Pierce et al. [2] are, on the other hand, consistent with both thermodynamics and observed deformation mechanisms and will be used to further improve the present description.

5. References


EXTENDED ABSTRACT

Thermodynamic-Mechanical Modeling of Martensite Formation in Fe-19Cr-3Mn-4Ni-0.15N-0.2C Austenitic Cast Steel

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Abstract:
Cast austenitic Fe-Cr-Mn-Ni steels are characterized by an excellent combination of strength and ductility. The present study aims to describe the mechanical properties of an Fe-19Cr-3Mn-4Ni-0.15N-0.2C cast steel in view of the plasticity mechanisms involved namely the dislocations glide in the austenite, the transformation-induced plasticity (TRIP), and the twinning-induced plasticity (TWIP). In the absence of external stresses, the experimental steel, designed on the basis of thermodynamic calculations, remains fully austenitic at temperatures as low as -196 °C. The mechanical properties were determined by uniaxial static tensile tests in the temperature range of -40 °C to 200 °C. The microstructure of specimens strained until fracture was examined by light optical microscopy and electron backscattering diffraction (EBSD) analysis. The ferromagnetic content, indicative of the deformation-induced γ→α martensite content, was determined with the aid of magnetic saturation measurements. The stress and temperature range associated with stress- and strain-induced martensite formation were presented for the description of the TRIP effect in the austenitic steel. The results are shown in Stress-Temperature-Transformation (STT) diagrams. In addition to the STT diagram, a Deformation-Temperature-Transformation (DTT) diagram was constructed to represent the strain values corresponding to each critical stress level in the respective STT diagram. A DTT diagram enables the separation of strain contributions owing to the glide of dislocations in the austenite as well as those due to the deformation-induced twinning and martensitic transformation. The summation of these strain contributions yields the experimental uniform elongation of the steel which was remained above 50% in the considered temperature range of 40 °C to 200 °C. In summary, the relationship between flow curves and deformation-induced microstructural changes is described by means of the STT and DTT diagrams.

Key words:
Stress-temperature-transformation diagram (STT), deformation-temperature-transformation diagram (DTT), TRIP/TWIP, austenitic cast steel
1. Introduction

Stress- and strain-induced phase transformations can occur during deformation of cast austenitic steels. Depending on the chemical composition and the deformation temperature, various deformation mechanisms may occur. Examples are $\gamma \rightarrow \alpha$ and $\gamma \rightarrow \alpha + \gamma$ martensitic transformations and deformation twinning. Deformation-induced martensite formation and twinning may lead to an increase of ductility and strength via transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP), respectively. To understand the deformation mechanisms in austenitic steels, it is important to describe the conditions favoring each mechanism for instance the temperature-dependent stress values required to trigger the TRIP or TWIP effects. The stress-temperature-transformation (STT) and deformation-temperature-transformation (DTT) diagrams have been developed for the purpose of concise illustration of such information. Use of DTT diagrams was first proposed by Schumann and co-workers. [1] The construction procedure and the relationship between STT and DTT diagrams were later elaborated by Gutte and Weiß for the 1.4301 austenitic stainless steel. [2] In this paper, the STT and DTT diagrams are presented for a solid-solution strengthened austenitic cast steel.

2. Experimental Procedure

2.1 Production of the Cast Steel

The steel was melted in a vacuum induction furnace under a nitrogen partial pressure of 450 mbar before being cast into a water-cooled copper mould with a dimension of 230 x 35 x 95 mm$^3$. To avoid the pore formation during casting, the nitrogen partial pressure was raised to 1500 mbar during casting. The reached chemical composition of the cast steel is given in Table 1.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>N</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>19NC 1715</td>
<td>0.154</td>
<td>0.167</td>
<td>18.70</td>
<td>2.94</td>
<td>4.22</td>
<td>0.52</td>
</tr>
</tbody>
</table>

2.2 Heat Treatment

To avoid the possible presence of strain-induced martensite in tensile test specimens, the heat treatment step was performed after machining of tensile specimens. The heat treatment followed the objectives of dissolving carbides and nitrides likely present in the as-cast microstructure and allowing for the partial homogenization of the steel in the austenitic phase field. The solution annealing treatment consisted of holding the steel at 1150°C for 30 minutes under an argon atmosphere.

2.3 Tensile Tests and Magnetic Saturation Measurements

The specimens were tensile tested at a strain rate of 4 x 10$^{-4}$ s$^{-1}$ using a Zwick 1475-type universal testing machine. With the aid of a thermal chamber which surrounded the tensile specimen and the sample holding jaws, different temperatures in the range of -40°C to 200°C could be adjusted. A Metis MSAT-type magnetic saturation device equipped with a Lakeshore 480 fluxmeter was used for the quantification of the ferromagnetic phase content in fractured tensile specimens. This equipment enables the measurement of magnetic flux density in specimens magnetized until saturation. The ferromagnetic phase fraction of the steel is then calculated after an internal correction for the chemical composition.

2.4 Light Optical Microscopy

The microstructures were examined by light optical microscopy to determine the delta ferrite fraction and to make a comparison with the martensite contents determined by the magnetic saturation results. The specimens were ground under a stream of hot water to avoid deformation-induced martensite formation during preparation. The specimens were finally electro-polished and etched with nitric acid.

3. Results and Discussion

3.1 Analysis of the Microstructure and Deformation-Induced Martensite Formation

Shown in Figure 1 is the $\gamma$-martensite fraction as a function of deformation temperature during quasi-static uniaxial tensile tests. Deformation-induced martensite forms when the trigger stress is reached during the tensile test. At the $M_T$ temperature, the trigger stress is just equal to the tensile strength. At temperatures lower than the $M_T$ temperature, the martensitic transformation may occur. A martensite content of 56% was observed after tensile deformation at -40°C.

![Figure 1: Alpha martensite content in the gauge section of fractured tensile specimens as a function of tensile test temperature. The phase fractions were determined by magnetic saturation measurements.](image)

As shown in the light optical micrographs of Figure 2, the deformed microstructure contains a delta ferrite fraction of 3 to 4 vol.% which existed even before tensile deformation. As demonstrated in Figure 2, decreasing tensile test temperature increases the chemical driving force for the $\gamma \rightarrow \alpha$ martensite formation and leads to the deformation-induced $\gamma$-martensite formation (Figure 2a). At temperatures above the $M_T$, twinning and dislocation glide in the austenite act as the dominant deformation mechanisms. (Figure 2b).

![Figure 2: Optical micrographs of the test steel after tensile deformation until fracture at various temperatures: (a) The austenitic matrix after tensile testing at -40°C has partially transformed to martensite; (b) The austenitic matrix after testing at 70°C has remained untransformed.](image)
3.2 Stress-Temperature-Transformation and Deformation-Temperature-Transformation Diagrams

To create the STT and DTT diagrams, the analysis of the microstructure and flow curves at various temperatures is needed. The yield strength, tensile strength and the corresponding elongations can be determined directly from the flow curves. In the flow curves of austenitic steels tensile tested below the $M_s$ temperature, two inflection points may be identified. The first inflection point denotes the triggering stress for the alpha martensite formation. The second inflection point, on the other hand, represents the theoretical tensile strength of the austenite in the absence of TRIP effect. The direct experimental determination of the tensile strength of austenite is only possible with tensile tests above the $M_s$ temperature. The triggering stress for deformation twinning and epsilon martensite formation may be determined by the microstructural analysis of interrupted tensile test specimens. The theoretical uniform elongation of the austenite, $\varepsilon_{\text{up}}$, may be inferred from the second inflection point.

![Flow curves](image)

Figure 3: a) STT diagram, b) DTT diagram, and c) flow curves for the test steel

4. Conclusions

- Various deformation mechanisms were activated in a solid solution strengthened Fe-Cr-Mn-Ni steel with the aid of tensile tests at temperatures between -40°C and 200°C.
- STT and DTT diagrams were developed for the newly-developed steel to account for the observed temperature dependence of mechanical properties.

5. References