INELASTIC STRESS-STRAIN RELATIONSHIPS FOR THE AISI 310 STAINLESS STEEL IN THE TEMPERATURE RANGE 20°–900°C

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The behaviour of AISI 310 stainless steel during monoaxial tensile tests is studied in this paper. We begin by examining the mechanical characteristics over a wide range of temperatures (293-1173 K) for two different cross-head velocities ($3.33 \cdot 10^{-5}$ ms^{-1} and $8.33 \cdot 10^{-7}$ ms^{-1}) and find them to be in good agreement with those already reported in the literature.

The data obtained from 57 tensile tests have been elaborated statistically with a view to obtaining some mathematical descriptions of the stress-strain diagrams and to formulating some constitutive laws.

The statistical analyses performed with Fisher's function F showed a good agreement between the laws proposed and the experimental data. It also revealed that the material examined is not particularly sensitive to the strain velocity, and that at a fixed temperature laws of the same type as that attributed by several authors to Ludwik represent very well the plastic behaviour of the material.

Further analysis, carried out at a temperature of 293 K and for various strain levels, demonstrated that the effect of the strain velocity, which is, as already mentioned, rather small, varies with the strain itself.

1. Introduction

The stainless steels most frequently employed in the construction of fast reactor elements are of the AISI 304 and AISI 316 types. However, in view of its characteristics of corrosion resistance and thermal stability, the AISI 310 stainless steel is beginning to be considered as a possible future candidate. For this reason we have need of constitutive laws describing the plastic behaviour of this material over an extremely wide range of temperatures, in creep and in fatigue.

The creep behaviour of AISI 310, with particular attention being paid to the damage phenomenon, was the subject of earlier studies /1, 2/. This paper examines the behaviour of this material during a monoaxial tensile test. Statistical elaboration of the data obtained from 57 tensile tests performed over a wide range of temperatures (293-1173 K) and for two different cross-head velocities ($3.33 \cdot 10^{-5}$ and $8.33 \cdot 10^{-7}$ ms^{-1}) has made it possible to propose some mathematical descriptions of the stress-strain diagrams and the formulation of some constitutive laws.

2. Material

The material used in this research was a batch of hot-drawn AISI 310 steel bars, all taken from the same casting. They were first subjected to chemical analysis to determine percentage composition, grain size, precipitates, carbides and other impurities. The homogeneity of the material proved to be sufficient and compatible with the subsequent tensile tests. The chemical analysis is given in Table I. Metallographic analyses showed a structure composed of an austenitic matrix with grains of mean diameter equal to 50 μm. The original bars were then subdivided into small bars of length 100 mm. These were then thermally heat-treated (at 1373 K, for fifty minutes, followed by cooling in water) to obtain a further homogenization of the material. Hardness tests performed after the thermal treatment gave values lying between 71 and 73 RB.

3. Tensile Tests

In order to obtain the necessary data for the mathematical descriptions of the σ - ε diagrams and the formulation of the constitutive laws in plastic field, tensile tests have been carried out on an INSTRON machine in a controlled atmosphere (argon) on 57 test samples with circular cross section, diameter 4 mm and gauge length 30 mm. These tests were performed at the temperatures and cross-head velocities given in Table II. The test temperature was controlled with a standard deviation of $\pm$ 2 K.

Fig. 1 gives the behaviour in function of the temperature of the tensile strength (true and engineering) σ_u of the yield strength (true and engineering) $\sigma_{0.2}$, of the conventional uniform plastic percentage elongation A_{pu} and of the conventional ultimate plastic percentage elongation A_{pb}. From Fig. 1 it can be seen that the tensile strength is maintained at fairly high levels up to temperatures of the order of 773 K, but shows an abrupt decrease at higher temperatures. The strain rate has little influence at room temperature, whereas at higher temperatures higher velocities correspond to high tensile strengths. The yield strength always decreases with the temperature and is less influenced by the strain rate with respect to σ_u. The A_{pb} elongation is just about constant between 573 K and 873 K, but after that it grows with the temperature, while the behaviour of A_{pu} is in phase with σ_u. As in the case of σ_u, the elongations grow with the strain rate. These observations agree with other results already available in the literature [3].

The load-elongation curves obtained from the tensile tests have been memorised by points in a Hewlett Packard 2100 A computer. By means of successive elaborations we obtained from these data engineering stresses and strains, $\bar{\sigma}$ and $\bar{\varepsilon}$, true stresses and strains, σ and ε, plastic strain, ε_p, and total and plastic true strain rates, $\dot{\varepsilon}$ and $\dot{\varepsilon}_p$, according to the usual conventions (see, for example [4]). In Figs. 2, 3, 4 and 5 the curves type $\bar{\sigma}-\bar{\varepsilon}$, $\sigma-\varepsilon$, $\sigma-\varepsilon_p$, $\dot{\varepsilon}-\dot{\varepsilon}_p$ and $\dot{\varepsilon}_p-\varepsilon_p$ at 293 K and $v = 3.33 \cdot 10^{-5}\,ms^{-1}$ and $8.33 \cdot 10^{-7}\,ms^{-1}$, respectively, are reported.

4. Mathematical Description of the Diagram $\sigma-\varepsilon$

Many formulae have already been proposed in the literature for a mathematical description of the $\sigma-\varepsilon$ diagram. Osgood [5] has reported 17, but none of them includes the influence of the strain rate and/or of the temperature. The influence of these two parameters is rather significant, however, particularly for practical applications. Formulae which take into account either the one or the other parameter have also been proposed, see, for example the classic text of Dieter [6], and are of the type

$$\sigma = \sigma_o \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right]^m \qquad (1)$$

with ε and T constant, and

$$\sigma = \sigma_o \frac{e^{a_o T_o/T}}{e^{a_o}} \qquad (2)$$

with ε and $\dot{\varepsilon}$ constant.

We have employed laws of the following type in order to describe the plastic behaviour of AISI 310:

$$\sigma = \sigma_o \left[\frac{\varepsilon_p}{\varepsilon_{op}}\right]^{n_1} \cdot \left[\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{op}}\right]^{m_1} \frac{e^{a_{o,1} T_o/T}}{e^{a_{o,1}}} = k_1\, \varepsilon_p^{n_1}\, \dot{\varepsilon}_p^{m_1}\, e^{a_1/T} \qquad (3)$$

$$\sigma = \sigma_o \left[\frac{\varepsilon_p}{\varepsilon_{op}}\right]^{n_2} \cdot \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right]^{m_2} \frac{e^{a_{o,2} T_o/T}}{e^{a_{o,2}}} = k_2\, \varepsilon_p^{n_2}\, \dot{\varepsilon}^{m_2}\, e^{a_2/T} \qquad (4).$$

Having indicated with σ_o the reference stress producing at a reference temperature T_o the natural plastic strain ε_{op} with a true plastic strain rate $\dot{\varepsilon}_{op}$ or with a true strain rate ε_o. It will be observed that from equations (3) and (4) it is possible, letting one or more of the variables be equal to a constant, to obtain laws of the same type as equation (1) or (2), and also links between σ, ε_p and $\dot{\varepsilon}_p$, similar to the one proposed by Coleman et al. [7].

While it is formally the same as equation (3), a law of the type indicated in equation (4) is in fact easier to use for the designer, because the true strain rate $\dot{\varepsilon}$ is related very simply to the cross-head velocity v:

$$\dot{\varepsilon} = \frac{v}{l_o(1+\bar{\varepsilon})} \tag{5}$$

whereas the true plastic strain rate ε_p assumes a more complex form. In order to determine this strain rate, bearing in mind that

$$\varepsilon = \varepsilon_{el} + \varepsilon_p \tag{6}$$

$$\varepsilon_{el} = \sigma/E \tag{7}$$

we find

$$\dot{\varepsilon} = \frac{v}{l_o(1+\bar{\varepsilon})} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_p = \frac{1}{E}\frac{d\sigma}{dt} + \dot{\varepsilon}_p \tag{8}$$

and thus:

$$\frac{d\sigma}{dt} = \frac{d}{dt}\left[\bar{\sigma}(1+\bar{\varepsilon})\right] = \frac{d\bar{\varepsilon}}{dt}\cdot\frac{d}{d\bar{\varepsilon}}\left[\bar{\sigma}(1+\bar{\varepsilon})\right] = \frac{v}{l_o}\cdot\left[\bar{\sigma}+(1+\bar{\varepsilon})\frac{d\bar{\sigma}}{d\bar{\varepsilon}}\right] \tag{9}$$

therefore:

$$\dot{\varepsilon}_p = \frac{v}{l_o(1+\bar{\varepsilon})}\left\{1 - \frac{1}{E}\left[\sigma+(1+\bar{\varepsilon})^2\frac{d\bar{\sigma}}{d\bar{\varepsilon}}\right]\right\} . \tag{10}$$

In order to determine the constants which appear in equations (3) and (4), statistical examinations have been carried out on the data obtained from all 57 tensile tests, evaluating the influence of ε_p, $\dot{\varepsilon}_p$ or $\dot{\varepsilon}$ and T, assumed to be independent variables. The results obtained from this type of analysis are set out in Table III, which also shows, in addition to the values of k_1, n_1, m_1, a_1 and k_2, n_2, m_2, a_2 and their standard deviations, the corresponding values of Fisher's function F [8], which make it possible to establish the validity of the laws proposed. The values of Fisher's function F are the ratios of the sum of squares removed by the regression to the residual sum of squares each divided by its respective degrees of freedom. The Tables also show the values of F_1, which make it possible to estimate the influence of the removal of an independent variable.

Table IV, compiled according to the same criterion, was obtained by elaborating the data at all temperatures, but only for two tests at 293 K and at 873 K, in order to give the same statistical weight to all the temperatures. From a comparison of these two tables it can be seen how the consideration of a significant number of tests at two temperatures (Table III) gives very similar results to those of Table IV. Table V and VI give the results for laws at constant temperature of the tests at 293 K and 873 K.

5. Discussion of the Results

Examination of the results given in Tables III and IV reveals first of all that in laws with three independent variables it is equally important to consider the $\dot{\varepsilon}_p$ or $\dot{\varepsilon}$. Furthermore, it can be seen that laws with the two independent variables ε_p and T only are rather more significant than others. In other words, this fact shows that AISI 310 steel, like other metals and alloys with face-centered cubic crystal structure is not very sensitive to variations in strain rate.

Examination of Tables V and VI shows that, at fixed temperatures, laws with two independent variables are very significant even if, at the temperatures at which the greater number of tests have been performed (293 K and 873 K) the equation $\sigma = K \varepsilon_p^n$ appears to represent very well the plastic behaviour of AISI 310.

Ludwigson [9] has also come to this same conclusion in the field of large-scale deformations for a stainless steel of the AISI 304 type, tested, however, in a more restricted range of temperatures (293-373 K). Ludwigson has found in this case values for the exponent of ε_p, similar to the constant k of the material, roughly double those given in Tables III, IV, V and VI.

Still in the field of laws having ε_p as the only independent variable, i.e. laws which ignore the important influence of the strain rate and above all of the temperature, Klueh et al. [10] have found for ferritic steel 2.25 Cr-1Mo, values of k and n that are fairly close to our own.

From Tables III and VI, we can see that the exponent m of the strain rate almost always assumes negative and rather small values. This can be explained by referring to equations (5) and (10), in which we see that $\dot{\varepsilon}$ and $\dot{\varepsilon}_p$ are, in their turn, functions of the cross-head velocity and of the strain. From Figs. 4 and 5 we observe that as ε_p (and thus also $\bar{\varepsilon}$) increases, the true and plastic strain rates in the field of large-scale deformations decrease, whereas the stress increases.

It can likewise be seen that, still in the field of large-scale deformations, work-hardening occurs in association with the cross-head velocity. In order to illustrate better the effects of the plastic deformation and the strain rate, function in its turn of the engineering strain and the cross-head velocity, whose influence must be evaluated at a constant strain, laws of the following type are used:

$$\sigma = k_3 \, \varepsilon_p^{n_3} \left(\frac{1}{1+\bar{\varepsilon}}\right)^{p_3} v^{m_3} \qquad (11)$$

which for $m_3 = p_3$ comes under equation (3) for T = const. Statistical analysis at 293 K has produced the results set out in Table VII. This statistical analysis also yielded a negative value of m_3, albeit with a high variance. From equation (11), and hypothesising, mainly valid for large-scale deformations, that to ε_p = constant there is a corresponding $\bar{\varepsilon}$ = constant, we find

$$m_3 = \frac{\ln \sigma_1/\sigma_2}{\ln v_1/v_2} \tag{12}$$

which coincides with the definition given by Dieter [6].

If, on the other hand, we analyse only two tests, one at $v = 3.33 \cdot 10^{-5} ms^{-1}$, and the other at $v = 8.33 \cdot 10^{-7} ms^{-1}$, we find a positive value for m_3 which, however, takes into account all the points of the curve σ-ε.

From equation (12), applied to the data relative to two tests at 293 K, the values of m_3, reported in Table VIII, have been obtained. From this we can see that the effect of the cross-head velocity is always very small, variable with the strains and work-hardening occurs at high strains.

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List of Symbols

a = constant associated with the temperature in equation (2)

k = constant of the material in equation (3)

l_o = original length of the test sample

m = exponent of the strain rate in equation (3) and of the cross-head velocity in eq. (11)

n = exponent of the strain in equation (3)

p = exponent of a function of the strain in equation (11)

t = time, in s

v = cross-head velocity in ms^{-1}

A = percentage elongation

E = Young's modulus

F = Fisher's F function

F_1 = value of Fisher's function F relative to the removal of a variable

T = absolute temperature in degrees Kelvin

σ = true stress in MPa

$\overline{\sigma}$ = engineering stress in MPa

ε = true strain

$\overline{\varepsilon}$ = engineering strain.

Index of the Variables

$\cdot$ $= \frac{d}{dt}$

u = relative to the stresses, maximum in the tensile tests

0, 2 = relative to the yield stresses at a percentage permanent strain (elongation) of 0, 2%

p = plastic component

pb = relative to A, plastic after rupture

pu = relative to A, uniform plastic at the maximum load

o = reference, in the constitutive laws

F_{ab} = relative to F and F_1, tabular.

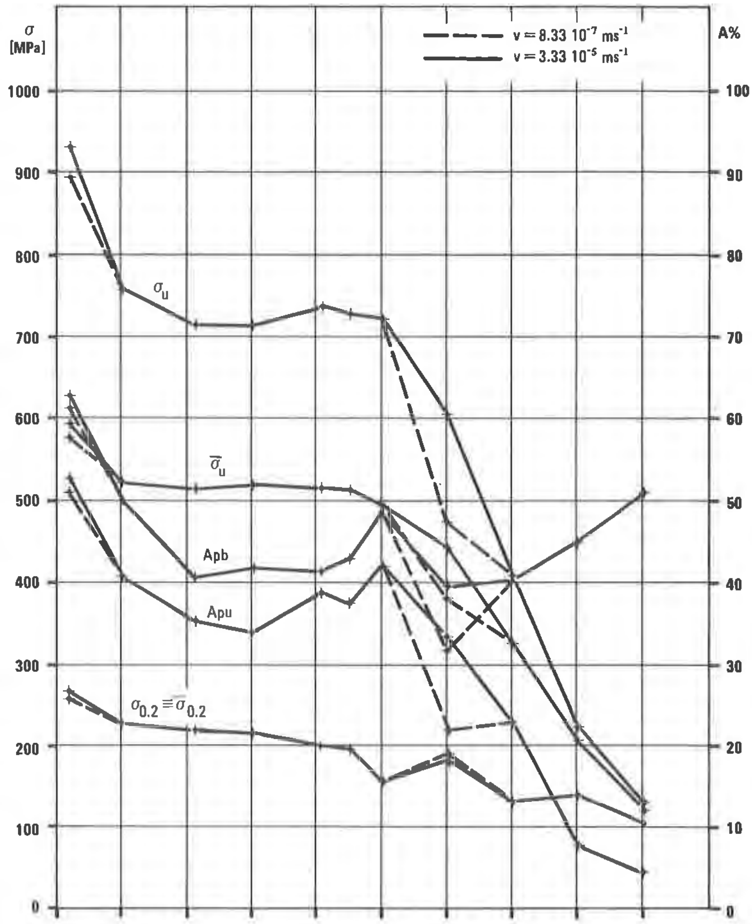

Fig. 1 Mechanical properties for AISI 310 stainless steel as a function of test temperature

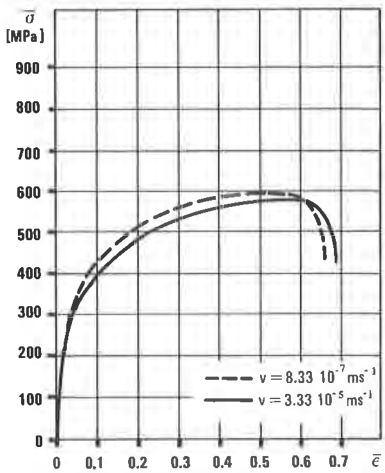

Fig. 2 Conventional stress-strain ($\bar{\sigma}$-$\bar{\epsilon}$) curve for AISI 310 stainless steel at 293 K and v = 3.33 · 10^{-5} ms^{-1} and v = 8.33 · 10^{-7} ms^{-1}

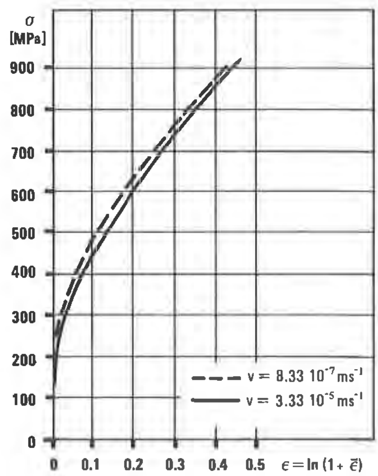

Fig. 3 True stress-true strain curve for AISI 310 stainless steel at 293 K and v = 3.33 · 10^{-5} ms^{-1} and v = 8.33 · 10^{-7} ms^{-1}

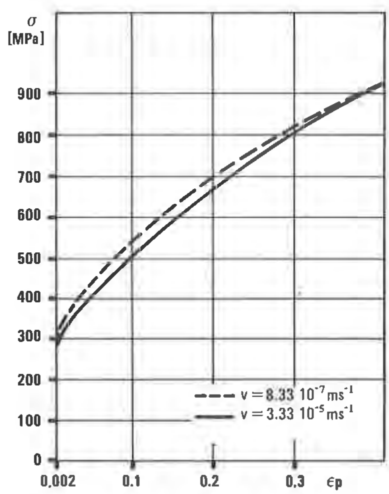

Fig. 4 True stress-true plastic strain curve for AISI 310 stainless steel at 293 K and v = 3.33 · 10^{-5} ms^{-1} and v = 8.33 · 10^{-7} ms^{-1}

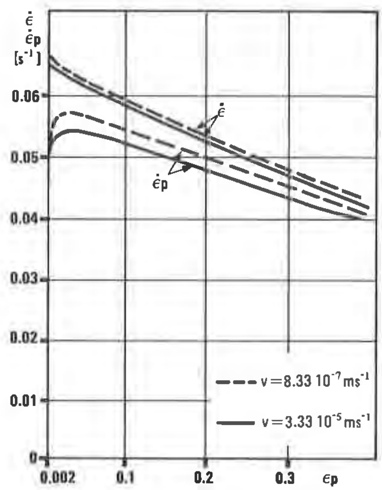

Fig. 5 True strain rate, true plastic strain rate - true plastic strain curves for AISI 310 stainless steel at 293 K and v = 3.33 · 10^{-5} ms^{-1} and v = 8.33 · 10^{-7} ms^{-1}.

Table III – Results of Statistical Analysis of All Tests for Eq.s (3), (4)

	DATA	DEP. VAR.	INDEP. VAR.S	k	n	m	s	F	F_{TAB}	F_i	$F_{1,TAB}$	Referred to Eq.
1	1230 (57 tests)	σ	ε_p $\dot{\varepsilon}_p$ T	531,1	0,2242 ±0,0029	-0,0057 ±0,0036	178,3± 5,9	2749	$F_{0.005,3,00}$= =4.28	–		
2		σ	ε_p $\dot{\varepsilon}$ T	529,4	0,2231 ±0,0028	-0,0068 ±0,0038	178,8± 5,8	2749		–		
3		σ	$\dot{\varepsilon}_p$ T	247	–	0,0448 ±0,0085	268 ±14,1	180,6	$F_{0.005,2,00}$= =5.30	5597	$F_{1,0.005,1,00}$= =7.88	1
4		σ	ε_p $\dot{\varepsilon}_p$	772	0,2411 ±0,0037	0,0360 ±0,0045	–	2098		817,8		1
5		σ	ε_p T	538,9	0,2233 ±0,0028	–	181 ± 5,5	4117		2,37	$F_{1,0.25,1,00}$= =1.32	1
6		σ	$\dot{\varepsilon}$ T	260,9	–	-0,0189 ±0,0088	240 ±14,3	166,1		6230	$F_{1,0.005,1,00}$= =7.88	2
7		σ	ε_p $\dot{\varepsilon}$	768,5	0,2348 ±0,0037	-0,0341 ±0,0046	–	2078		833,8		2
8		σ	ε_p	887,4	0,2371 ±0,0038	–	–	3928	$F_{0.005,1,00}$= =7.88	7836	$F_{1,0.005,1,00}$= =7.88	5
9		σ	$\dot{\varepsilon}_p$	404,6	–	0,0035 ±0,0093	–	0,137	$F_{0.5,1,00}$= =0.4549	4195		7
10		σ	$\dot{\varepsilon}$	314,5	–	-0,0597 ±0,0094	–	40	$F_{0.005,1,00}$= =7.88	3986		4
11		σ	T	214,2	–	–	248,7±13,8	325 9		6260		5

Table I – Chemical Analyses

Element	C	Si	Mn	Ni	Cr	S	P
Chemical analyses (wt - %)	0.09	1 76	1.31	20.8	25 78	0.006	0 026
AISI 310 Specifications (wt - %)	0.25 max.	1 50 max	2 00 max	19.0 - 21.0	24 0 - 26.0	0 030 max	0 045 max

Table II – Test Conditions

TEMPERATURE (K)	HEAD CROSS VELOCITIES $[m\,s^{-1}]$	NUMBER OF TESTS
293	$3.33\,10^{-5}$ $8.33\,10^{-7}$	15 12
373	$3.33\,10^{-5}$	1
473	$3.33\,10^{-4}$	3
573	$3.33\,10^{-5}$	1
673	$3.33\,10^{-5}$	3
723	$3.33\,10^{-5}$	2
773	$3.33\,10^{-5}$	2
873	$3.33\,10^{-5}$ $8.33\,10^{-7}$	8 4
973	$3.33\,10^{-5}$	2
1073	$3.33\,10^{-5}$	[illegible]
1173	$3.33\,10^{-5}$	2

Table IV – Results of Statistical Analyses of Tests at All Temperatures (with only two Tests at 293 K and 873 K) for Eq.s (3), (4)

	DATA	DEP. VAR.	INDEP. VAR.S	k	n	m	s	F	F_{TAB}	F_1	$F_{1,TAB}$	Referred to line
1	370 [20 tests]	σ	ϵp, $\dot{\epsilon} p$, T	510.7	0.2397 ±0.0058	0.0086 ±0.0106	233.4±15.4	752.8	$F_{0.005,3,00}$= =4.28	–		
2		σ	ϵp, $\dot{\epsilon}$, T	523.4	0.2380 ±0.0058	0.0026 ±0.0101	229.5±15.4	751.5		–		
3		σ	$\dot{\epsilon} p$, T	223.6	–	0.0728 ±0.0243	367.1±35	56.3	$F_{0.005,2,00}$= =5.3	1720	$F_{1,0.005,1,00}$= =7.88	1
4		σ	ϵp, $\dot{\epsilon} p$	659.2	0.2591 ±0.0071	0.0666 ±0.0123	–	659.5		221.4		1
5		σ	ϵp, T	520	0.2388 ±0.0058	–	228.1±14.3	1130		6.99	$F_{1,0.01,1,00}$= =6.63	1
6		σ	$\dot{\epsilon}$, T	169.5	–	0.0411 ±0.0257	308.4±36.8	61.2		1691	$F_{1,0.005,1,00}$= =7.88	2
7		σ	ϵp, $\dot{\epsilon}$	666.4	0.2487 ±0.0073	0.0579 ±0.0129	–	640.4		221.6		2
8		σ	ϵp	614.4	0.2548 ±0.0074	–	–	1199.5	$F_{0.005,1,00}$= =7.88	254.2	$F_{1,0.005,1,00}$= =7.88	5
9		σ	$\dot{\epsilon} p$	309.9	–	0.0163 ±0.0259	–	0.397	$F_{0.5,1,00}$= =0.455	110		3
10		σ	$\dot{\epsilon}$	219.9	–	0.1264 ±0.0265	–	23.84	$F_{0.005,1,00}$= 7.88	74		7
11		σ	T	186.1	–	–	330.5±33.1	99.5		1709		5

Table V – Results of Statistical Analyses of All Tests at 293 K for Eq.s (3), (4)

	DATA	DEP. VAR.	INDEP. VAR.S.	k	n	m	F	F_{TAB}	F_1	$F_{1,TAB}$	Referred to line
1	685 [27 tests]	σ	ϵp, $\dot{\epsilon} p$	958.7	0.2183 ±0.0035	-0.0044 ±0.0041	1994	$F_{0.005,2,00}$= =5.30	–		
2		σ	ϵp, $\dot{\epsilon}$	958.1	0.2175 ±0.0035	-0.0042 ±0.0042	1995		–		
3		σ	ϵp	976.9	0.2177 ±0.0034	–	3988	$F_{0.005,1,00}$= =7.88	1.133	$F_{1,0.5,1,00}$= =0.4549	1
4		σ	$\dot{\epsilon} p$	586.1	–	0.0355 ±0.0105	11.36		3914	$F_{1,0.005,1,00}$= =7.88	1
5		σ	$\dot{\epsilon}$	446.1	–	-0.0238 ±0.0108	4.84	$F_{0.05,1,00}$= =3.84	3957		2

Table VII – Statistical Analyses of Tests for Eq. (11)

DATA	TEMP. [K]	DEP. VAR.	INDEP. VAR.S	k_3	n_3	p_3	m_3	F	F_{TAB}
685 [27 tests]	293	σ	ϵp $\dot{\overline{\epsilon}}$ v	684.7	0.1573 ±0.0051	-1.1102 ±0.0036	-0.0024 ±0.0036	1810	$F_{0.005,3,00} = 4.28$
46 [2 tests]	293	σ	ϵp $\dot{\overline{\epsilon}}$ v	676.2	-0.1341 ±0.0049	-1.3222 ±0.0667	-0.0072 ±0.0026	2729	$F_{0.005,3,46} = 4.88$
243 [14 tests]	873	σ	ϵp $\dot{\overline{\epsilon}}$ v	408.2	0.1543 ±0.0086	-1.7604 ±0.1889	-0.008 ±0.0059	630.8	$F_{0.005,3,00} = 4.28$

Table VIII – Strain Rate Hardening Coefficient at 293 K

ϵp	0.02	0.07	0.1	0.2	0.3	0.4	
m_3	-0.02	-3.59	$1.6\ 10^{-3}$	$3.53\ 10^{-3}$	$3.44\ 10^{-3}$	$3.53\ 10^{-3}$	

Table VI – Results of Statistical Analyses of All Tests at 873 K for Eq.s (3), (4)

	DATA	DEP. VAR.	INDEP. VAR.S	k	n	m	F	F_{TAB}	F_1	$F_{1,TAB}$	Referred to line
1	243 (14 tests)	σ	ϵp $\dot{\epsilon} p$	686.3	0.2171 ±0.0062	0.0049 ±0.0068	666.6	$F_{0.005,2,00} = 5.30$	–		
2		σ	ϵp $\dot{\epsilon}$	669.8	0.2183 ±0.0060	-0.0018 ±0.0068	665.1		–		
3		σ	ϵp	674.7	0.2183 ±0.0060	–	1335	$F_{0.005,1,00} = 7.88$	0.5048	$F_{1,0.5,1,00} = 0.4549$	1
4		σ	$\dot{\epsilon} p$	398.9	–	0.0669 ±0.0164	16.76		1231	$F_{1,0.005,1,00} = 7.88$	1
5		σ	$\dot{\epsilon}$	308.3	–	0.0088 ±0.0175	0.2531	$F_{0.5,1,00} = 0.4549$	1329		2