CYCLIC PLASTIC DEFORMATION–INDUCED MARTENSITIC TRANSFORMATION IN AUSTENITIC STEELS

J. KALETA and G. ZIĘTEK
Institute of Materials Science and Applied Mechanics,
Technical University of Wroclaw, 50–370 Wroclaw, Poland.

ABSTRACT

The paper is part of a broader research project aimed at studying changes in cyclic properties, energy cumulation and fatigue life of metastable austenitic steels undergoing the martensitic transformation at room temperature induced by externally applied cyclic stress.

The study was aimed at evaluating the limit value of cyclic plastic strain on reaching which the martensitic transformation in high–nickel AISI 304L steel begins. Additionally, the crossed magnetomechanical effect (the Villari effect) was shown to be fully applicable in evaluating the amount of the a'–martensite.

Another problem consisted in working out an adequate analytical representation of the cyclic deformation curve (CSSc) covering a wide range of strain. A new four–parameter power model of an elastic–plastic material was used. The model is capable of allowing for the experimentally observed point of inflection on the CSSc. This point separates the single–phase martensite region from the two–phase (austenite + martensite) one. The model incorporates a new material constant termed the martensitic transformation cyclic limit. The analysis was verified with results obtained from 304L steel. The tests were carried out at an increasing load level and the control signal was sinusoidal. The measured quantities were: total, elastic and plastic strains, stress and hysteresis loop area. The experimental results fully confirmed the validity of the model.

KEYWORDS

CSSc, modelling, plasticity–induced martensitic transformation, AISI 304L steel.

INTRODUCTION

A spontaneous martensitic transformation begins at some temperature M_s. An athermal plastic deformation–induced martensitic transformation may be observed at much higher temperature $M_s \leq T \leq M_d$. The M_d temperature in many steels may reach room temperature ($T = 293^0 K$) or even slightly below. The martensite nucleation process may be therefore triggered upon attaining at ambient temperature a certain threshold value of plastic strain (Baldus, 1995; Bayerlein et al., 1989).

The literature pertaining to the subject still leaves a few crucial questions unanswered. For example, what is the critical value of plastic strain $\varepsilon_{pl(M)}$ for the martensitic transformation to start? What is the actual sequence of transformation stages: $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ or, perhaps, $\gamma \rightarrow \alpha'$, i.e. without the $\varepsilon-$ martensite?

The problem is worth studying for both scientific and practical reasons. It concerns a wide variety of austenitic steels, mainly high–manganese and high–nickel alloy steels. Structural components fabricated of such steels may have their strength properties severely affected if the martensitic transformation starts due to a local plastic deformation in austenite. That is why the evaluation of critical values of plastic strain, the determination of amount of the martensite transformation completed under cyclic loading conditions and the analysis of selected cyclic properties have been chosen as the chief goals of the present paper. Structural aspects of the problem, though immensely important, would need a separate study and are omitted here.

EXPERIMENTAL DETAILS

The experiments were aimed at demonstrating that martensite can be formed as a result of plastic deformation and at recording the curves of cyclic deformation $\sigma_a(\varepsilon_a)$. Material used was an austenitic steel of the AISI 304L grade. Chemical composition of the steel is given in Table 1.

Table 1: Chemical composition of the investigated steel.

Element	Cr	Ni	Mn	Si	Mo	P	C	S
%	18.35	10.00	1.25	0.19	0.10	0.02	0.015	0.001

In as–received condition the presence of austenite was confirmed as well as the absence of a ferromagnetic phase ($\delta-$ ferrite). Cylindrical specimens with a diameter of 5.8 mm were tested in uniaxial tension–compression ($R = -1$, $f = 0.2Hz$). The tests were carried out on a hydraulic pulser (MTS-810) at an increasing load level and with the sinusoidal control signal applied. At first, until the amplitude $\sigma_a = 235MPa$ was attained, the stress amplitude was controlled, then, up to fracture ($\varepsilon_a = 0.0078$) – the total strain amplitude. The measured quantities were: total (ε_a), elastic (ε_{el}) and plastic (ε_{pl}) strains, stress (σ) and hysteresis loop area (ΔW). In addition, the magnetic field strength (H) was recorded using a magnetoresistive probe. No external magnetic excitation was applied. The recorded signal H was due to the Villari effect (reverse magnetostriction) occurring in the ferromagnetic phase. The methodology of magnetic investigations and, in particular, the potential of the Villari effect were presented elsewhere (Kaleta and Żebracki, 1995; Kaleta, 1996; Kaleta and Żebracki 1996; Kaleta et al., 1996).

ANALYSIS OF RESULTS

Static tests

Figures 1a and 1b show the static tensile curve $\sigma(\varepsilon)$ and the corresponding magnetic field strength H_m signal. An increase in strain is in general accompanied by a linear increase in H_m. This attests to the presence of a freshly formed ferromagnetic phase (α'–martensite). The two distinct drops on the $H_m(\varepsilon)$ curve have not been explained satisfactorily. They might have been the result of abrupt changes in the transformation rate and a more thorough structural examination is needed to go beyond these general remarks. The $H_m(\varepsilon)$ signal gets saturated and then decreases as the ultimate tensile strength is attained.

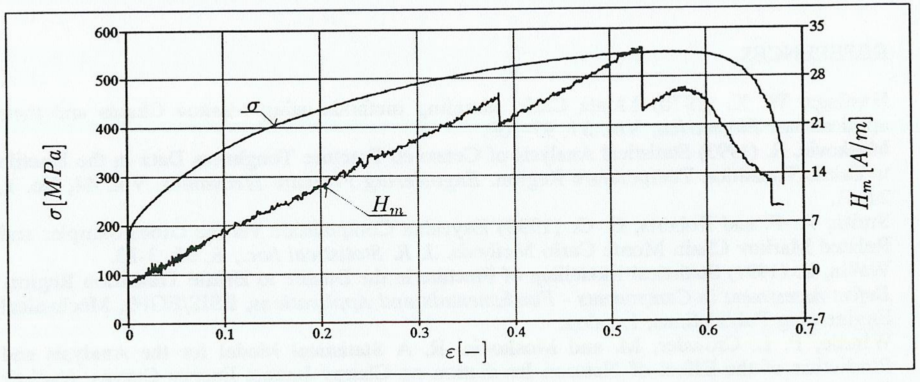

Fig. 1: Static tensile plot $\sigma - \varepsilon$ and the $H_m(\varepsilon)$ dependence.

Dynamic tests

Figures 2a and 2b, respectively, present variation of $\varepsilon(\varphi)$ and $\sigma(\varphi)$ during one cycle as depending on the load level. Figure 3a shows hysteresis loops $\sigma(\varepsilon)$ obtained at an increasing load level. By joining apexes of successive loops one can obtain a curve of cyclic deformation $\sigma_a(\varepsilon_a)$. It is to be noted that this curve here, in contrast to curves from many other

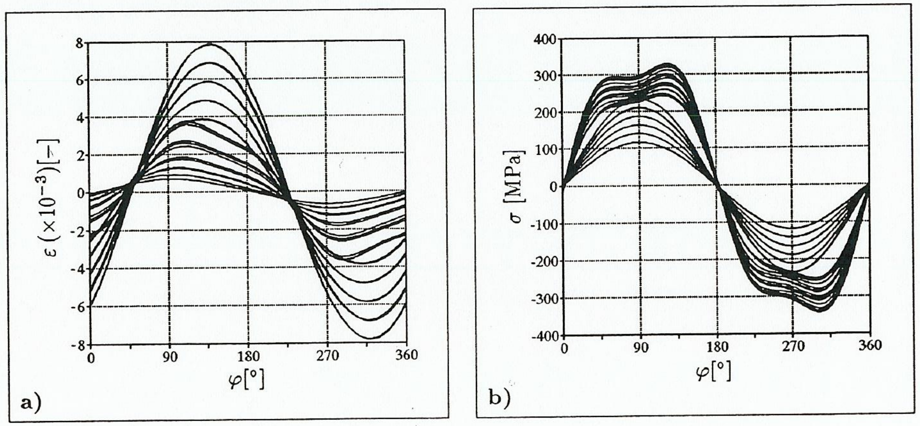

Fig. 2: Variation of signals during one cycle as dependent on the load level: a) $\varepsilon(\varphi)$; b) $\sigma(\varphi)$.

materials, has a point of inflection corresponding to a strain $\varepsilon_a = 0.0038$ ($\varepsilon_{pl} = \varepsilon_{pl(M)}) \cong 0.003$). A similar result was obtained by the authors with a 1H18N9T (18/8 type) steel (Fig. 3b). Similar values can also be found in (Baldus, 1995; Bayerlein et al., 1989). Apart from the cyclic yield point (here $\sigma_0 = 120MPa$), the analytic description of a cyclic deformation curve $\sigma_a(\varepsilon_a)$. should also account for a new material constant σ_M (for the time being called the cyclic limit of the martensitic transformation).

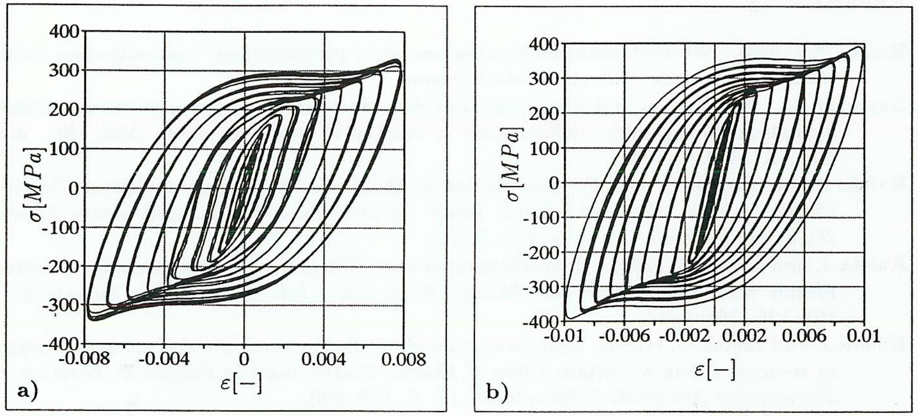

Fig. 3: Hysteresis loops $\sigma(\varepsilon)$ and the cyclic deformation curve $\sigma_a(\varepsilon_a)$ at increasing load: a) AISI 304L steel; b) 1H18N9T steel.

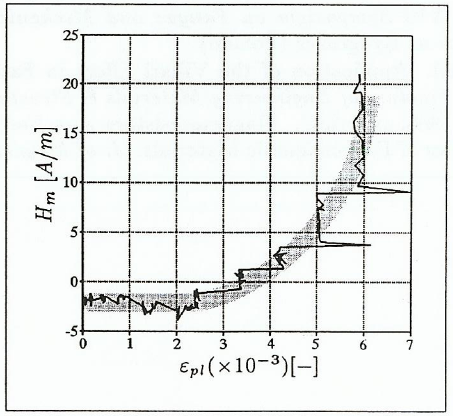

Fig. 4: $H_m(\varepsilon_{pl})$ variation.

In order to demonstrate that the limit value $\varepsilon_{pl} = \varepsilon_{pl(M)}$ can be associated with the onset of the α'–martensite transformation it is necessary to look closer at the magnetic results. Fig. 4 presents the function $H_m(\varepsilon)$. Within the plastic strain region $0 \leq \varepsilon_{pl} \leq 0.003$ no distinct increase of H can be observed (fine fluctuations visible on the plot should be ascribed to the inherent indeterminacy of the method itself). A marked rise of H is seen above the $\varepsilon_{pl(M)}$ value which is a clear manifestation of the ferromagnetic α'–phase presence. Microscopic examinations confirmed this observation.

THE MODEL AND ITS IDENTIFICATION

A cyclic deformation curve (being a function relating stress amplitude to strain amplitude) for materials with plastic deformation–induced martensitic transformation can be defined as a combination of three terms. The characteristic stress amplitude values (together with the corresponding strain amplitudes) at which the dependence undergoes qualitative changes are:

- σ_0 – initial cyclic yield point,
- σ_M – transition stress value at which single–phase material transforms into two–phase one (cyclic limit of the martensitic transformation).

On the cyclic deformation plot the σ_M value is a point of inflection. The models that have been used recently for a wide class of materials (Kaleta and Ziętek, 1992, 1993, 1994) are incapable of allowing for this feature. It is necessary, therefore, to work out a new adequate model of $\sigma_a(\varepsilon_a)$. According to our proposal, the curve is approximated using a power model of an elastic–plastic body, both for single– and two–phase regions, namely:

$$\varepsilon_a = \begin{cases} \dfrac{\sigma_a}{E} & for \quad \sigma_a \leq \sigma_0 \\ \dfrac{\sigma_a}{E} + \left\langle \dfrac{\sigma_a - Y(\sigma_a, \sigma_M)}{K} \right\rangle^n & for \quad \sigma_0 < \sigma_a \leq \sigma_M \\ \dfrac{\sigma_a}{E} + \left\langle \dfrac{\sigma_a - \sigma_M}{K_1} \right\rangle^{n_1} & for \quad \sigma_a > \sigma_M \end{cases}$$

where:

$$\langle x \rangle = \begin{cases} x & for \quad x \geq 0 \\ 0 & for \quad x < 0 \end{cases}$$

For amplitudes smaller or equal to σ_0 the material is assumed to be linear–elastic. Above σ_0 the total strain is taken as a sum of the linear–elastic strain and the plastic strain. The plastic strain is a power function of a surplus stress above the "instantaneous" plastic limit if the working stress is lower than σ_M and a power function of a surplus stress above the σ_M value for the two–phase material.

The function $Y(\sigma_a, \sigma_M)$ is a representation of the yield limit dependent upon the stress amplitude. Allowing for the experimental results, this function in this paper was assumed as:

$$Y(\sigma_a, \sigma_M) = \begin{cases} \sigma_0 & for \quad \sigma_a \leq \sigma_0 \\ a\sqrt{\sigma_M - \sigma_a} & for \quad \sigma_0 < \sigma_a \leq \sigma_M \\ 0 & for \quad \sigma_a > \sigma_M \end{cases}$$

where:

$$a = \frac{\sigma_0}{\sqrt{\sigma_M - \sigma_0}}$$

By reflection with respect to the both axes one can obtain the $\sigma_a(\varepsilon_a)$ for compressive stresses.

Table 2 lists the material constant values for both steels tested. Graphical representation of the results can be seen in Fig. 5. As seen from the analysis, the assumed model proved to be fully applicable in representing the $\sigma_a(\varepsilon_a)$ curves.

Table 2: Parameter volues obtained from the analysis.

Stal	E [MPa]	σ_0 [MPa]	σ_M [MPa]	$\varepsilon_{pl(M)}$ [-]	K [MPa]	n [-]	K_1 [MPa]	n_1 [-]
AISI 403L	190000	120	240	0.003	9450	1.6	613e5	0.8
1H18N9T	190000	150	290	0.003	3620	2.2	644e5	0.8

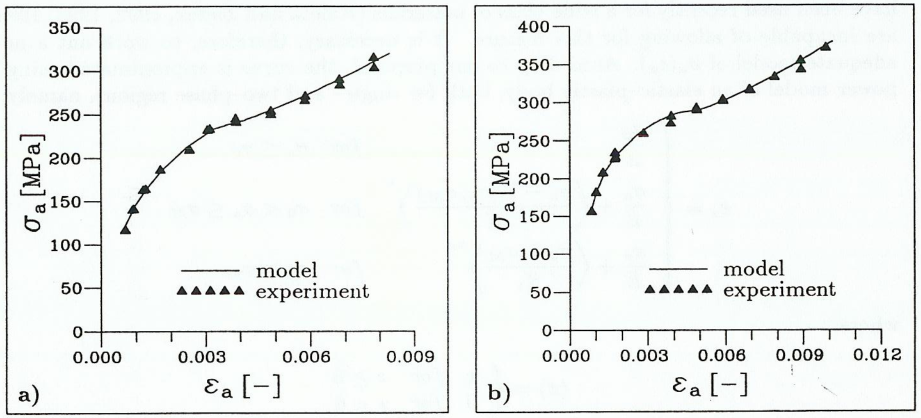

Fig. 5: The cyclic deformation curve $\sigma_a(\varepsilon_a)$ fitted with a four-parameter elastic–plastic model line: a) AISI 304L steel; b) 1H18N9T steel.

CONCLUDING REMARKS

- Both quasi–static and cyclic plastic deformation can induce martensitic transformation in austenitic steels at room temperature ($\approx 293K$).
- The limit value of cyclic plastic strain necessary to initiate the martensitic transformation is $\varepsilon_{pl}(M) \cong 0.003$.
- Martensitic transformation gives rise to variation of cyclic properties which is demonstrated by a different shape of the cyclic deformation curve (CSSc).
- The Villari effect can be helpful in determining the onset of the transformation and in evaluating the kinetics of α''– phase formation.
- The proposed four–parameter model of an elastic–plastic material is a good approximation of the cyclic deformation curve $\sigma_a(\varepsilon_a)$ in austenitic steels with plasticity–induced martensitic transformation.

- There are logical reasons for introducing a new material constant σ_M that is understood as the martensitic transformation cyclic limit.
- The a priori assumed function $Y(\sigma_a, \sigma_M)$ should be analyzed in more detail in a separate study.

REFERENCES

Baldus K.(1995). Wechselverformungsverhalten eines metastabilen, austenitischen Edelstahls. *Msc thesis.* Universität–GH Siegen.

Bayerlein M., Christ H–J. and Mughrabi H.(1989). Plasticity–induced martensitic transformation during cyclic deformation of AISI 304L stainless steel. *Mat. Sc. and Eng.* A114, L14–L16.

Kaleta J. and Ziętek G. (1992). Description of the CSSc by a Certain Classof Elastic–Plastic Models. *Proc. pf 3rd Int. Conf. on Low–Cycle Fatigue and Elasto–Plastic Behaviour of Materials.* 459–464. Berlin.

Kaleta J. and Ziętek G. (1993). Identification of the CSSc and $\sigma-\varepsilon$ Hysteresis for Selected Metals with Masing and Non–Masing Behaviour. *Int. Conference "Fatigue–93".* 121–126. Montreal.

Kaleta J. and Ziętek G. (1994). Representation of Cyclic Properties and Hysteresis Energy in α–brass Using a Certain Class of Elastic–Plastic Models.*Fatigue & Fracture of Engineering Materials & Structures.* 17. 8. 919–930.

Kaleta J. and Żebracki J. (1995). Influence of fatigue in ferromagnetics on the Villari effect. *Conference Proceedings–Experimental Methods in Machine Construction.* I 319–330. Szklarska Poręba (Poland).

Kaleta J. (1996, in print). Plasticity–induced martensitic transformation during cyclic deformation in austenitic steels. *XVI Symposium on Fatigue and Mechanics of Materials and Structures.* Pieczyska nr Bydgoszcz (Poland).

Kaleta J. and Żebracki J. (1996, in print). Application of the Villari Effect in Fatigue Examination of Nickel. *Fatigue & Fracture of Engineering Materials & Structures.*

Kaleta J., Tumański S. and Żebracki J.(1996, in print). Magnetoresistors as a Tool for Investigatin of Mechanical Properties of Ferromagnetic Materials. *J. of Magnetism and Magnetic Materials.*