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ON THE STRAIN-HARDENING PARAMETERS OF S355J2H STEEL CONSIDERING THE INFLUENCE OF TEMPERATURE

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Abstract: *Calculation of stresses in the steel elements subjected to the influence of thermo-mechanical loads requires taking into account the influence of temperature on material mechanical properties, including stress-strain curve. In this paper, on the basis of Ludwik, Hollomon, Swift and Voce equations, the modelling of strain-hardening curves of S355J2H steel considering the influence of temperature is discussed. The consideration were made on the basis of experimental results published in the literature as stress-strain curves S355J2H steel for selected temperatures. The values of the parameters in the equations of the individual models were determined, which allowed to analytical description of the material strain-hardening curves.*

Keywords: Mechanics, Thermomechanics, Modelling.

1. Introduction

The modelling of thermo-mechanical states of metals and their alloys requires defining stress-strain dependence as the function of temperature. The mathematical modelling of the tensile curves, including strain-hardening curves, has been the subject of research and analysis from the beginning of the last century. With the development of computer methods and simulation tests, the interest in this problem has increased, especially when it comes to modeling of thermo-mechanical states in technological processes of metals and their alloys. Then, different models of material strengthening are used and functions are sought which combine the temperature with stress-strain curve parameters such as yield stress, longitudinal modulus of elasticity or reinforcement modulus.

2. Mathematical Models of Strain-Hardening Curves

Ludwik (1909) began modelling of the stress-strain curve and described it with this function:

$$\sigma = \sigma_0 + K_L \varepsilon^{n_L} \tag{1}$$

where σ represents stress, σ_0 yield stress, ε plastic strain, K_L and n_L are the experimentally determined parameters. In turn, Hollomon (1945) suggested a function:

$$\sigma = K_H \varepsilon^{n_H} \tag{2}$$

Swift (1952) regarding the Hollomon's law introduced the constant into the strain term:

$$\varepsilon = \varepsilon_0 + K_S \sigma^{n_S} \text{ or } \sigma = K_S^{'} \left(\varepsilon + \varepsilon_0\right)^{n_S^{'}} \tag{3}$$

where ε_0, K_S, K'_S, n_S i n'_S are the parameters.

During the tests of AISI 304 austenitic steel Ludwik's equation for plastic strains smaller then 0.1 showed differences in the experimentally obtained stress-strain curve, Ludwigson (1971) proposed a modified form of the Ludwik's equation:

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$$\sigma = K_{1L}\varepsilon^{n_{1L}} + K_{2L}\exp(n_{2L}\varepsilon) \qquad (4)$$

In modelling the stran-hardnienig curve at elevated temperatures based on the relationship between stress and strain defined by Voce (1948), the following function is used (Sivaprasad et al.,1997):

$$\sigma = \sigma_1 + (\sigma_s - \sigma_1)\left[1 - \exp\left(-\frac{\varepsilon - \varepsilon_1}{\varepsilon_c}\right)\right] \qquad (5)$$

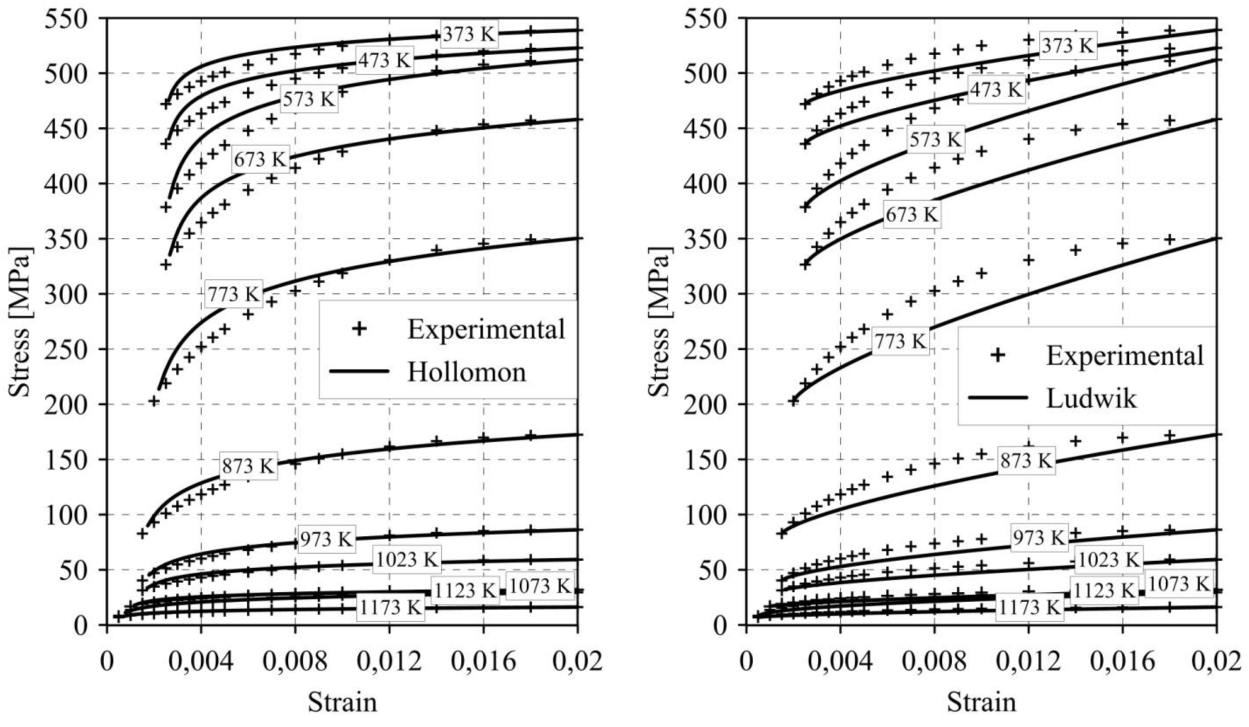
where ε is a plastic strain, σ_1 and ε_1 represent first measurement of the stress and the strain respectively, σ_s saturation stress, ε_c strain constant. If $\varepsilon_1 = 0$ (limit of applicability of Hook's law or yield point), then:

$$\sigma = \sigma_s - K_V \exp(n_V \varepsilon) \qquad (6)$$

where $n_v = -1 / \varepsilon_c$.

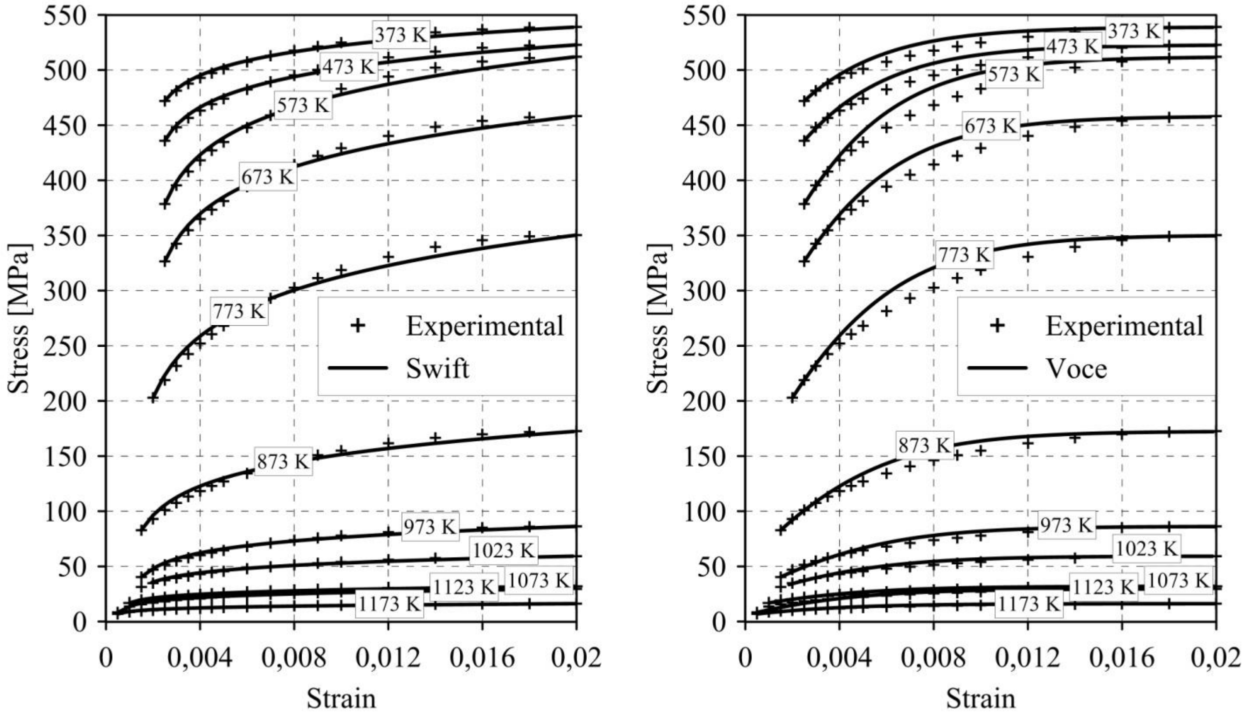
Tab. 1: The values of the parameters in the Hollomon, Ludwik, Swift and Voce equations.

	Hollomon		Ludwik		Swift			Voce	
T [K]	K_H [MPa]	n_H	K_L [MPa]	n_L	K'_S [MPa]	n'_S	ε_0	K_V [MPa]	n_V
373	595.623	0.025	1091.586	0.686	629.030	0.038	0.000552	67.010	-320.757
473	598.873	0.033	1364.178	0.676	640.770	0.050	0.000470	86.900	-324.231
573	640.525	0.055	2200.745	0.684	711.770	0.081	0.000405	133.550	-330.040
673	588.637	0.061	2223.998	0.689	661.720	0.090	0.000393	131.660	-331.900
773	520.860	0.097	2588.759	0.699	604.110	0.133	0.000281	147.410	-332.185
873	289.489	0.127	1413.884	0.676	326.120	0.156	0.000156	89.690	-329.945
973	144.013	0.125	559.759	0.612	156.100	0.145	0.000091	45.900	-337.570
1023	93.107	0.111	411.527	0.661	103.820	0.138	0.000169	28.020	-325.894
1073	50.166	0.112	208.059	0.653	54.542	0.134	0.000150	15.130	-311.631
1123	62.539	0.186	149.298	0.485	56.673	0.162	0.000007	21.380	-325.011
1173	29.028	0.147	105.904	0.612	29.477	0.151	0.000066	9.300	-310.,561



a) *b)*

Fig. 1: Strain-hardening curves of structural steel S355J2H at temperatures 373 – 1173 K modelled by the equations: a) Hollomon; b) Ludwik.

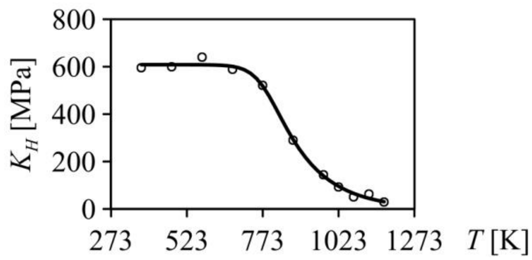


a) *b)*

Fig. 2: Strain-hardening curves of structural steel S3 55J2H at temperatures 373 – 1173 K modelled by the equations: a) Swift; d) Voce.

This paper presents an analysis of models of strain-hardening curves of the material as a function of temperature for the steel S355J2H based on the results of experimental studies contained in the research report Outinen et al. (2001). The parameters of the Hollomon's, Ludwik's, Swift's and Voce's equations for different temperatures were determined (Tab. 1, Figs. 1 and 2). Then the functions of these parameters depending on the temperature were determined, which for Swift's and Hollomon's present equations (7) – (11) and Figs. 3 and 4. The comparison of the stress-strain curves described by Swift and Hollomon laws for the temperature 775K with the experimental results and the curves obtained by interpolation from 875K and 675K in Fig. 5 is presented.

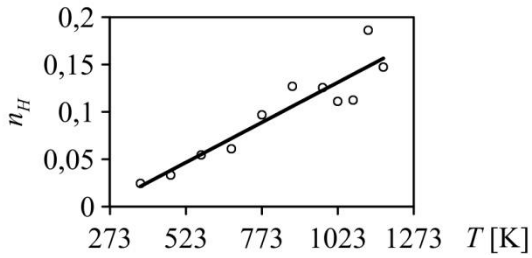
a)



$$K_H(T) = \frac{a}{(1+\exp(b - c\cdot T))^{\frac{1}{d}}} \qquad (7)$$

$$a = 608.3728 \quad c = -0.0289$$
$$b = -22.5101 \quad d = 3.8131$$

b)

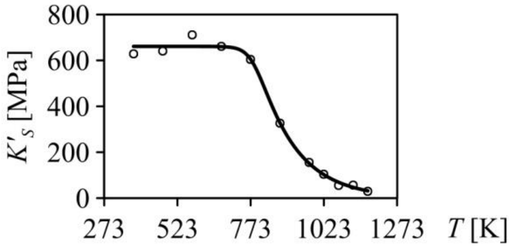


$$n_H(T) = a + b\cdot T \qquad (8)$$

$$a = -0.0417$$
$$b = 1.6894\cdot 10^{-4}$$

Fig. 3: Parameters in the Hollomon equation as a function of temperature and suggested models.

a)

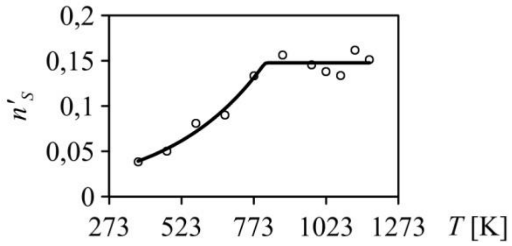


$$K'_S(T) = \frac{a}{(1+\exp(b-c\cdot T))^{\frac{1}{d}}} \tag{9}$$

$a = 661.0531 \quad c = -0.0431$

$b = -33.7699 \quad d = 5.5351$

b)

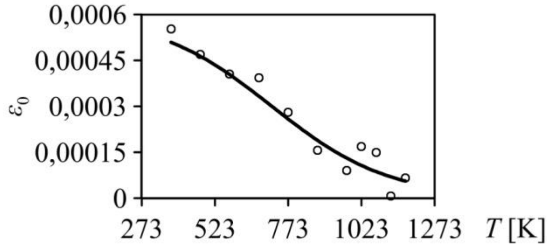


$$n'_S(T) = \frac{a}{(1+\exp(b-c\cdot T))^{\frac{1}{d}}} \tag{10}$$

$a = 0.1477 \quad c = 0.4150$

$b = 336.8851 \quad d = 137.1254$

c)



$$\varepsilon_0(T) = \frac{a}{1+\exp(b-c\cdot T)} \tag{11}$$

$a = 0.0006 \quad c = -0.0050$

$b = -3.5861$

Fig. 4: Parameters in the Swift equation as a function of temperature and suggested models.

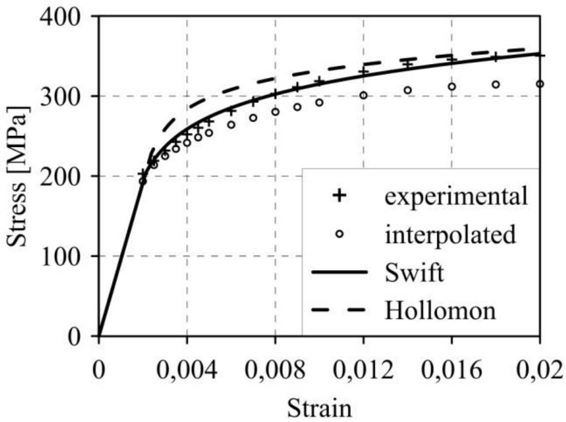


Fig. 5: The comparison of the stress-strain curves described by Swift and Hollomon laws for the temperature 775K with the experimental results and the curves obtained by interpolation.

3. Conclusions

The closest approximation of modelled stress-strain curves to the experimental results was achieved through using the Swift's law, then the Hollomon's and the Voce's law. Application of the Ludwik's law gives the greatest divergence from the experimental stress-strain curves.

The determined values of parameters for individual equations (laws) as a temperature function allow to define a stress-strain curve for any temperature and represent an alternative solution to the interpolation method.

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