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Abstract: The cyclic behaviour of X38CrMoV5 (AISI H11) tool steel with a nominal hardness of 47HRC has been predicted. Basically, thermo-elastoplastic and thermo-elastoviscoplastic constitutive laws are investigated. First, various uniaxial isothermal conditions (LCF) with different strain rate, strain amplitude and temperature level are investigated. Then the constitutive laws are examined under various TMF loading conditions. The simulated results by both the approaches are compared with experimental results in terms of stress–strain behaviour and cyclic softening. Some applications of the model for simulation of thermal fatigue sample are shown. Taking into consideration the results of this work, the goal is to further characterise the limitations of these constitutive laws under complex and severe loading conditions, *i.e.,* under variable temperature, variable strain amplitude and thermal fatigue structural specimen.

Keywords: tempered martensitic steels; Low Cyclic Fatigue; LCF; Thermo-mechanical Fatigue; TMF; thermal fatigue; constitutive laws; behaviour modelling; numerical simulation; viscoplasticity.

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1 Introduction

Hot-working tools are of primary concern for industrial production and in particular mass production, *i.e.*, high-pressure die casting, hot forging, stamping and rolling, *etc*. The hot-work tools are, in most cases, made of steels. The surface of tools is basically damaged by the cyclic and progressive process under transient temperature cycling, *i.e.*, the process of non-isothermal fatigue. It results in alternating compressive and tensile stresses at the surface of the tool that arise from differential thermal expansion/contraction during sudden transient temperature changes (Rézaï-Aria, 2002; Velay *et al*., 2002a).

Hence the material demands an advanced modelling of its mechanical behaviour under such severe conditions. Depending upon the design and application philosophies and approaches, thermo-elastic, thermo-elastoplastic or thermo-elastoviscoplastic models can be used. However, the validity of such constitutive laws needs to be examined under several cyclic loading conditions. For the thermo-elastoplastic model, parameters are identified by several tensile tests performed at different temperature levels ranging from 20°C–600°C. The constitutive thermo-elastoviscoplastic model includes kinematic and isotropic parts in order to consider the effects of strain rate, dynamic recovery and cyclic softening (Zhang *et al*., 2002; Velay *et al*., 2006).

The experimental database is briefly shown here. This database comprises tensile test, LCF and TMF tests, which have been carried out in the CROMeP laboratory. The research activities of Research Centre on Tools, Materials and Forming Processes (CROMeP) are focused towards optimisation of forming tools and dies. These topics are of high relevance for manufacturing industries and they require a multidisciplinary approach, in order to solve the underlying scientific and technical issues. The total staff is about 55 people, including seven professors, 12 assistant professors, six technicians, two administrative assistants and an average of 23 doctoral candidates and five masteral students. The main author of this article is a third year PhD student in CROMeP.

2 Material and experimental data

The steel X38CrMoV5 (AISI H11) is regarded as a multipurpose material owing to its properties. It exhibits a high tensile strength at elevated temperatures, good fracture toughness (~90 MPa√m for tempered martensite microstructure at room temperature) and good thermal conductivity (~26–29W/m.K at 200°C–600°C), which makes it belong to the heat-resistant hot-work tool steels class. Owing to its chemical composition (Table 1) and subsequent microstructural changes during heat treatment (Table 2), X38CrMoV5 is regarded as a mechanical shock- and heat-resistant hot-work tool steel (Velay *et al.*, 2002b; Velay *et al.*, 2005).

2.1 Chemical composition

Table 1 Chemical composition (weight %) of X38CrMoV5 steel (major alloying elements)

Steel	*C*	*Cr*	*Mn*	*V*	*Ni*	*Mo*	*Si*	*Fe*
X38CrMoV5	0.40	5.05	0.49	0.47	0.20	1.25	0.92	bal

Source: Oudin (2001)

Table 2 Heat treatment procedure to achieve martensite microstructure for X38CrMoV5-47 HRC

Steel	*Austenitisation*	*Ist tempering*	*2nd tempering*	*Hardness*
X38CrMoV5	990°C/1h/air	550°C/2h/air	603°C/2h/air	47

Source: Oudin (2001)

2.2 Tensile test

Tensile tests of the material with a nominal hardness of 47HRC are carried out at different temperature levels on a solid flat specimen from 200°C to 600°C to extract the thermomechanical and thermophysical properties of the material.

2.3 Thermomechanical and thermophysical properties

Table 3 represents the values of Thermal Expansion (α), Young Modulus (E), Ultimate Tensile Stress (σu), Conventional Yield Stress σ 0.2 (0.2% strain offset), Poisson Ratio (ν), Density (ρ), Thermal Conductivity (K) and Specific Heat Capacity (Cp) as a function of temperature (Rézaï-Aria, 2002; Zhang *et al.*, 2002).

2.4 LCF tests

LCF experiments have been carried out on cylindrical test specimens at different temperature levels between 300°C and 600°C with different strain amplitudes; some of the test conditions are presented in Table 4. Symmetric tests have been carried out at strain rates of 10^{-2}/s and 10^{-3}/s, whereas some tests are carried out with a relaxation time between 60 s to 90 s, in tensile, double tensile and compressive phases at a strain rate of 10^{-3}/s (Velay *et al.*, 2006).

Table 3 Thermophysical and thermomechanical properties of material X38CrMoV5

T°C	*20*	*200*	*300*	*400*	*500*	*600*
α * 1E-6	13.5	13.6	13.7	13.9	14	14.2
E (Mpa)	213 270	184 734	178 932	169 836	153 167	126 243
σu (MPa)	1460	1350	1290	1230	1060	815
σ 0.2 (MPa)	1200	1110	1065	1000	880	605
ν	0.30	0.30	0.30	0.30	0.30	0.30
ρ (Kg/m3)	7847	7789	7755	7718	7679	7639
K (w/m.K)	29.8	31.8	32.1	31.8	30.9	29.4
Cp (J/Kg.K)	482	561	589	621	669	745

2.5 TMF tests

TMF tests have also been performed on a tubular test specimen of X38CrMoV5-47HRC, at various temperature ranges (between 200°C–600°C), heating and cooling time, mechanical strain amplitudes and rates (Velay *et al*., 2002b; Oudin, 2001).

Table 4 Representations of TMF test conditions

Δεm (%)	*Tmin – Tmax (°C)*	*t heat (sec)*	*t cool (sec)*	*Period (sec)*
1.50	200 – 600	100	130	230
1.00	200 – 600	100	140	240
0.50	200 – 600	100	140	240
1.00	300 – 600	75	85	160
0.70	400 – 600	50	50	100
1.50	200 – 500	75	115	190
1.00	200 – 500	75	110	185
1.50	200 – 550	88	138	226

3 Simulation

Numerical simulations are performed by utilising two behaviour models, *thermo-elastoplastic* and *thermo-elastoviscoplastic,* which are briefly discussed as follows:

3.1 Thermo-elastoplastic model

For the mathematical thermo-elastoplastic numerical simulation, experimental data have been obtained after carrying out a tensile test (Figure 1) of a solid specimen at different temperatures (Medjedoub *et al*., 2003).

$$\sigma(T) = f\{\varepsilon_{el}(T)\} \text{ with } \varepsilon_{pl}(T) = \varepsilon_{tot}(T) - \varepsilon_{el}(T) - \varepsilon_{th}(T). \quad (1)$$

$$\varepsilon_{el}(T) = \sigma(T) / E(T);\ \varepsilon_{mech}(T) = \varepsilon_{el}(T) + \varepsilon_{pl}(T)\ and\ \varepsilon_{th}(T) = \alpha(T)\Delta T \quad (2)$$

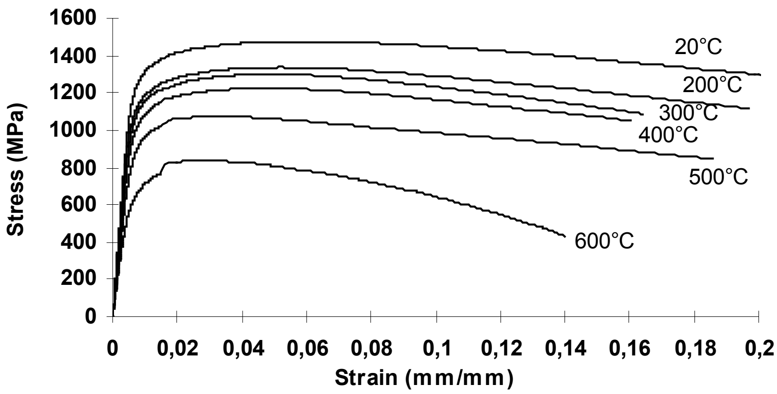
where:

ε_{el} = elastic strain

ε_{mech} = mechanical strain and ε_{th} is thermal strain.

The thermo-elastoplastic model implemented in ABAQUS requires tensile tests results to be introduced by piece straight-line segments. The results in terms of the evolution of stress as a function of plastic strain at different temperatures have been further implemented in the ABAQUS 6.4 programme for simulation.

Figure 1 Results of tensile tests at different temperature levels



Source: Medjedoub *et al*. (2003)

3.2 Thermo-elastoviscoplastic model formulation

A constitutive Chaboche-type (Chaboche, 1986) model is utilised in our numerical simulation. This model is based on a unified viscoplastic approach considering the superposition of kinematic and isotropic hardening describing the cyclic hardening/ softening and Bauschinger effects.

In the model, it is postulated that the evolutions of the transient inelastic strain during each hysterises loop can be described through kinematic variables (Velay, 2003):

$$X_i = \frac{C_i}{D_i} v(1 - e^{-D_i v \varepsilon_p});\ v = \pm 1;\ i = 1,\ 2 \quad (3)$$

$v = +1$; if $\varepsilon_p > 0$ and $v = -1$; if $\varepsilon_p < 0$.

The slow evolutions of the stress during the successive cycles to the (cyclic softening of the material) is reproduced through an isotropic hardening variable (drag stress) (Velay, 2003):

$$R_i = Q_i(1 - e^{-b_i p});\ i = 1,\ 2 \quad (4)$$

p is the cumulated plastic strain, which can be defined by:

$\dot{p} = |\dot{\varepsilon}_p| = \left\langle \frac{f}{K} \right\rangle^n$ where f corresponds to the yield surface given as:

$$f = \left| \sigma - \sum_{i=1}^{2} X_i \right| - \sum_{i=1}^{2} R_i - R_0 . \tag{5}$$

Finally,

$$\sigma = \pm(\sigma_v + R_1 + R_2 + R_0) + X_1 + X_2 \tag{6}$$

where:

$\sigma v = K \dot{\varepsilon}_p^{1/n}$ = viscous stress (*i.e.*, strain rate-dependent)

C_i, D_i, Q_i, b_i, K, n and R_0 = temperature-dependent material parameters (Velay, 2003).

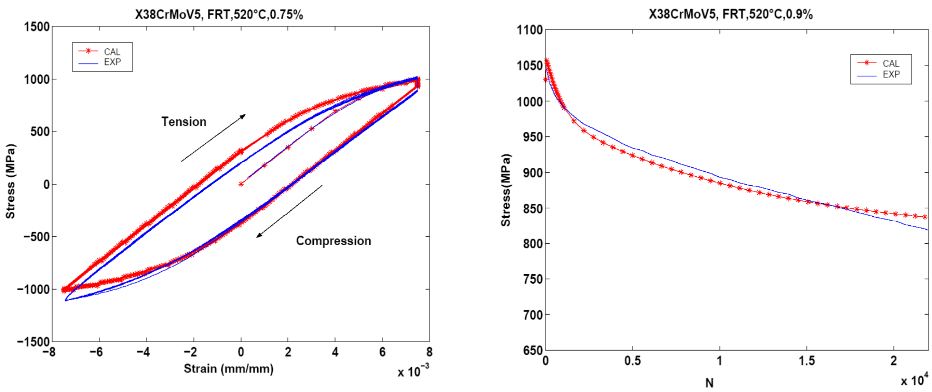
The identification has been carried out through a LCF test for temperatures between 20°C to 600°C with an amplitude of deformation of ±0.8% and different strain rates ($\dot{\varepsilon} = 10^{-4} s^{-1}$, $10^{-3} s$, $10^{-2} s^{-1}$). These parameters have been validated with 1D formulation for each level of temperature (Velay, 2003).

4 Discussion

4.1 LCF simulation

All LCF test results have been simulated with the thermo-elastoviscoplastic formulation considering the same test conditions (Table 1), as cyclic softening cannot be simulated with the thermo-elastoplastic model. The simulated and experimental results are then further compared in terms of hysterisis loops and cyclic softening curves. Comparative results as hysterisis loops with relaxation in the compression phase and corresponding cyclic softening are shown in Figure 2.

Figure 2 (a) Comparative experimental hysteresis loop at 520°C with relaxation in tensile phase (b) Comparative experimental cyclic softening curve at 520°C



(a) (b)

Generally, for all the simulated test conditions (Table 1), the results show a good correspondence with the experimental results in terms of hysterises loops. Whereas for the comparison of cyclic softening curves, errors are calculated by the Euclidian norm method (Equation (7)) and are presented in Table 5.

$$\frac{\| \sigma(\exp) - \sigma(\text{sim}) \|^2}{\| \sigma(\exp) \|^2}. \tag{7}$$

In the above equation σ(exp) stands for the experimental value of stress, whereas σ(sim) stands for the simulated (calculated) value of stress.

Table 5 Results of comparative experimental cyclic softening curves at each temperature

Temperature (ºC)	$\Delta\varepsilon(\%)$	$\dot{\varepsilon}(s^{-1})$	*Relaxation time (sec)*	*Euclidian norm (%)*
500	0.5	2.10^{-2}	0	14.40
	0.6	$2.4.10^{-2}$	0	14.35
520	0.6	10^{-2}	0	7.41
	0.75	10^{-3}	0	5.85
520	0.6	10^{-3}	20	6.76
	0.75	10^{-3}	20	4.68
520	0.6	10^{-3}	60	7.81
	0.75	10^{-3}	20	8.35

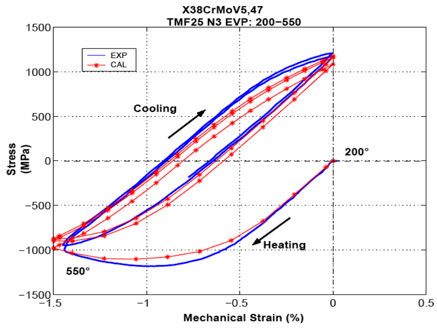
Source: Velay (2003)

4.2 *TMF simulation*

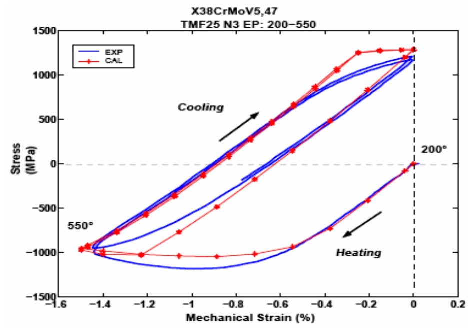
TMF simulation is based on two models, thermo-elastoplastic and thermo-elastoviscoplastic. The simulation is carried out for all the available test conditions (Table 4) (Velay *et al.*, 2005; Medjedoub *et al.*, 2003). Results of both models are compared with experimental results in terms of stress–mechanical strain loops. As a general interpretation of all the comparative results, we present in Figures 3(a–c), the results for the test conditions of 200°C–550°C with a strain amplitude of 1.5% and 200°C–600°C with a strain amplitude of 0.7% (thermo-elastoviscoplastic model), respectively.

For the test condition of 200°C–600°C with a strain amplitude of 0.7% (Figure 3c), it is shown that in the first heating phase both curves show normal behaviour till a bit before the end of first heating. After reaching Tmax, both curves show absolutely different results in all the remaining cycles. It is to be noted here that for the said test condition the value of Tmax is found to be 607°C experimentally, whereas 603°C is the temperature of the second tempering of material. During the experimental thermal cycles of these specimens, when temperature crosses 603°C, a drastic microstructural change occurs in the material. Consequently the thermo-mechanical and thermo-physical properties change with respect to temperature. Whereas the thermo-elastoviscoplastic model has been developed in the hypothesis of structural stability.

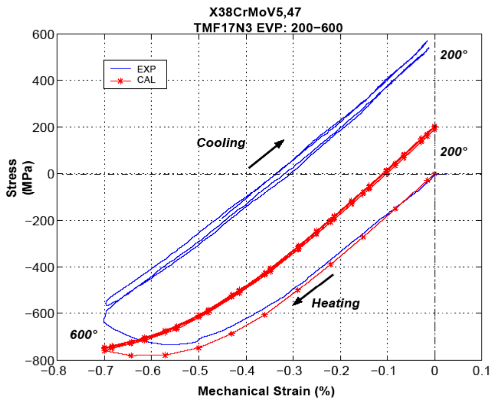
Figure 3 (a) TMF 200°C–550°C, $\Delta\varepsilon_m = 1.5\%$, stress-mechanical strain comparison with the thermo-elastoviscoplastic model (b) TMF 200°C–550°C, $\Delta\varepsilon_m = 1.5\%$, stress-mechanical strain comparison with thermo-elastoplastic model (c) TMF 200°C–600°C, $\Delta\varepsilon_m = 0.7\%$, stress-mechanical strain comparison with thermo-elastoviscoplastic model



(a)



(b)



(c)

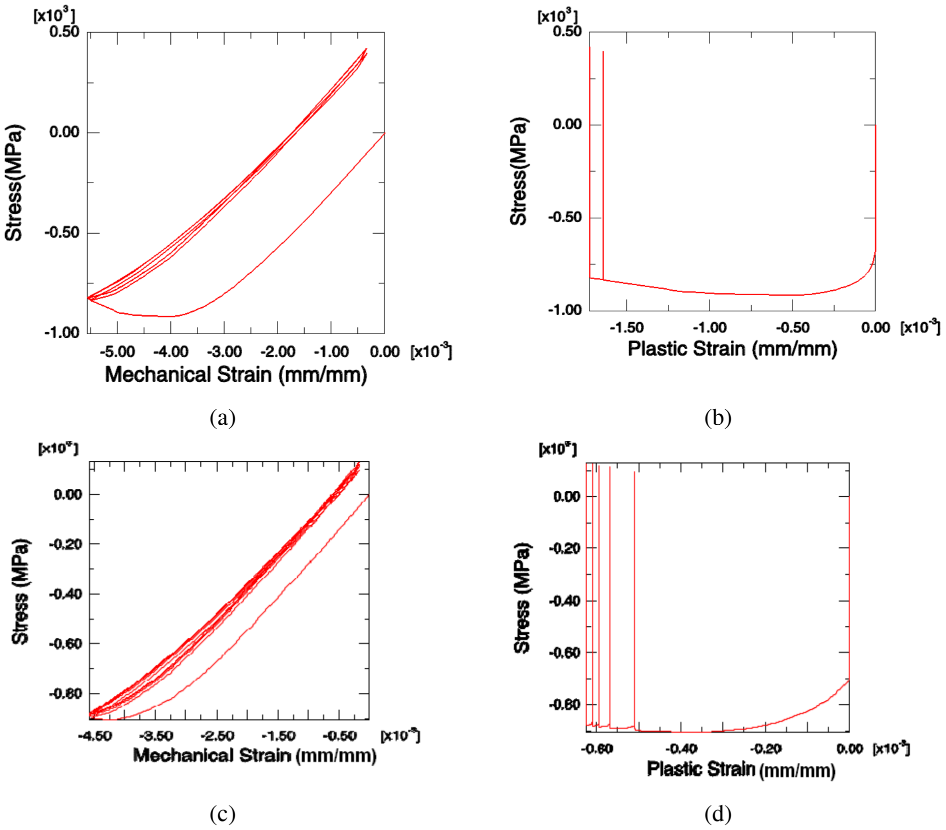
4.3 TF simulation

Thermo-mechanical simulations of tubular cylindrical thermal fatigue test specimen re carried out by using both the models. Thermo-elastoplastic simulations have already been carried out in the CROMeP Laboratory (Medjedoub *et al.*, 2003). We recalculated these thermal and mechanical simulation for comparison with the results of thermo-elastoviscoplastic model. The experimental results are available in terms of temperature at several positions, *i.e.*, at the surface and in-depth. These results are used to identify external and internal thermal boundary conditions by the implementation of a numerical simulation on ABAQUS 6.4.

The results of simulation with the thermo-elastoplastic model have been plotted in terms of stress as a function of mechanical strain and plastic strain (Figures 4a–b). In Figure 4(a), the same problem is observed in the hysterisis loop with the thermo-elastoplastic model, which has already been discussed in the previous section. The plotted results in terms of stress–plastic strain (Figure 4b) shows that with the thermo-elastoplastic model, plastic strain stabilises after two or three cycles;

whereas, with thermo-elastoviscoplastic model (Figure 4d) plastic strain continues to accumulate for each cycle. The application of thermo-elastoviscoplastic model in terms of stress–mechanical strain loops, is shown in Figure 4(c).

Figure 4 (a) Calculated stress–strain loops using thermo-elastoplastic model (b) Calculated stress–plastic strain loops using thermo-elastoplastic model (c) Calculated stress–strain loops using thermo-elastoviscoplastic model (d) Calculated stress–plastic strain loop using thermo-elastoviscoplastic model



(a) (b)

(c) (d)

5 Conclusion

These numerical simulations have been carried out to predict the behaviour of the 47HRC H11 tool steel using thermo-elastoplastic and thermo-elastoviscoplastic (Chaboche-type model). These laws have been applied to a total of 66 LCF and TMF test conditions, which have been carried out on different lots of specimen. The comparative results are shown in terms of hysterises loops with LCF and TMF experiments. The thermoelastoplastic model is not able to predict cyclic-softening behaviour.

The thermo-elastoviscoplastic model has shown good comparative results for most of the LCF and TMF test conditions, but as discussed in the section of TMF simulation, it has shown a clear difference with the experimental result (Figure 3c) when the temperature exceeds 603°C. We have considered a simplified thermo-elastoviscoplastic model without recovery. Whereas time recovery parameters become effective after 550°C. For TMF tests, which are carried out at low strain rate, strain recovery parameters may become significant for an optimised validation of stress values. The microstructural behaviour of material will also be studied when Tmax exceeds 550°C.

An application of models for the simulation of a thermal fatigue test specimen is also presented. The experimental data in this regard is not available owing to the limitations of measuring stress and mechanical strain in biaxial state. Work in this regard, specifically the development of a new thermal fatigue test bench is in progress to address the difficulties of measuring mechanical strain. Once it is achieved, it will be possible to apply and further validate these constitutive laws on a structural specimen.

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