Fatigue behavior and phase transformation in austenitic steels in the temperature range -60°C ≤ T ≤ 25°C

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Abstract

Fatigue behavior and phase transformation in the metastable austenitic steels AISI 304, 321 and 348 were investigated in the temperature range from -60°C to 25°C by means of stress-strain hysteresis, electrical resistance and magnetic measurements. The steels show differences in austenite stability, which lead to significant changes in deformation induced martensite formation and fatigue behavior in total strain controlled low cycle fatigue tests. Dependent on the type of steel and testing temperature similar values of martensite fraction but different strengths developed.

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Austenitic steel; deformation induced martensite; fatigue behaviour; low temperature.

Nomenclature

ΔR change in electrical resistance

ε_{a,t} total strain amplitude

\bar{ε}_{a,p} mean value of plastic strain amplitude

σ_a stress amplitude

ξ α’-martensite fraction measured with a magnetic ferritescope sensor

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1. Introduction

Various austenitic steels are in a metastable state up to ambient temperature and can transform into martensite due to plastic deformation [1-3]. Phase transformation from paramagnetic austenite into ferromagnetic $\alpha'$-martensite leads to a significant change in the fatigue behavior and can be detected by non-destructive magnetic and electric measuring techniques [4-6]. The austenite stability, viz. susceptibility to formation of deformation induced martensite, depends on the chemical composition, the temperature and the degree of plastic deformation. The influence of the chemical composition on the austenite stability is usually characterized with the martensite start temperature $M_s$ for thermally induced martensite formation and the so-called $M_{d30}$ temperature for deformation induced martensite formation. Several empirical equations have been developed to calculate these temperatures [7, 8]. Mostly the equations according to Eichelmann and Angel are used to estimate the $M_s$- and $M_{d30}$-temperature, respectively. However, these widely known equations do not include the influence of the content of titanium and niobium, which are added to improve the resistance against intergranular corrosion, on the austenite stability. Moreover, additional alloying with titanium ($Ti \geq 5 \cdot C$) or niobium ($Nb \geq 10 \cdot C$) leads to the formation of titanium- or niobium-carbides which reduces the carbon content in solution and therefore reduce the austenite stability. The deformation induced martensite formation has been intensively investigated [9] and modelled [10] for monotonic loading of austenitic steels at ambient (AT) and low temperature (LT). Furthermore the deformation induced martensite formation under cyclic loading at AT [1-5, 7, 8] and LT [11-14] is known in literature, but only few models exist, which describe deformation induced martensite formation under cyclic loading at AT [8]. No model of deformation induced martensite formation under cyclic loading exists for LT and only few data about their influence on the fatigue behaviour of austenitic steel at LT are available. Hence a comprehensive database for cyclically loaded metastable austenitic steels and detailed information about the deformation induced martensite formation at LT is necessary.

2. Materials and experimental setup

The investigated materials are the three metastable austenitic steels AISI 304 (X5CrNi1810, 1.4301), AISI 321 (X6CrNiTi1810, 1.4541) and AISI 348 (X10CrNiNb189, 1.4546). Their chemical compositions are given in Tab. 1. To obtain a homogeneous microstructure, solution annealing at $T = 1050\,^\circ C$ for 35 min with subsequent quenching in helium atmosphere was performed. Afterwards grain sizes of $64 \, \mu m$ (AISI 304), $43 \, \mu m$ (AISI 321) and $34 \, \mu m$ (AISI 348) were measured.

Table 1. Chemical composition of investigated metastable austenitic steels (weight-%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Ti</th>
<th>Nb</th>
<th>Mn</th>
<th>Mo</th>
<th>N</th>
<th>Cu</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>V</th>
<th>W</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>0.040</td>
<td>18.29</td>
<td>8.19</td>
<td>0.01</td>
<td>0.02</td>
<td>1.40</td>
<td>0.18</td>
<td>0.078</td>
<td>0.19</td>
<td>0.36</td>
<td>0.040</td>
<td>0.012</td>
<td>0.03</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>AISI 321</td>
<td>0.035</td>
<td>17.59</td>
<td>9.29</td>
<td>0.30</td>
<td>0.03</td>
<td>1.45</td>
<td>0.23</td>
<td>0.008</td>
<td>0.28</td>
<td>0.56</td>
<td>0.037</td>
<td>0.008</td>
<td>0.11</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>AISI 348</td>
<td>0.021</td>
<td>17.44</td>
<td>9.34</td>
<td>0.01</td>
<td>0.36</td>
<td>1.47</td>
<td>0.34</td>
<td>0.009</td>
<td>0.09</td>
<td>0.54</td>
<td>0.023</td>
<td>0.009</td>
<td>0.11</td>
<td>0.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

In Tab. 2 monotonic mechanical properties at AT, hardness as well as $M_s$- and $M_{d30}$-temperature of the investigated austenites in the solution-annealed state are given. The AISI 304 has the highest hardness of 208 HV and also the best monotonic properties of the investigated steels at AT. Furthermore the austenite stability decreases from AISI 304 over AISI 321 to AISI 348 what is indicated by increasing values of the $M_s$- and $M_{d30}$-temperature.
Table 2. Mechanical properties (selection) and parameters to characterize martensitic transformation

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_0$ [MPa]</th>
<th>$\sigma_p 0.2$ [MPa]</th>
<th>$\alpha$ [%]</th>
<th>hardness HV10</th>
<th>$M_s$ [°C]</th>
<th>$M_{s30}$ [°C]</th>
<th>$\alpha'$ at fracture [vol.-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>638</td>
<td>247</td>
<td>77</td>
<td>208</td>
<td>-171</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>AISI 321</td>
<td>602</td>
<td>208</td>
<td>59</td>
<td>176</td>
<td>-91</td>
<td>43</td>
<td>36</td>
</tr>
<tr>
<td>AISI 348</td>
<td>616</td>
<td>257</td>
<td>51</td>
<td>177</td>
<td>-66</td>
<td>48</td>
<td>50</td>
</tr>
</tbody>
</table>

Total strain controlled low cycle fatigue tests were performed on a servo-hydraulic testing system using a constant total strain amplitude of $\varepsilon_{\Delta e} = 1\%$ at a load ratio of $R_c = -1$, a frequency of 0.2 Hz and a triangular load-time function in the temperature range $-60^\circ C \leq T \leq 25^\circ C$. Fatigue tests up to $25^\circ C$ were performed using a cooling chamber developed at the Institute of Materials Science and Engineering at the University of Kaiserslautern. The gauge length of the specimen and the applied measuring technique are completely embedded in the cooling chamber. The cooling system works with liquid nitrogen which is expanded to a cooling gas through a nozzle. By adjusting the flow of nitrogen, defined temperature set points at the specimen surface can be tuned using a thermocouple. During the fatigue tests stress-strain hysteresis ($\sigma$-$\varepsilon$), electrical resistance ($\Delta R$) and magnetic induction data ($\zeta$), as an indicator for the amount of deformation induced $\alpha'$-martensite, were measured. The $\alpha'$-martensite fraction was measured in-situ with a ferrite scope sensor. The measured magnetic fraction of this sensor is indicated in vol.-% ferrite. In literature a linear correlation between vol.-% ferrite and vol.-% $\alpha'$-martensite is given [6] but only up to 60 vol.-% of $\alpha'$-martensite. Because of higher martensite fractions, which developed in the fatigue tests, in the following diagrams the $\alpha'$-martensite fraction will be indicated as $\xi$ in vol.-% without transforming these data in vol.-% martensite.

3. Results

The investigation was started with fatigue tests at AT. Figure 1 shows the development of the stress amplitude $\sigma_a$ (a), change in electrical resistance $\Delta R$ (b) and change in the magnetic induction $\zeta$ (c), which directly correlates with the ferromagnetic $\alpha'$-martensite fraction, versus the number of cycles N. The $\sigma_a$, N-curves illustrate the cyclic hardening processes after a certain incubation period in a similar way for all steels, but the fatigue process is fundamentally determined by deformation induced austenite-martensite transformation. Because of the lower austenite stability from AISI 304 to AISI 348 higher values in martensite fraction occur and higher stress amplitudes are reached during cyclic loading.

![Fig. 1. Development of (a) stress amplitude $\sigma_a$, (b) change in electrical resistance $\Delta R$ and (c) ferromagnetic $\alpha'$-martensite fraction $\xi$ versus the number of cycles N](image)
Apart from the geometry the electrical resistance also depends on the resistivity, which is strongly influenced by the load- and cycle-dependent defect density and the austenite-martensite phase transformation. Hence a significant increase of $\Delta R$ was detected due to the deformation induced phase transformation (Fig. 1b). After a material dependent number of cycles $N$, the formation of $\alpha'$-martensite starts and increases continuously with increasing number of cycles up to specimen failure (Fig. 1c). According to the $M_S$- and $M_{A30}$-temperatures of the investigated metastable austenitic steels the AISI 304 steel is more stable compared to the titanium-alloyed AISI 321 and the niobium-alloyed AISI 348 steels. The comparison between AISI 348 and AISI 304 demonstrates that increasing austenite stability leads to a decrease in martensite fraction. Cyclic hardening of the AISI 321 and AISI 348 steel leads to a maximum stress amplitude in the range of the tensile strength $\sigma_f = 602$ and 616 MPa of the solution-annealed material states.

The influence of the testing temperature in the range -60°C to 25°C on the cyclic deformation behavior and phase transformation was investigated at the same total strain amplitude of $\varepsilon_{str} = 1\%$. Figure 2 shows the development of the stress amplitude versus the number of cycles. Due to a decrease in temperature an increase of the stress amplitude occurs for all investigated steels. The maximum stress amplitude occurs at -60°C in each case and is 1270 MPa for AISI 304, 1115 MPa for AISI 321 and 1076 MPa for AISI 348. This significant cyclic hardening can be correlated with two phenomena, an increase of the amount of martensite and the strength of martensite. But as AISI 304 has the highest content of carbon this causes higher stresses at the same volume fraction of martensite (comp. Fig. 2 and Fig. 3). This behavior was also observed during monotonic loading of metastable austenitic steels at low temperatures [9].

![Fig. 2. Development of the stress amplitude $\sigma_s$ versus the number of cycles $N$ at different testing temperatures in total strain control low cycle fatigue tests](image)

The development of deformation induced martensite fraction $\xi$ during the fatigue tests in the temperature range -60°C to 25°C shows the typical sigmoidal shape (Fig. 3) and is comparable to the results of isothermal tensile tests [9, 10]. After an initial phase with a martensite fraction close to zero and a following non-proportional increase of the rate of martensite formation $d\xi/dN$, a constant increase of $d\xi/dN$ is observed. A third phase with a decreasing $d\xi/dN$ was also detected with exception of the tests at AT and 0°C for AISI 304 due to specimen failure. An increase of austenite stability from AISI 348 to AISI 304 leads to a decrease of maximum martensite fraction in the saturation state $\xi_{max}$. Hence a change in the rate of martensite formation was detected. At a definite temperature AISI 348 has the highest $d\xi/dN$, but with decreasing temperature only a small increase of $d\xi/dN$ and $\xi_{max}$ occurs, whereas lower temperatures lead to significant changes in $d\xi/dN$ and $\xi_{max}$ for AISI 304 and AISI 321.
Figure 4a shows the maximum martensite fraction, which developed during fatigue tests. At ambient temperature and 0°C in AISI 304 and in AISI 321 no plateau in $\xi$, N-curves (arrows in Fig. 4a) was reached. Besides investigations on the influences of low temperature on the development of deformation induced martensite during cyclic loading, the mean plastic strain amplitudes, which are the arithmetic averages of the plastic strain amplitude from 10 % to 90 % of the number of cycles to failure, were identified (Fig. 4b). Generally the plastic strain amplitudes are about ten times higher than the plastic strain amplitudes for tempered steels. Interesting as well is that at -30°C respectively -60°C higher austenite stability and therefore a smaller amount of martensite for AISI 304 leads to smaller plastic strain amplitudes of 0.36 % / 0.28 % for AISI 304 compared to 0.39 % / 0.36 % for AISI 321 and 0.42 % / 0.40 % AISI 348 whose martensite fractions are nearly equal.

These results indicate that, due to the difference in chemical composition, mainly in carbon content, a different strength of martensite can be achieved. Obviously changes in the chemical composition of austenitic steels as well as changes in the loading temperature allow to identify an optimum of martensite fraction resulting in best fatigue properties. For example the same $\xi_{\text{max}}$ = 60 vol.-% can be achieved with AISI 321 at 0°C and AISI 304 at -60°C. But the martensite formation rate and therefore cyclic hardening behavior is significantly different leading to a smaller number of cycles to failure and a higher maximum...
stress amplitude of $N_f = 540$, $\sigma_a = 908$ MPa for AISI 321 compared to $N_f = 1050$, $\sigma_a = 1270$ MPa for AISI 304. Fig. 4c shows the number of cycles to failure $N_f$ versus the temperature. It is obvious, that generally a decrease of load temperature leads to an increase of the fatigue life.

4. Conclusion

Low cycle fatigue tests with a total strain amplitude of 1 % were performed in the temperature range $-60^\circ C \leq T \leq 25^\circ C$ using the metastable austenitic steels AISI 304, AISI 321 and AISI 348. According to the chemical composition and the resulting $M_s$- and $M_{d30}$-temperatures, increasing cyclic hardening due to increasing austenite martensite transformation occurred with decreasing testing temperature and decreasing austenite stability. The formation of martensite showed typical sigmoidal curves reaching a plateau at different material and temperature dependent values. A decrease of the martensite plateau from AISI 348 to AISI 304 at low temperatures leads to reduced ductility and higher stress amplitudes due to the highest carbon content in AISI 304. Changes in the chemical composition and in the temperature allow to identify an optimum martensite fraction resulting in best fatigue properties.

Acknowledgements

The support of this work by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) is gratefully acknowledged.

References