 [4], results are presented for a stationary crack where the martensite transformation at the crack tip is included. Using this constitutive model with a cohesive zone model on an advancing crack would make it possible to investigate how the martensite transformation influences the crack propagation.

As a first step the simulations are run with a cohesive zone model with a constant traction-separation law. The behavior of the crack tip will be compared for when the phase transformation is active and then when no phase transformation is present.

Using a cohesive zone model for this problem the first simulation might show a difference in behavior already, but taking into consideration that the fracture toughness is different for the martensitic and austenitic phases, the material response in the vicinity of the crack tip will change and the traction separation law *might* have to account for these changes. An example of possible alterations that could be made to the cohesive zone model to account for the phase transformation are proposed.

3 The Austenitic Stainless Steel

The constitutive model is calibrated against experimental data for a Ni-Cr steel. The steel is referred to as, AISI 304 (SUS 304), austenitic stainless steel [5]. The composition is 18% chromium and 8% nickel. It has a carbon content of maximum 0.08 wt% [1].

4 Applications

Austenitic stainless steels are commonly used in engineering applications due to their versatility and exceptional mechanical properties. An important property of an austenitic steel is its excellent corrosion resistance against many different hostile environments. The mechanical properties of stainless steel have a determining role for the suitability of particular uses.

Areas of application involve use at cryogenic temperatures, where the low temperature ductility is a crucial factor. Cryogenic applications involve missiles, space vehicles and liquid natural gas storage tanks. In these applications the low temperature toughness is a crucial property. The low temperature toughness is closely connected to brittle fracture, and this can be one reason to investigate how martensitic transformation can affect the crack propagation. Austenitic steels are easily formable and can be used at a wide range of temperatures. High temperature applications generally promote diffusion-dependant phase transformation, while lower temperatures promote the diffusion-less martensitic transformation.

5 Stress- and Strain-Induced Martensite

Looking at the martensite transformation it can be seen as a mode of plastic deformation and it may be either stress- or strain-induced. A strain-induced transformation only occurs after plastic deformation has taken place in the austenite. If the transformation is stress-induced the martensite is transformed before any plastic deformation has occurred. In the phase transformation model used, the strain-induced martensite is of interest.

The fracture toughness will be dependent on the exact characteristics of the transformation. Strain-induced martensite formation is expected to increase the fracture toughness, as discussed in [3]. This is believed to stem from the highly dissipative phase transformation which, together with the plasticity in the austenite, reduces the energy available for crack propagation and consequently increasing the toughness.

If the martensitic transformation is induced by small elastic stresses in the austenite without plastic deformation, very little of the austenite would be left and its contribution to the overall toughness would be negligible. The stress level at which martensite is formed plays a big role in the toughening of the material. The strain energy reduction seen during the martensitic formation is dependent on the stress at which martensite is formed and also its related so-called invariant shear strain. Thus, lowering the stress level at which the transformation occurs will reduce the effect of toughening in the material [3].

6 Transformation toughening

The process of phase transformation under straining can be seen as a mode of plastic deformation. Hence, the process is capable of absorbing part of the elastic strain energy in the body otherwise available for crack extension. The phase transformation can also greatly influence the mechanical properties of the material. It has been indicated that the toughness increment associated with the martensitic phase transformation in austenitic steels is generally positive [2].

In a study by Yi and Gao [11], transformation zones for stationary and advanced cracks have been analysed in shape memory alloys. In this study it is shown that the martensite transformation will increase the toughness of the shape memory alloy and reduce the stress intensity at the crack tip.

7 A Special Alteration of the TS-law

The continuum model might not be sufficient to capture the effect of the phase transformation on the propagating crack. That is why a method for modeling the alteration of the fracture process, which is not captured by the continuum model, is proposed. The model can account for the decreased ductility by exploiting a special traction-separation law which is dependant on the martensitic fraction, z.

The bilinear and the trapezoidal TS-law is altered, and the alteration is based on how the mechanical properties of the austenitic steel are affected by the martensitic transformation. A similar approach was proposed in an article by Olden *et al* [9]. In this paper a model which combines hydrogen embrittlement with cohesive zones is proposed. When hydrogen diffuses into the steel structure it becomes brittle and the surface energy decreases. This effect is accounted for by introducing a bilinear TS-law in which the peak traction is lowered with increasing hydrogen content, effectively decreasing the fracture energy of the material. The results presented in this paper show good conformation with the experiments carried out.

A similar reasoning can be used to argument for the need to develop a similar method for the more brittle martensitic phase. The model proposed in this paper has no experimental results to compare to, but it is interesting to see the effects of such changes. In order to fully validate this method experiments would need to be conducted in the future.

There are a multitude of different ways that the phase transformation could plausibly alter the TS-law. The proposed alteration for the bilinear model is such that the peak traction is taken as a linear combination of the traction suitable for the austenitic phase and the trac-

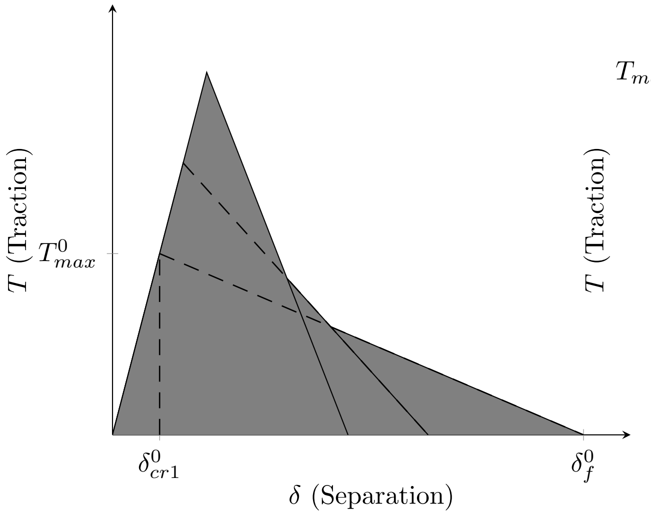


Figure 1: The altered bilinear traction-separation law.

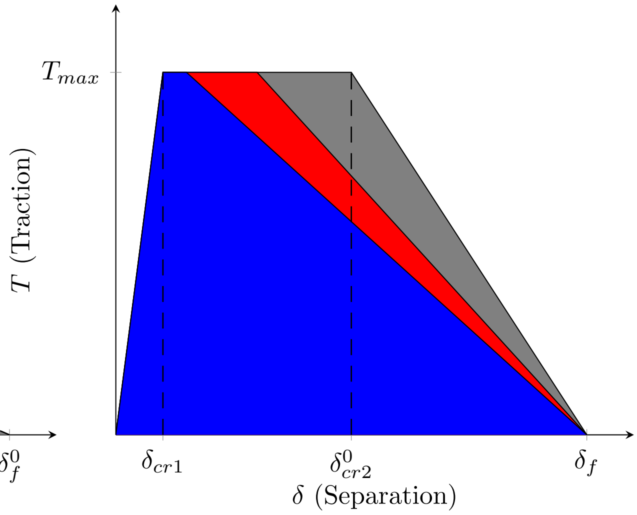


Figure 2: The altered trapezoidal traction-separation law.

tion suitable for the martensitic phase, i.e.

$$T_{max} = T_{max,a} * (1 - z) + z * T_{max,m} \tag{1}$$

In order to retain the basic appearance of the bilinear model it is modeled such that the initial stiffness is kept constant, and the point of peak traction moves along the same tangent throughout the deformation, see figure 1.

The trapezoidal law is changed based on the fact that the austenite is more ductile than the martensite. From previous sections it is mentioned that the bilinear TS-law and the trapezoidal law is more suited for brittle respectively ductile fracture simulations. Using this information and scaling the δ_{cr2} with z-fraction the TS-law will make the behavior of the crack propagation more brittle with a higher z-fraction. The scaling is done with a linear combination, see equation below..

$$\delta_{cr2} = \delta_{cr2} * (1 - z) + z * \delta_{cr1} \tag{2}$$

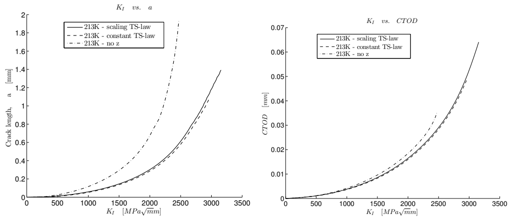
The change is illustrated in figure 2.

8 Results

The model used for the simulations is a disc-shaped model with a mode I crack displacement field applied.

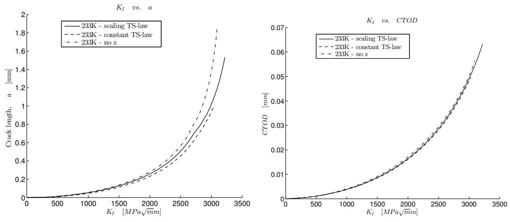
The simulations are run at three different temperatures; 213K, 233K and 293K. The two altered TS-laws are compared to the standard TS-laws. The crack opening displacement (CTOD) and crack length are compared for the different temperatures when the phase transformation is switched on and off.

Below are figures showing all results.



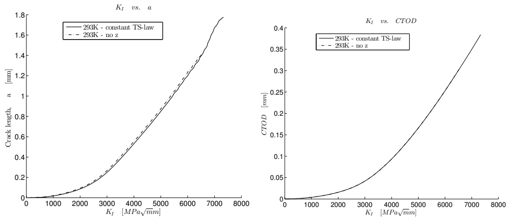
(a) **(b)**

Figure 3: Simulations for the bilinear TS-law. Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 213 K.



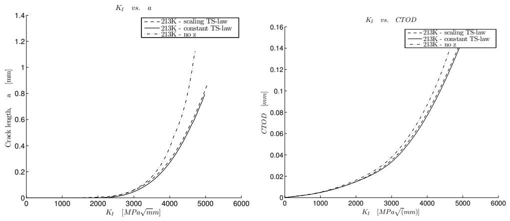
(a) **(b)**

Figure 4: Simulations for the bilinear TS-law. Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 233 K.



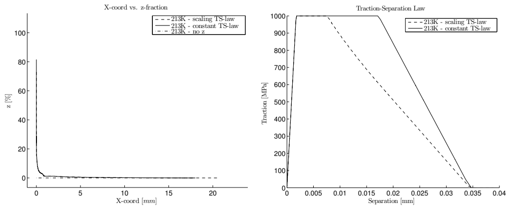
(a) **(b)**

Figure 5: Simulations for the bilinear TS-law. Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 293 K.



(a) **(b)**

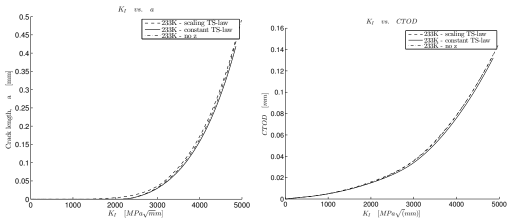
Figure 6: Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 213 K.



(a) **(b)**

Figure 7: Figure (a) shows the z-fraction, z, as a function of the x-coordinate at the crack tip and figure (b) shows the TS-law when altered and when constant, both at 213 K.

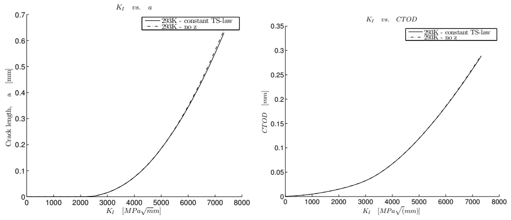
8.0.1 233 K



(a) **(b)**

Figure 8: Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 233 K.

8.0.2 293 K



(a) **(b)**

Figure 9: Figure (a) shows the crack length, a, as a function of the stress intensity factor and figure (b) shows the $CTOD$ as a function of the stress intensity factor, both at 293 K.

9 Discussion and Conclusions

It is clear that temperature has an effect on when phase transformation occurs. Running the same model at different temperatures clearly shows that there is most martensite at the temperature 213K. At the temperature 293K the simulations show a negligible fraction of martensite, which barely influences the crack propagation. Since the crack propagation is examined when phase transformation is present, the highest temperature yields the same results for when the phase transformation is turned on and off.

Comparing the results from 213K looking at both a bilinear and a trapezoidal TS-law. There are visible differences in the behavior of both the crack length and the CTOD. The crack length and the CTOD is plotted against the stress intensity factor, K_I, which scales the applied displacement field. The plots then tells us that the crack with no phase transformation will open up more, and propagate further than when phase transformation is present for the same load amplitude. Looking at the higher temperature, 233K, it still shows some difference, but when 293K is reached the difference in behavior is negligible. There is zero or almost zero martensite present and the curves showing both the crack length and the CTOD plotted against K_I almost coincide.

Looking at the alteration of the trapezoidal TS-law, it yields results that show that the crack propagates further. This implementation makes the fracture more brittle, thus lowering the fracture energy, the results turn out as expected. Results off simulations when using the altered bilinear TS-law shows that the crack propagates slower. This is explained by the fact that the maximum traction is increased, which contributes to higher stresses in the vicinity of the crack tip. The higher stresses promote more martensitic phase transformation, which slows down the crack.

It is interesting to think about what might cause this change in behavior of the crack propagation. There are many different mechanisms that could give an effect. One is the fact that the martensitic transformation yields a local increase in volume, which creates stresses that could counteract the stresses causing the crack to open.

The phase transformation can be seen as a plastic deformation and needs energy to take place. The process is a dissipative which means that it absorbs energy which could otherwise be used for crack propagation. This could also be a mechanism affecting the crack propagation behavior.

Another mechanism that affects the crack propagation is the change in material properties as martensite is formed. Austenite is softer and more ductile than martensite. The fracture energy of the martensitic phase is also likely lower, since the phase is more brittle. These factors might also have an influence on the propagating crack.

10 Future Work

Another topic that is frequently discussed in literature related to the martensitic transformation and fracture mechanics is fatigue crack growth. As mentioned previously, the cohesive element implemented in this project includes a damage formulation which makes it compatible with cyclic loading. The phase transformation model which is used throughout this paper is however based on isotropic J_2-plasticity [5]. This type of plasticity model states that yielding occurs when the tensile stress reaches a critical value, the yield stress, for uniaxial loading. If the loading is then reversed, the model predicts elastic unloading until the yield stress in compression is reached. Experimental results show that this prediction is inaccurate for metals and steel [10]. Uniaxial tests show that after being loaded plastically in tension or compression, the specimen yields at much lower stresses when the loading is reversed. This effect is called the *Bauschinger effect.* In order to capture this type of behavior during cyclic loading other hardening models are needed. When isotropic hardening is used the yield surface will most likely expand during the first cycles, and then stay fixed since the same load cycle is repeated.

A more suitable model for this type of analysis is kinematic hardening, which means that the yield surface retains its shape and size, while the position in the deviatoric plane changes with plastic deformation. This means that the Bauschinger effect can be captured, since yielding occurs earlier when loading is reversed. Since the derivation and implementation of such a model is fairly complex and time consuming, it is not included in this project. It would, however, be an interesting topic for future projects.

11 References

[1] `http://www.tecni-cable.co.uk/s.nl/ctype.KB/it.I/id.136/KB.36576/.f` Tecnicable, collected 180515

[2] S. Antolovich, B. Singh, *On the Toughness Increment Associated with the Austenite to Martensite Phase Transformation in TRIP Steels.* Metallurgy Transactions 1971;2:2135-41

[3] S.D. Antolovich, D. Fahr, *An Experimental Investigation of the Fracture Characteristics of Trip Alloys.* Engineering Fracture Mechanics, Vol. 4, pages 133-144, 1972

[4] H. Hallberg, L. Banks-Sills, M. Ristinmaa, *Crack Tip Transformation Zones in Austenitic Stainless Steel.* Division of Solid Mechanics, Lund University, 2011

[5] H. Hallberg, P. Håkansson, M. Ristinmaa, *Thermo-Mechanically Coupled Model of Diffusionless Phase Transformation in Austenitic Steel.* Division of Solid Mechanics, Lund University, 2010

[6] H. Hallberg, P. Håkansson, M. Ristinmaa, *A Constitutive Model for the Formation of Martensite in Austenitic Steels under Large Strain Plasticity.* Division of Solid Mechanics, Lund University, 2007

[7] A. Lundberg, S. Eliasson, *Investigation and Comparison of Cohesive Zone Models for Simulation of Crack Propagation*, Division of Solid Mechanics, Lund University, 2015

[8] F. Nilsson, *Fracture Mechanics - From theory to applications.* Royal Institute of Technology, 2001

[9] V. Olden, C. Thaulow, R. Johnsen, E. Ostby, *Cohesive zone modeling of hydrogen-induced stress cracking in 25% Cr duplex stainless steel.* Norwegian University of Science and Technology, 2007

[10] N. Ottosen, M. Ristinmaa, The Mechanics of Constitutive Modeling. Elsevier Ltd, First Edition 2005

[11] S. Yi, S. Gao, *Fracture Toughening Mechanism of Shape Memory Alloys Due to Martensite Transformation*, 1999