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Crack propagation behavior of solution annealed austenitic high interstitial steels

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ABSTRACT

Austenitic stainless steels provide a beneficial combination of chemical and mechanical properties and have been used in a wide field of applications for over 100 years. Further improvement of the chemical and mechanical properties was achieved by alloying nitrogen. But the solubility of N within the melt is limited and can be increased in substituting Ni by Mn and melting under increased pressure. In order to avoid melting under pressure and decrease production costs, a part of N can also be substituted by C. This leads to austenitic high interstitial steels (AHIS). Within the solution annealed state strength and ductility of AHIS is comparable or even higher of those of AHNS and can be further improved by cold working. Unfortunately the endurance limit does not follow this trend as it is known from cold-worked austenitic CrNi steels. This is due to the differences of the slip behavior which is governed by the stacking fault energy as well as other near field effects. Construction components operating under cyclic loads over long periods of time cannot be considered being free of voids or even cracks. Thus the crack propagation behavior is of strong interest as well. This contribution presents the tensile, fatigue, crack propagation and fracture toughness properties of AHNS and AHIS in comparison to those of CrNi-steels. The differences are discussed in relation to microstructural characteristic as well as their alterations under cyclic loading.

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1. Introduction

Austenitic steels are the material of choice in a wide field of applications. The beneficial combination of strength, ductility, and corrosion resistance finds applications in biomedical, automotive, mechanical and process engineering [1–3]. In accordance with the chemical composition e.g. CrNi, CrNiMo, CrNiMoN, CrNiMnMoN as well as MnC (Hadfield type of steels), CrMnN, CrMnCN and CrMnMoN are common for austenitic steels. CrNiMoN, CrNiMoMnN, CrMnN and CrMnMoN are considered being high nitrogen steels [4] while CrMnCN represent high interstitial steels [5].

For CrNi, CrNiMo, and CrNiMoN an overview of both fatigue and crack propagation as well as the related microstructural evolution is given by [6–15]. CrNiMnMoN were investigated by [15,16] accordingly, while the fatigue behavior is mainly characterized by cyclic softening. In CrNi steels wavy slip and strain induced phase transformation from fcc to α′-Martensite was reported [17]. CrNiMo steels also showed wavy slip but only a weak tendency to strain induced phase transformation [7,15,18]. Nitrogen leads to an increase of strength resulting from solid solution hardening and an increase of ductility by the higher density of free electrons, which enhances the metallic character of the interatomic bonds [4]. Planar slip is promoted by dissolved N as a further consequence of this near-field effect [19,20].

Microstructural investigations of MnC are mainly conducted after rolling, tensile, or tribological loading. Srain induced $\gamma \rightarrow \varepsilon$ transformation, twinning and dislocation cells were reported [21–23]. The phase transformation $\gamma \rightarrow \varepsilon$ is prone for MnC steels with a stacking fault energy (SFE) below 20 mJ/m^2 [24,25]. Similar to N-free Ni-alloyed austenitic steels the mechanical behavior of alloys with a SFE > 20 mJ/m^2 is characterized by cyclic hardening within the first cycles followed by cyclic softening until fracture [25–27], while the cyclic behavior is governed by wavy slip [28].

In contrast the high nitrogen steels of CrMnN-type only show dislocation arrangements typical for planar slip within the plastic zone in front of the crack tip as reported by Kamenova et al. [29]. A more detailed investigation on the fatigue behavior of CrMnMoN was reported by [30–32]. Cyclic softening prevailed while solely planar slip and the tendency to strain induced

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Table 1
Chemical composition in wt.% and solution annealing temperature T_{sa}.

	Ni-austenite		Mn-austenite						
Alloyed with	CrNi	CrNiMo	MnC	CrMnN		CrMnMoN	CrMnCN		
Brand name	AISI 304	AISI 316L	Hadfield steel	P 900[a]	P 900 N[a]	P 2000[a]	CarNit		
Designation	Ni0.07	NiMo0.09	GCMn1.20	NMn0.71	NMn0.90	NMnMo0.85	CNMn1.07	CNMn0.96	CNMn0.85
T_{sa} [°C]	1050	1070	1050	1085	1085	1150	1150	1150	1150
Al	0.003	–	0.034	0.013	0.015	0.001	0.0086	0.008	0.007
C	0.026	0.018	1.200	0.086	0.065	0.100	0.489	0.344	0.260
Co	0.12	0.11	0.01	0.02	–	0.01	–	–	–
Cr	17.86	16.56	0.10	18.16	18.18	17.26	18.82	18.20	18.26
Cu	0.352	0.27	0.02	0.03	–	0.04	–	–	0.03
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.
Mn	1.86	1.75	12.17	19.32	18.93	12.30	18.89	18.89	18.52
Mo	0.30	2.04	–	0.06	0.04	3.03	0.07	0.06	0.04
N	0.040	0.076	0.000	0.627	0.830	0.750	0.578	0.614	0.590
Nb	0.02	–	–	–	–	0.01	–	–	0.01
Ni	8.32	10.15	0.05	0.35	0.38	0.14	0.41	0.34	0.26
P	0.029	0.030	0.011	0.021	0.018	0.017	0.020	0.018	0.018
S	0.024	0.024	0.004	0.001	0.001	0.008	0.002	0.002	0.001
Si	0.56	0.38	0.42	0.40	0.30	0.81	0.43	0.30	0.26
Ti	0.01	–	–	–	–	–	–	–	–
V	0.09	–	0.01	0.06	0.06	0.03	0.05	0.04	0.05
C + N	0.066	0.094	1.200	0.713	0.895	0.850	1.067	0.958	0.850
N/C	1.536	4.222	0.000	7.291	12.769	7.500	1.183	1.782	2.269
C/N	0.651	0.237	∞	0.137	0.078	0.133	0.845	0.561	0.441

[a] Brand names are registered trademarks of Energietechnik Essen GmbH, Essen, Germany.

Table 2
Compact C(T) specimen proportions.

Material designation	Proportion (mm)		
	W	B	a_0
Ni0.07	51.0	25.4	10.2
NiMo0.09			
NMn0.71			
NMnMo0.85			
CNMn0.85			
CNMn1.07			
CNMn0.96	51.0	16.8	10.2
NMn0.90	33.2	15.3	6.6
GCMn1.20			

W – specimen width, B – specimen thickness, a_0 – original crack size.

twinning and $\gamma \rightarrow \varepsilon$ transformation are reported being typical. This also holds true for CrMnN and CrMnCN steels as shown by Ref. [19,33]. In conclusion it became clear that the fatigue limit of solution annealed austenitic steels is mainly ruled by the amount of interstitially dissolved alloying elements like C and N.

However, there is a lack of information on stable crack propagation behavior and the resulting microstructural changes in such steels. Thus this contribution should present the stable crack growth behavior of Ni-free N-alloyed CrMnC-steels and discuss the differences to CrNiC-as well as to N-free ones.

2. Materials and methods

2.1. Materials

Nine austenitic steels from the above mentioned groups CrNi, CrNiMo, as well as MnC, CrMnN, CrMnCN and CrMnMoN with different sums and ratios of C and N were investigated. The designation was chosen with respect to the main alloying elements as well as to the sum of the interstitials C and N. The content of C, N or C + N alloying is brought about by the designation when the interstitial content of the referred species is above 0.15 wt.%. The number given in the designation represents the sum of C + N in wt.%. E.g. CNMn0.85 refers to the group of Mn-austenites with C > 0.15 wt.%, N > 0.15 wt.% and C + N = 0.85 wt.%. The chemical composition and solution annealing temperature T_{sa} of the investigated alloys is given in Table 1.

The blanks before solution annealing were wrought bars in case of Ni0.07, NiMo0.09, NMn0.90, NMnMo0.85, CNMn0.85, CNMn0.96 and CNMn1.07, a wrought retaining ring in case of NMn0.71, and centrifugally cast tubes in case of GCMn1.20 (G ~ Guss, german for cast). After heat treatment the grain size, hardness, and tensile properties were measured according to [34–37] respectively.

2.2. Fatigue tests

To characterize the fatigue behavior uniaxial total strain controlled ($\varepsilon_{a,t}$) tension–compression tests were carried out using

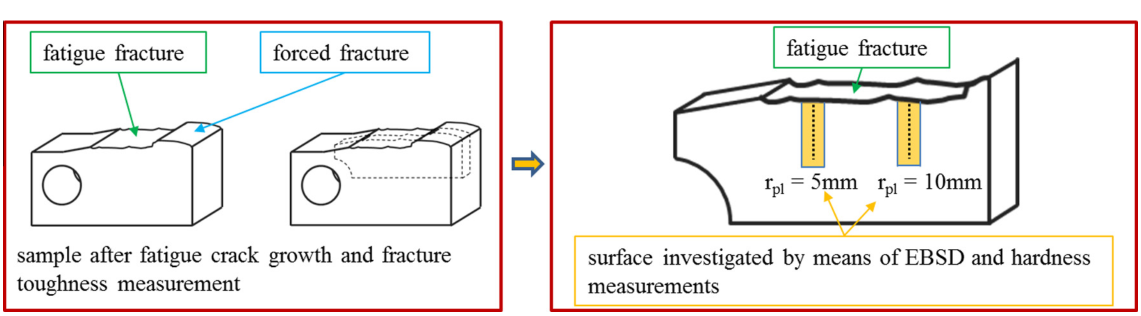

Fig. 1. Sequence of metallographic specimen generation after crack propagation measurements.

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