The influence of martensitic transformation on mechanical properties of cast high alloyed CrMnNi-steel under various strain rates and temperatures

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Abstract. Metastable austenitic steels show excellent mechanical properties, such as high strength combined with excellent ductility and toughness due to martensitic transformation under mechanical loading (transformation induced plasticity effect). A good energy consumption, and, in the case of high-alloyed metastable austenitic steels, a high corrosion resistance, increase the potential of these materials for diverse applications, also in regard of safety requirements. Up to now, numerous wrought alloys were investigated concerning mechanical behaviour, TRIP-effect, martensitic transformation behaviour and modelling of transformation kinetics or stress-strain behaviour. New high alloyed cast CrMnNi-steels, developed at Technical University Bergakademie Freiberg, provide the chance to reduce processing steps, production time and costs. In order to understand the influence of temperature on the martensitic phase transformation behaviour and therefore on mechanical properties and failure, the mechanical response under tensile loading in a temperature range between -70°C and 200°C was investigated. The mechanical behaviour under compressive loading was also examined in a wide range of strain rates between $10^4$ s⁻¹ and $10^7$ s⁻¹ to obtain information about the strain rate effect on stress-strain behaviour and microstructural changes.

1. Introduction

Steels using the transformation induced plasticity (TRIP)-effect show high strength and excellent ductility plus high toughness. So far, most investigations deal with wrought alloys, which have to be cold or hot-worked.

In this paper, a recently developed cast high alloyed CrMnNi-steel is investigated. The mechanical behaviour of such steels is closely linked with a martensitic transformation caused by applying a mechanical load. Weiß et al. [1,2] developed stress-temperature-transformation (STT) diagrams for high alloyed wrought steels X5CrNi18-10 (1.4301, AISI304) and X6CrNiTi18-10 (1.4541, AISI 321).
These diagrams characterize typical temperatures and stresses, which define the temperature and stress ranges where transformation occurs. The highest temperature where martensite is formed by mechanical loading is called $M_d$-temperature [3]. Below this temperature, a critical stress level (triggering stress) is required for activating the transformation process. Several transformation routes are proposed in literature: $\gamma \rightarrow \varepsilon$, $\varepsilon \rightarrow \alpha'$ and $\gamma \rightarrow \alpha'$.

However, it is well known that the transformation behaviour is related to stacking fault energy (SFE). The stacking fault energy is a function of chemical composition and of temperature.

In this paper, the influence of temperature on martensitic transformation and stress-strain behaviour is shown for tensile loading, as well as the influence of strain rate for compressive loading.

2. Materials and methods

After melting in an induction furnace, the material was cast in a copper mould under argon gas atmosphere, using technique of rising casting. Tensile and compressive specimens were heat treated at 1050°C for 30 minutes, to retransform any martensite brought in through mechanical machining. The chemical composition of the cast CrMnNi-alloy is listed in table 1.

| Table 1. Chemical composition of cast high alloyed CrMnNi-TRIP-steel. |
|-----------------|------|-----|-----|-----|-----|
| Fe and others   | C    | Cr  | Ni  | Mn  | Si  |
| wt. %           | bal. | 0.05| 15.9| 6.1 | 6.8 | 0.9 |

The corresponding initial microstructure is characterized by a dendritic solidification, consisting of coarse austenitic grains (grain size ~ 1mm) and small amounts of $\delta$-ferrite (< 5%), figure 1. Using the empiric equation of Schramm and Reed [4], the SFE is calculated to 17.5mJ/m². Many observations on high alloyed metastable austenitic steels have a SFE of 20mJ/m² as a critical value governing the kind of deformation mechanism [4-7]. Below this value, the formation of deformation martensite is favoured, instead of mechanical twinning above 20mJ/m².

For mechanical testing at moderate values a servohydraulic testing machine was used, whereas the tests at high strain rates under compressive loading were performed with drop impact test and a Split-Hopkinson-pressure-bar (SHPB). After straining, tensile and compressive specimens were cut off to samples for light-optical-microscopy, SEM, EBSD-measurements and magnetic balance testing. With the magnetic balance test the fraction of $\alpha'$-phase can be measured, e.g. described by Talonen [8].

3. Results and discussion

The TRIP-effect involves an anomaly in elongation values with decreasing temperature, especially in uniform elongation, figure 2. The unusual deformation response is explained by a change in the dominating deformation mechanism of slip, martensite phase transformation (TRIP-effect) or mechanical twinning (TWIP-effect). Weiß correlates the beginning of this anomaly with the formation of $\varepsilon$-martensite and the $M_d$/$\gamma \rightarrow \varepsilon$ temperature for comparable steels, but with less manganese [1,2].

The maximum elongation value is assumed among 60°C and 100°C, corresponding with beginning formation of $\alpha'$-martensite, resulting in a strong increase of ultimate tensile strength below this temperature range.

Regarding the stress values at 0.2% plastic strain in figure 2, a second anomaly in mechanical behaviour is observed. At temperatures below 20°C, a decrease in yield strength with a minimum at -40°C occurs. Due to the subsidence of triggering stress for $\gamma \rightarrow \alpha'$-formation below the value of yield stress [3,9] the so called stress-induced martensitic transformation appears. This stress-induced transformation causes a micro plasticity, resulting in lower values for elastic slope and yield strength [9].
The temperature dependence of flow stress and strain hardening behaviour is plotted in figure 3 and figure 4, respectively. The cast CrMnNi-alloy shows a pronounced TRIP-effect, which is indicated by high strain hardening values and microstructural observations. At low temperatures the austenitic phase transforms almost completely to $\alpha'$-martensite. The formation of $\alpha'$-phase leads to a sigmoidal shape of the flow curve, especially at low temperatures. The first $\alpha'$-martensite is measured at 60°C, whereas at higher temperatures mechanical twinning is observed.

The martensitic transformation to $\alpha'$-phase leads to a maximum in strain hardening, corresponding to an inflection point in the flow curve. The lower the temperature, the higher the maximum in strain hardening. With increasing temperature, this maximum is lowered and moved to higher strain values, disappearing at least. As a result of a rise in SFE with increasing temperature, a change in deformation mode to mechanical twinning occurs, resulting in another strain hardening behaviour.

The influence of strain rate on compressive flow stress is shown in figure 5. The yield strength increases slightly with rising strain rate. The strain rate has a strong influence on strain hardening in terms of a transition from isothermal (0.0004s$^{-1}$) to adiabatic behaviour at high strain rates (2200s$^{-1}$). Due to plastic deformation and short deformation time, heat is generated and remains in the specimen. The temperature increase in the sample causes a rise in SFE and therefore inhibits martensitic transformation. For this reason the strain hardening is lowered with increasing strain and strain rate.

The evolution of microstructure during straining at room temperature is explained by the following steps: First of all, thin slip bands emerge, causing a fragmentation of coarse austenitic grains. In these
slip bands a high density of stacking faults is generated. If this stacking fault density exceeds a critical value, an indication as $\varepsilon$-martensite is possible. The intersections of slip bands and the shear band-grain boundary intersections build nucleation sites for the formation of $\alpha'$-phase, figure 6 [6,10-12].

4. Conclusions
The examined cast CrMnNi-alloy shows a distinctive TRIP-effect and therefore has excellent mechanical properties. The material undergoes a change in deformation behaviour with varying temperature. While above 100°C twinning occurs, $\alpha'$-martensite is detectable below this temperature. The formation of $\alpha'$-martensite during straining is distinguishable in a sigmoidal shape of flow curves and in a pronounced maximum in strain hardening. At temperatures below 20°C an anomaly in yield strength is observed which can be explained by the effect of stress-induced martensitic transformation. At higher strain rates a temperature rise in specimen and a transition from isothermal (0.0004s$^{-1}$) to adiabatic (2200s$^{-1}$) material behaviour occurs. Therefore, with increasing strain rate martensitic transformation is inhibited and a lower strain hardening effect is observed.

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