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Modelling of cyclic plasticity for austenitic stainless steels 304L, 316L, 316L(N)-IG

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HIGHLIGHTS

- Stress-strain amplitudes of cyclic stress strain curves defined by design codes are provided as reference data.
- A macroinstruction simulating cyclic plasticity and producing hardening parameters of constitutive models is developed.
- Hardening parameters of the nonlinear Chaboche model are provided for stainless steels 316l-N, 316L, 304L at different temperatures.
- Ratcheting is simulated by using the produced hardening parameters.

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ABSTRACT

The integrity assessment of structures subjected to cyclic loading must be verified with regard to cyclic type damage including time-independent fatigue and progressive deformation or ratcheting.

Cyclic damage is verified simulating the material elastic-plastic loop and looking at the accumulated net plastic strain during each cycle at all points of the structure subjected to the complete time history of loadings.

This work deals with the development of a numerical model producing the Chaboche hardening parameters starting from stress-strain data produced by testing of materials. Then, the total plastic strain can be simulated using the Chaboche inelastic constitutive model requested for finite element analyses. This is particularly demanding for pressure vessels, pressurised piping, boilers, and mechanical components of nuclear installations made of stainless steels.

A design optimisation by iterative analyses is developed to approach the stress-strain test data with the Chaboche model. The parameters treated as design variables are the Chaboche parameters and the objective function to be minimised is a combination of the deviations from test data. The optimiser calls a macroinstruction simulating cyclic loading of a sample for different material temperatures.

The numerical model can be used to produce hardening parameters of materials for inelastic finite element verifications of structures with complex joints like elbows subjected to a combination of steady sustained and cyclic loads.

1. Introduction

Cyclic type damage of structures must be verified according to design Codes [1,2] including time-independent fatigue and progressive deformation or ratcheting. These verifications can be carried out on results of finite element (FE) analyses simulating stress-strain states of components under cyclic loading. Two hardening models, parametric in temperature, have been investigated for austenitic stainless steels: the first is a multilinear kinematic hardening model used for fatigue analyses as it simulates material hardening at stable hysteresis loops; the second is the Chaboche's nonlinear hardening model suitable to simulate ratcheting and shakedown occurring with non-symmetric hysteresis loops [3]. Cyclic damage is verified simulating the material elastic-plastic loop and looking at the accumulated net plastic strain during each cycle at all points of the structure subjected to the complete time history of loadings. This is particularly demanding for pressure vessels and piping, boilers, and mechanical components of nuclear installations made of stainless steels.

Service experience and results obtained from research and development work, including the fusion and the fast breeder reactor programmes, recommend as structural material the solution-annealed type 316L-N steel, i.e. a low carbon grade where

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Table 1
Cyclic strength coefficients and cyclic strain hardening exponents for 316L-N [2].

Parameter	$T=20\,°C$	$450 \le T \le 600\,°C$	$T=650\,°C$
A_f [MPa]	798.3	722	679
n_f	0.3387	0.3025	0.2365

Table 2
Cyclic strength coefficients and cyclic strain hardening exponents for 316L and 304L [2].

Parameter	$T=20\,°C$	$300 \le T \le 550\,°C$	$T=600\,°C$[a]
A_f [MPa]	711.9	638.7	628.2
n_f	0.351	0.310	0.248

[a] Last column provides data for 316L only.

Table 3
True stress-plastic strain amplitudes of CSS curves for 316L-N; values at the first row are uniaxial yield stresses.

$T=20\,°C$		$450 \le T \le 600\,°C$		$T=650\,°C$	
σ_a [MPa]	$\varepsilon_{a,pl}$	σ_a [MPa]	$\varepsilon_{a,pl}$	σ_a [MPa]	$\varepsilon_{a,pl}$
282	0.00	138	0.00	133	0.00
465	1.98E-3	446	1.97E-3	466	1.97E-3
510	2.60E-3	485	2.59E-3	498	2.59E-3
549	3.22E-3	517	3.21E-3	524	3.20E-3
583	3.83E-3	546	3.83E-3	547	3.82E-3
614	4.45E-3	572	4.44E-3	567	4.44E-3
642	5.07E-3	595	5.06E-3	585	5.05E-3
668	5.68E-3	617	5.67E-3	602	5.67E-3
692	6.30E-3	637	6.29E-3	617	6.28E-3
715	6.91E-3	656	6.90E-3	631	6.90E-3
737	7.53E-3	673	7.51E-3	645	7.51E-3
757	8.14E-3	690	8.12E-3	657	8.12E-3

Table 4
True stress-plastic strain amplitudes of CSS curves for 316L and 304L; values at the first row are uniaxial yield stresses.

$T=20\,°C$		$300 \le T \le 550\,°C$		$T=600\,°C$[a]	
σ_a [MPa]	$\varepsilon_{a,pl}$	σ_a [MPa]	$\varepsilon_{a,pl}$	σ_a [MPa]	$\varepsilon_{a,pl}$
235	0.00	120	0.00	102	0.00
406	1.98E-03	389	1.98E-03	423	1.98E-03
450	2.64E-03	426	2.64E-03	455	2.63E-03
486	3.29E-03	457	3.29E-03	481	3.28E-03
519	3.95E-03	484	3.94E-03	504	3.94E-03
548	4.60E-03	508	4.60E-03	524	4.59E-03
575	5.25E-03	529	5.25E-03	542	5.24E-03
599	5.91E-03	549	5.90E-03	558	5.89E-03
622	6.56E-03	568	6.55E-03	573	6.54E-03
644	7.21E-03	585	7.20E-03	587	7.19E-03
664	7.86E-03	602	7.85E-03	601	7.84E-03
684	8.51E-03	617	8.50E-03	613	8.49E-03

[a] Last column provides data for 316L only.

nitrogen is added to compensate the loss of strength due to a reduction in carbon content [4].

For DEMO and for future fusion machines, structural steels like ferritic/martensitic and Eurofer, a low activation martensitic steel with good ductility and excellent resistance to radiation swelling, require post-weld annealing and are sensitive to low temperature irradiation embrittlement. Furthermore, they show cyclic softening during fatigue so complicating design against fatigue and creep-fatigue [5].

The main structural material for the ITER vacuum vessel and in-vessel components (blanket and divertor) is the austenitic stainless steel 316L(N)-IG (ITER Grade). The main driving force for the selection of this material from similar austenitic steels is its high minimum tensile mechanical properties combined with good toughness [6,7]. Recommended mechanical properties of 316L(N)-

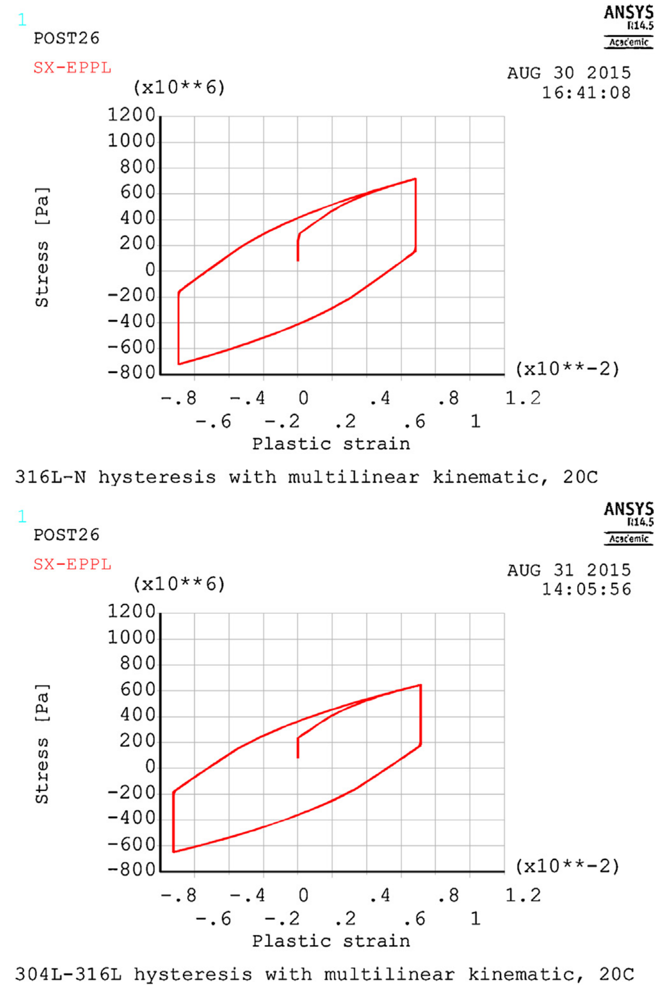

Fig. 1. Hysteresis loops produced by FE analysis with multilinear kinematic hardening model at 20 °C: 316L-N at top, 316L and 304L at bottom.

IG are those of RCC-MR 316L-N [6,4] as there are minor differences in chemical composition between 316L(N)-IG and RCC-MR 316L-N regarding stricter control of the impurity levels (P, S, Co, Nb, Ta). So, the hardening parameters produced in the following for 316L-N are also relevant to 316L(N)-IG as the raw data of both the materials are the same in the database [2].

Standard austenitic stainless steels 316L and 304L are used for some other structural components of ITER: vacuum vessel ports, cryostat, thermal shield, magnet system [6,8]; so the behavior of these materials is also investigated.

The aim of this paper is to explain the numerical procedure developed to produce the material modeling parameters; furthermore, hardening parameters for stainless steels are provided to simulate the behavior of nuclear components under cyclic loading conditions.

Full range of data including maximum plastic strains and temperatures as provided in the database [2] are used to produce hardening parameters for the analysis and verification of components according to design rules and limits [1,2].

All temperatures available in the database [2] are used to produce parametric hardening models; during analysis of components, all the material parametric models have to be implemented in the simulation so the finite element code will interpolate data considering local temperature at each mesh node.

Parameters of the elastic-plastic constitutive models where provided for copper alloys [9]. Then, the results of FE analysis can be post-processed using numerical codes implementing proce-