Reconciling martensite formation in the sub-zero Celsius regime with the theory of martensite formation in steel

Abstract: The activities involved a thorough re-interpretation of an existing data set acquired on sub-zero Celsius martensitic transformation in a precipitation-hardening stainless steel with different nitrogen contents. The martensitic transformation was monitored with magnetometry as austenite is paramagnetic and martensite is ferromagnetic.

The temperature below which martensite forms from austenite during continuous cooling was tailored by deliberate addition of nitrogen to 17-4 PH steel. More nitrogen leads to a lower threshold temperature below martensite forms, referred to as martensite start M_s. Martensitic transformation can occur athermally, i.e. during cooling, or isothermally. The morphology of the forming martensite depends on the nitrogen content and the cooling rate (among others). For relatively low nitrogen contents, the morphology of martensite is referred to as lath martensite. This martensite has an internal structure of dislocations necessary to accommodate the transformation strain occurring on transforming the parent fcc crystal lattice into the bcc martensite lattice. For higher nitrogen contents also plate martensite forms, which is internally twinned. This latter transformation is observed to be accompanied by bursts in the transformation rate as measured with in-situ magnetometry measurements (Fig. 1). Isothermal transformation at temperatures above M_s shows mainly lath martensite which appears thermally activated. For a nitrogen content of 0.20 wt%, plate martensite can form isothermally at a very low temperature. For intermediate nitrogen contents, plate martensite can be preceded by lath martensite, while on heating from boiling nitrogen temperature previously formed martensite plates appear to act as nucleation sites for thermally activated martensite with an internally dislocated structure, thereby developing into lenticular martensite. The observations were rationalized by relating M_s to the driving force for martensite formation. In the temperature range (i.e. coupled nitrogen content and M_s) where lath martensite forms athermally, M_s depends strongly on nitrogen content; for the regime where plate martensite forms athermally this dependence is less pronounced (Fig. 2). This observation correlates with the temperature dependence of the critical resolved shear stress for dislocation generation/movement (the internal structure in laths) and for twinning (the internal structure in plate martensite) in the bcc crystal structure. The first is strongly temperature dependent, the second is not. This interpretation is also consistent with thermally activated (isothermal) martensite being generally of lath type and thermally activated martensite forming during heating. The origin of thermal activation is most likely the movement of screw dislocations in the bcc lattice.

Additionally, unique results obtained at European Synchrotron Radiation Facility (ESRF) with Dark Field X-ray Microscopy on in-situ isothermal martensite formation were reinterpreted. The data set provides information on lattice rotation, as a measure for plastic strain, and the distribution of elastic residual stress in the remaining austenite.

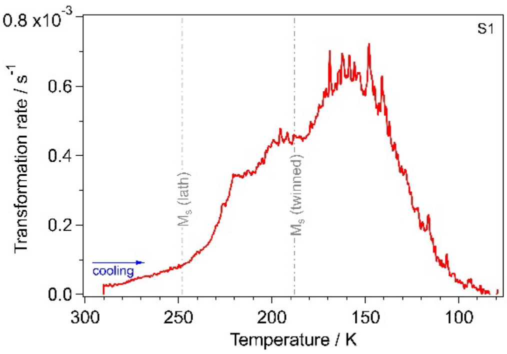

Fig. 1 Transformation rate obtained from in-situ magnetometry measurements in dependence of temperature during isochronal cooling for a specimen with 0.08 wt% N (S1). For temperatures below 189 K (M_s for twinned martensite) bursts appear.

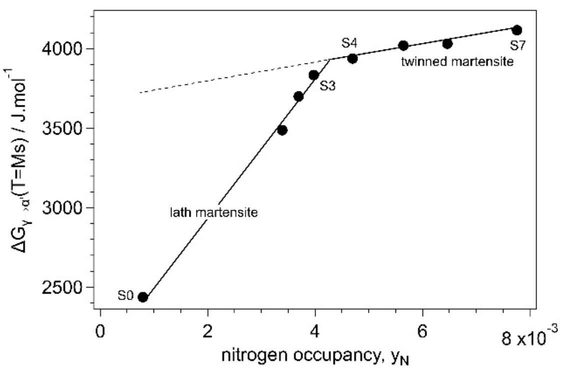

Fig.2 Dependence of the driving force for martensite formation at M_s in dependence of the nitrogen occupancy of octahedral interstices in austenite. During cooling the driving force increases. For samples S0-S3 first lath martensite forms, thereafter plate (twinned); for S4-S7 plate martensite forms immediately.

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