

# COUPLED TRANSFORMATION AND PLASTICITY IN NITI

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## ABSTRACT

Description of mechanisms of plastic deformation in NiTi shape memory alloys (SMA) is far from trivial as the basic understanding of these mechanisms is still missing. Experiments suggest that different mechanisms are active at different temperatures. Both B19' martensite and B2 austenite reveal elasto-plastic behavior at elevated stresses, but probably the most interesting phenomena both from the theoretical and practical point of view is the plastic deformation generated alongside the process of martensitic transformation (TRIP). It was recently recognized that  $\{20\cdot1\}_M$  deformation twinning in martensite, which is inherited after the reverse transformation into  $\{411\}_A$  austenite twins can play an important role in the TRIP mechanism.

In this contribution, we present an overview of experimental and theoretical studies of TRIP mechanisms in NiTi SMA with the main focus on their macroscopic description and formulation of the governing equations. We show that TRIP in NiTi cannot be fully described by equations for the Greenwood–Johnson mechanism and suggest a new modelling approach.

**KEYWORDS:** NITI, TRANSFORMATION-INDUCED PLASTICITY, THERMOMECHANICAL BEHAVIOR MODELING.

## INTRODUCTION

Plastic deformation in NiTi SMA is usually an undesirable phenomenon which destroys the admirable deformation recoverability of the material derived from martensitic transformation. Not only does it induce some irrecoverable strain, but it also usually leads to overall functional fatigue of the material associated with shortening of transformation plateau, increasing of hardening, increasing of the volume fraction of retained martensite after unloading and/or two-way shape memory effect (Figure 1). For this reason, both its experimental study and theoretical description attracts attention and advances on all decisive scales: atomistic scale, describing structure and dynamics of crystal defects (dislocations or deformation twins) [Chowdhury, 2017], single crystal scale, involving crystal plasticity and effects of plastic slip on the compatibility at the phase interface or twinning planes, and polycrystalline scale focusing on interaction of anisotropic grains and reconstructing macroscopic material behaviour [Sittner, 2018a]. The basic understanding is reflected in the formulation of constitutive equations for the evolution of plastic deformation, which are then implemented into existing phenomenological SMA models [Cisse, 2016].

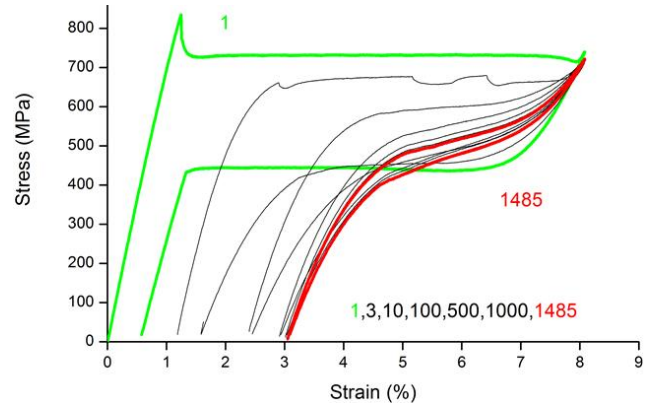


Figure 1: Evolution of stress-strain response of a NiTi wire during superelastic tensile cycling at constant temperature 60 °C.

## PLASTIC DEFORMATION MECHANISMS IN NITI

Both austenite and martensite phases deform plastically at high stresses. The yield stress of austenite decreases with increasing temperature and it is usually assumed that this is a conventional metal plasticity describable by the von Mises criterion. The mechanism of the plasticity of martensite is more complex: due to the lack of independent slip systems in B19' structure, deformation twinning is involved. The yield stress of martensite is almost temperature-independent and yielding interacts with martensitic transformation: plastic deformation of martensite can be partially recovered by the reverse transformation and leads to a considerable martensitic stabilization effect (an increase of  $A_f$  temperature). Moreover, deformation twinning is assumed to be related to the most active TRIP mechanism at elevated temperatures described by the sequence  $B2 \Rightarrow B19' \Rightarrow B2^T$ , i.e. martensitic transformation into twinned austenite coupled with dislocation plasticity [Sittner, 2018b]. The governing equation for this TRIP mechanism differs from Greenwood–Johnson type because the generated plastic deformation is not proportional to the rate of martensite volume fraction. Instead, a superposition of reversible transformation mechanism  $B2 \Leftrightarrow B19'$  with a newly proposed mechanism of reverse transformation  $B19' \Rightarrow B2^T$  describes properly our experimental data. The main features of  $B19' \Rightarrow B2^T$  transitions are: the generated plastic strain in austenite is equal to the transformation strain of disappearing martensite, the transition occurs in a broad temperature interval and in a highly heterogeneous manner.

# STRESS-TEMPERATURE PHASE DIAGRAM EXTENDED TO ELEVATED TEMPERATURES AND STRESSES

The mechanisms of plastic deformation of martensite and austenite and the TRIP mechanism associated with  $B19' \Rightarrow B2^T$  transition couple with mechanisms of reversible martensitic transformation and martensite reorientation. The resulting behavior can be explained on the simulated stress-temperature diagram (Figure 2), which corresponds quite well with experimental data acquired on a commercial medical grade superelastic NiTi wire. The diagram can be split into five temperature intervals with different deformation mechanisms:

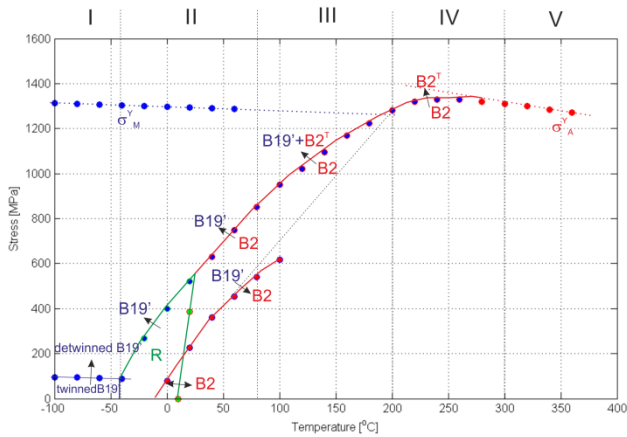


Figure 2: Stress-temperature phase diagram of superelastic NiTi in tension covering also deformation mechanisms at high temperatures and high stresses.

## Stage I: ( $T < -50^\circ\text{C}$ , twinning in the $B19'$ martensite)

The temperature induced martensite is reoriented at moderate stresses during loading and the oriented martensite can be further inelastically deformed at elevated stresses. Inelastic strains are not recovered on unloading but fully recovered on subsequent heating even if the martensite was deformed up to 13 %. A considerable effect of martensite stabilization was experimentally observed, which can be reconstructed in simulations if the dissipated energy in reverse  $B19'$  to  $B2(R)$  transformation depends on the inelastic strain of martensite.

## Stage II: ( $-50^\circ\text{C} - 75^\circ\text{C}$ , reversible martensitic transformation $B2(R) - B19'$ )

$B2(R)$  austenite transforms reversibly to oriented martensite which induces small unrecovered strains different for the forward and reverse transformation ( $\sim 0.1\%$ ), respectively [Heller, 2018]. The mechanism generating a small plastic deformation during  $B2(R) - B19'$  transformation can be captured by usual equations for the Greenwood–Johnson mechanism.

## Stage III: ( $75^\circ\text{C} - 200^\circ\text{C}$ , martensitic transformation $B2 - B19'$ )

The reverse transformation  $B19' \Rightarrow B2^T$  occurring simultaneously with the forward  $B2 \Rightarrow B19'$  transfor-

mation starts to be the dominant mechanism for induction of the plastic deformation. The plateau of the reverse transformation  $B19' \Rightarrow B2$  on unloading gradually disappears, first due to the heterogeneous distribution of plastic strain, then due to the dominance of the reverse transformation to  $B2^T$ .

## Stage IV: ( $200^\circ\text{C} - 300^\circ\text{C}$ , martensitic transformation $B2 - B19' - B2^T$ )

When the critical stress for the forward transformation reaches the yield stress of martensite at higher temperatures, we can see a dramatic decrease of material ductility in experiments caused by the localized deformation and necking. The onset of the forward transformation varies only slightly with temperature, which is related to a large inelastic strain of martensite. Martensite fully disappears to  $B2^T$  when it is created, but stress for the forward transformation is still below the yield stress of austenite. The  $B19' \Rightarrow B2^T$  transformation is the dominant mechanism of plastic deformation although hardly any martensite is detected in experiments.

## Stage V: ( $T > 300^\circ\text{C}$ , dislocation slip in $B2$ austenite)

The yield stress of austenite is below the critical stress for the forward martensitic transformation. The plasticity of austenite is the only mechanism of plastic deformation characterized by deformation hardening and by a decrease of the yield stress with increasing temperature.

## CONCLUSION

The work informs recent achievements in understanding and constitutive modelling of deformation mechanism of NiTi SMA due to coupled martensitic transformation and plastic deformation.

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