

Inelastic Stress-Strain Relationship for AISI 316 Stainless Steel in the Temperature Range 20° - 800 °C

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SUMMARY

For the design of LMFBR reactor systems, it is necessary to consider the time independent (short-term tensile) behaviour of the structural materials, such as austenitic stainless steels, which are important for nuclear applications because of their characteristics of mechanical and corrosion resistance at high temperatures. It is desirable, therefore, to have at one's disposal as input for calculations, a set of constitutive relations which describe the plastic behaviour of these materials over a wide range of temperatures under tensile loading.

In this work, a large collection of tensile stress-strain curves for different strain rates (4.17×10^{-5} - 4.17×10^{-2}) and for a variety of temperature conditions (293 - 1073 K) concerning the AISI 316 type stainless steels (annealed conditions) is examined.

A numerical analysis of the stress-strain data is performed, using a curve fitting program and taking into account the following constitutive equations, which describe the macroscopical mechanical behaviour of the metallic materials.

$$\left. \begin{aligned} \sigma &= A_1 \dot{\epsilon}_p^{n_1} \epsilon_p^{m_1} \exp(k_1/T) \\ \sigma &= A_2 \epsilon_p^{n_2} \exp(k_2/T) \\ \sigma &= A_3 \epsilon_p^{n_3} \epsilon_p^{m_3} \\ \sigma &= A_H \epsilon_p^{n_H} \\ \sigma &= A_V + B_V \exp(C_V \epsilon_p) \\ \sigma &= A_L + B_L \epsilon_p^{n_L} \\ \sigma &= A_{LU} \exp(C_{LU} \epsilon_p) + B_{LU} \epsilon_p^{n_{LU}} \end{aligned} \right\} \begin{array}{l} \text{power laws eq.} \\ \\ \\ \text{Hollomon eq.} \\ \text{Voce eq.} \\ \text{Ludwik eq.} \\ \text{Ludwigson eq.} \end{array}$$

where σ is the true stress, ϵ_p the true plastic strain, $\dot{\epsilon}$ the true strain rate, $\dot{\epsilon}_p$ the true plastic strain rate, T is the temperature expressed in degrees Kelvin and the other symbols are constants.

The statistical analysis shows that among laws having plastic strain as the only independent variable Voce's law is the best for temperatures above 293K and Ludwick and Ludwigson's law are the best at room temperature. Hollomon's law is sufficiently satisfactory for $T = 1074$.

As far as the power laws taking into account both the strain and the strain rate influence are concerned, it appears that the strain rate is a variable of low significance. As a conclusion, in the case of AISI 316 stainless steel deformed by uniaxial monotonic straining, different mathematical formulae are to be considered in order to describe the real response of the material to the load over a large behaviour range.

1. Introduction

The design of liquid metal fast breeder reactors (LMFBR) must take into consideration time independent (short-time tensile) behaviour of austenitic stainless steels which are the major structural alloys used in these sophisticated nuclear systems. It is useful therefore to have at one's disposal the constitutive equations which describe the plastic behaviour of these materials over the entire range of behaviour. However, the constitutive relationships for plasticity are not well established and according to Malvern /1/, it is more profitable to use "separate equations describing various kinds of ideal material response, each of which is a mathematical formulation designed to approximate physical observation of a real material response over a suitable restricted range". This philosophy, which in virtue of its interdisciplinary attitude can be accepted by different categories of scientists (continuum mechanics specialists, designers, metallurgists and solid state physicists), has been adopted by the authors in the course of research into relating the flow stress of AISI 316 type stainless steel to strain, strain rate and temperature in a given range of behaviour. The studies were conducted by performing: a) an experimental investigation of plastic behaviour under uniaxial monotonic loading over a variety of temperatures (273° to 1073°K) and strain rates (4.17×10^{-5} to $4.17 \times 10^{-2} \text{ s}^{-1}$); b) a numerical analysis of the stress-strain data by a curve fitting program which considered different types of phenomenological equations describing the stress-strain behaviour of the material. The results are reported here.

This work is part of continuing research within the Nuclear Reactor Safety Program at the JRC, Ispra Establishment, concerning the development of constitutive equations for stainless steels intended for use in advanced reactor systems /2-6/.

2. Experimental

2.1 Material

The material used in this work has been supplied by Uddeholm (Sweden) (heat LK 4290) in the form of 50 mm thick plate. The chemical analysis is given in Table I. The plate was machined into round samples with a 4 mm diameter and 20 mm gauge length. All specimens were machined to allow stressing in a direction parallel to the rolling direction of the plate material. Some of the specimens shown thereafter as AISI 316 I were obtained from the outer layer, and some, shown hereafter as AISI 316 II, from the inner layer. The specimens were annealed at 1080°C for half an hour and water quenched to give an austenitic grain of the order 3-4 according to A. S. T. M. -E112.

2.2 Tensile tests

Tensile tests have been carried out at steady state extension rates on an INSTRON machine in a controlled atmosphere of argon on 56 test samples (28 test samples of AISI 316 I and 28 of AISI 316 II). The test temperatures, controlled at a standard deviation of $\pm 2^\circ\text{K}$, and the cross-head velocities are given in Table II. Figs. 1, 2, 3 and 4 give the behaviour of the engineering tensile strength ($\sigma_{c,u}$) of the engineering yield strength at 0.2% ($\sigma_{c,0.2}$) of the conventional uniform plastic percentage elongation (A_{pu}) and at the breaking point (A_{pb}) as a function of the temperature for the AISI 316 I (Figs. 1 and 3) and AISI 316 II (Figs. 2 and 4) test samples. Figs. 5, 6, 7 and 8 give the behaviour of $\sigma_{c,u}$, $\sigma_{c,0.2}$, A_{pu} and A_{pb} as a function of the engineering strain rate $\dot{\epsilon}_c$. It can be seen that $\sigma_{c,0.2}$ is little affected by engineering strain rate $\dot{\epsilon}_c$, while $\sigma_{c,u}$ is sensitive to $\dot{\epsilon}_c$ at $T = 1073^\circ\text{K}$. The plastic elongations A_{pu} and A_{pb} are sensitive to $\dot{\epsilon}_c$ for both $T = 1073^\circ\text{K}$, and $T = 293^\circ\text{K}$. We can note that only the ultimate plastic elongation A_{pb} is plainly affected at 1073°K by the different sample positions (internal, external).

3. Mathematical description of the diagram

The load-elongation curves obtained from the tensile tests have been stored by points in a Hewlett-Packard 2100-A computer and then processed.

To estimate first the influence of true plastic strain ϵ_p , true strain rate both total ($\dot{\epsilon}$) and plastic ($\dot{\epsilon}_p$), and of the temperature on the plastic behaviour of the AISI 316 stainless steel, we have carried out a statistical analysis by means of exponential equations previously proposed /5/:

$$\sigma = \sigma_o \left(\frac{\epsilon_p}{\epsilon_{op}} \right)^{n_1} \left(\frac{\dot{\epsilon}_p}{\dot{\epsilon}_{op}} \right)^{m_1} \frac{\exp(a_{0,1} T_o / T)}{\exp(a_{0,1})} = k_1 \epsilon_p^{n_1} \dot{\epsilon}_p^{m_1} \exp(a_1 / T) \quad (1)$$

$$\sigma = \sigma_o \left(\frac{\epsilon_p}{\epsilon_{op}} \right)^{n_2} \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_o} \right)^{m_2} \frac{\exp(a_{0,2} T_o / T)}{\exp(a_{0,2})} = k_2 \epsilon_p^{n_2} \dot{\epsilon}^{m_2} \exp(a_2 / T) \quad (2)$$

where σ_o indicates the true reference stress produced at a reference temperature T_o at the true plastic strain ϵ_{op} with a true strain rate $\dot{\epsilon}_{op}$ or $\dot{\epsilon}_o$. K_1 , K_2 , a_1 and a_2 are constants n_1 and n_2 are strain hardening exponents and m_1 and m_2 are strain rate hardening exponents.

By means of linearization of equation (1) and (2) and of the following deletion of the variables ϵ_p , $\dot{\epsilon}_p$ (or $\dot{\epsilon}$) and T , assumed to be independent variables, we have a first estimate of how significant the variables themselves are. Table III gives the values of the coefficients which appear in the equations (1) and (2), the calculated and the reference table values, at the corresponding degrees of freedom and at the indicated probability levels, of the correlation coefficient R and of Fisher's function F that corresponds to the law examined and moreover the value of Fisher's function F_1 calculated after the removal of an independent variable.

By examination of this table, it can be seen that, with exponential laws such as those proposed, the most significant variable is the true plastic strain ϵ_p (it is in fact the

variable to the removal of which corresponds the highest value of F). Because of this, we have examined the following laws: Hollomon /7/, Voce /8/, Ludwik /9/ and Ludwigson /10/ which have only one independent variable ϵ_p .

$$\sigma = A_H \epsilon_p^{n_H} \quad (\text{Hollomon eq.}) \quad (3)$$

$$\sigma = A_V + B_V \exp(C_V \epsilon_p) \quad (\text{Voce eq.}) \quad (4)$$

$$\sigma = A_L + B_L \epsilon_p^{n_L} \quad (\text{Ludwik eq.}) \quad (5)$$

$$\sigma = A_{LU} \exp(C_{LU} \epsilon_p) + B_{LU} \epsilon_p^{n_{LU}} \quad (\text{Ludwigson eq.}) \quad (6)$$

where A_H , A_V , B_V , C_V , A_L , B_L , A_{LU} , B_{LU} and C_{LU} are material constants and n_H , n_L and n_{LU} are strain hardening exponents.

Tables IV, V, VI, VII, concerning AISI 316 I test samples and tables VIII, IX, X and XI, concerning AISI 316 II test samples, give the tabulated values appearing in these equations, each computed through non-linear regression analysis /6, 11/, with the computed and reference table values of the indicators of significance (R and F).

4. Discussion of the results and conclusions

The examination of Table III shows first of all that in exponential laws of type (1) and (2) or derived from them, one can consider both $\dot{\epsilon}_p$ or $\dot{\epsilon}$, connected very simply to the cross-head velocity as had already been found for AISI 316 at high temperatures /6/ and for AISI 310 /5/. Besides, the values of Fisher's function F_1 , calculated after removal of one of the variables, show that $\dot{\epsilon}$ (or $\dot{\epsilon}_p$) is an insignificant variable, while they show ϵ_p to be the most significant variable. Amongst laws having ϵ_p as the only independent variable, the results of the statistical analysis show Voce's law as the best for temperatures above 293°K and Ludwik and Ludwigson's laws as the best at room temperature. In fact, as was previously noticed /5/, even if Voce's law is the best from a statistical point of view, it does not show satisfactorily the behaviour of AISI 316 in the plastic field for small deformations, while we must consider Ludwik and Ludwigson's laws as the best and equivalent to one another. Also Hollomon's law is sufficiently satisfactory for $T=1073^\circ\text{K}$. Unlike what is shown in /12/ for 2,25 Cr-1 Mo stainless steel and in /6/ for AISI 316 stainless steel at high temperatures, it was not possible to determine a good linear relationship between the coefficients of Hollomon, Voce, Ludwik and Ludwigson's laws and $\sigma_{c,u}$. To examine whether there exists a significant difference of behaviour between the AISI 316 I and AISI 316 II test samples, the comparison between Hollomon's law exponents calculated through linear regression was used as a test. The result is that the difference in the behaviour between the outer layer (AISI 316 I) and the inner layer (AISI 316 II) is significant for the low strain rate only.

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C	Si	Mn	P	S	Cr	Ni	Mo	Co	B	N	Fe
0.05	0.35	1.65	0.020	0.008	16.9	12.4	2.45	0.023	0.001	0.082	balance

TABLE I. Chemical Composition (wt.%) of 316 Stainless Steel.

TEMPERATURE [K]	HEAD CROSS VELOCITIES v/8.33 (m/s)	NUMBER OF TESTS	
		AIISI 316 I	AIISI 316 II
293	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
473	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
673	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
773	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
823	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
873	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1
1073	10 ⁻⁷	1	1
	10 ⁻⁶	1	1
	10 ⁻⁵	1	1
	10 ⁻⁴	1	1

TABLE II. Experimental Conditions

AIISI 316 I	Data tests	DEP. VAR.	INDEP. VAR.	k	n	m	a [K]	R	R _{Tab,005}	F	F _{Tab,005}	F _I	F _{Tab,005}
523	28	σ	ε _p , ε _p , T	4838	0.2832	---	-0.0008	264.3	0.9469	1499	3.72	---	788
			ε _p , T	4812	0.2833	---	264.2	0.9469	2253	0.06			
			ε _p , T	200.7	---	0.0153	317.4	0.9864	48.5	4.28	3710		
			ε _p , ε _p , T	756.2	0.2913	-0.0010	---	0.8891	0.443	981	532		
			ε _p , T	479.3	0.2834	-0.0006	264.1	0.9469	1499	3.72	---		
			ε _p , T	212.2	---	0.0232	317.6	0.4031	50.4	4.28	3570		
584	28	σ	ε _p , ε _p	748.9	0.2916	-0.0026	---	0.8891	981	532	---	788	
			ε _p , ε _p , T	447.8	0.2676	-0.0033	269.6	0.9370	1390	3.72	---		
			ε _p , T	457.5	0.2674	---	269.9	0.9369	2085	0.89	---		
			ε _p , T	193.4	---	0.0094	316.1	0.4045	56.8	4.28	3394		
			ε _p , T	711.3	0.2753	-0.0055	---	0.8718	0.443	920	560		
			ε _p , ε _p , T	443.6	0.2682	-0.0048	269.5	0.9371	1393	3.72	---		
584	28	σ	ε _p , T	207.1	---	0.0190	316.6	0.4103	58.8	4.28	3279	788	
			ε _p , ε _p	704.2	0.2759	-0.0071	---	0.8720	922	558			

TABLE III. Influence of independent Variables and of Sample position (I and II).

Data	T	$\dot{\gamma}$	A_H	n_H	R	$R_{lab,005}$	F	$F_{lab,005}$
	(K)	(s ⁻¹)	(MPa)					
15	10 ⁻⁷	1114	0.3087	0.9687	0.760	915	8.510	
18	10 ⁻⁶	1212	0.3454	0.9804	0.708	186	7.701	
17	293	10 ⁻⁵	1081	0.2795	0.9684	0.725	101	7.922
16	10 ⁻⁴	10798	0.2779	0.9760	0.742	131	8.187	
23	10 ⁻⁷	995.86	0.3285	0.9712	0.641	166	6.987	
20	470	10 ⁻⁶	1014	0.3828	0.9816	0.679	225	7.254
21	10 ⁻⁵	933.4	0.3769	0.9749	0.679	163		
20	10 ⁻⁴	832.2	0.2989	0.9718	0.666	153	7.215	
19	10 ⁻⁷	1128	0.4575	0.9858		276		
19	10 ⁻⁶	1087	0.4354	0.9837	0.694	239	7.514	
19	10 ⁻⁵	1101	0.4530	0.9874	0.652	370	7.094	
22	10 ⁻⁴	1050	0.4233	0.9847	0.694	347	7.514	
15	10 ⁻⁷	1063	0.4665	0.9842	0.760	185	8.510	
17	10 ⁻⁶	1082	0.4614	0.9874	0.679	332	7.354	
17	10 ⁻⁵	951.8	0.3815	0.9790	0.725	161	7.922	
22	10 ⁻⁴	1019	0.4363	0.9901	0.652	471	7.094	
18	10 ⁻⁷	1018	0.4477	0.9870	0.708	283	7.701	
19	10 ⁻⁶	1038	0.4464	0.9823	0.694	220	7.514	
19	10 ⁻⁵	989.8	0.4377	0.9768	0.725	145	7.922	
19	10 ⁻⁴	971.4	0.4250	0.9860	0.694	280	7.514	
21	10 ⁻⁷	848.4	0.3731	0.9781	0.666	199	7.215	
18	10 ⁻⁶	935.0	0.4138	0.9861	0.708	265	7.701	
19	10 ⁻⁵	918.1	0.4150	0.9839	0.694	243	7.514	
20	10 ⁻⁴	941.8	0.4615	0.9915	0.679	494	7.354	
15	10 ⁻⁷	2163	0.1055	0.9908	0.760	323	8.510	
19	10 ⁻⁶	303.7	0.1619	0.9972	0.694	142.2	7.514	
19	10 ⁻⁵	435.6	0.2441	0.9959	0.725	85	7.922	
18	10 ⁻⁴	541.7	0.2836	0.9957	0.708	858	7.701	

TABLE IV. AISI-316 I Analysis of the Hollomon Equation.

Data	T	$\dot{\gamma}$	A_V	$-B_V$	$-C_V$	R	$R_{lab,005}$	F	$F_{lab,005}$	
	(K)	(s ⁻¹)	(MPa)	(MPa)						
15	10 ⁻⁷	1295	1040	2.336	0.9997	0.780	6219	7.60		
18	10 ⁻⁶	135.4	1096	2.312	0.9991	0.725	2737	6.68		
17	293	10 ⁻⁵	1231	955	2.673	0.9996	0.742	5509	6.93	
16	10 ⁻⁴	1112	821.3	3.409	0.9993	0.761	2714	7.23		
23	10 ⁻⁷	1138	973.1	2.571	0.9998	0.652	1083	5.92		
20	470	10 ⁻⁶	1009	848.0	3.011	0.9998	0.694	1369	6.30	
20	10 ⁻⁵	978.5	804.9	3.259	0.9998	0.694	5809	6.30		
21	10 ⁻⁴	980.5	748.5	3.087	0.9997	0.679	8823	6.16		
19	10 ⁻⁷	1095	969.5	2.732	0.9999	0.708	19974	6.48		
19	10 ⁻⁶	1147	1004	2.456	0.9998	0.708	16551	6.48		
22	10 ⁻⁵	1101	9672	2.581	0.9999	0.666	23731	6.03		
19	10 ⁻⁴	1022	870.4	2.820	0.9999	0.708	26672	6.48		
15	10 ⁻⁷	1359	1204	1.578	0.9999	0.780	29594	7.60		
20	770	10 ⁻⁶	1064	946.4	2.859	0.9998	0.694	10653	6.30	
17	10 ⁻⁵	1033	900.6	2.887	0.9996	0.742	5780	6.93		
17	10 ⁻⁴	955.6	822.2	2.987	0.9999	0.666	23217	6.03		
18	10 ⁻⁷	1057	943.7	2.495	0.9996	0.625	6047	6.68		
19	10 ⁻⁶	987.9	869.3	2.201	0.9998	0.708	15776	6.48		
19	820	10 ⁻⁵	1059	918.2	2.449	0.9998	0.742	1448	6.93	
19	10 ⁻⁴	921.7	785.6	2.966	0.9998	0.708	1418	6.48		
21	10 ⁻⁷	877	596.9	3.459	0.9998	0.679	1321	6.16		
18	10 ⁻⁶	867.6	760.2	3.338	0.9998	0.725	1453	6.68		
19	870	10 ⁻⁵	874.7	764.1	3.179	0.9997	0.708	8913	6.48	
19	10 ⁻⁴	808.3	701.2	3.340	0.9996	0.694	6908	6.30		
15	10 ⁻⁷	154.6	561	97.29	0.9967	0.802	533	7.60		
19	10 ⁻⁶	263.3	114.3	31.32	0.9955	0.708	548	6.48		
19	10 ⁻⁵	36.3	192.1	15.94	0.9986	0.742	1546	6.93		
18	10 ⁻⁴	362.5	249.5	11.89	0.9994	0.725	3891	6.68		

TABLE V. AISI-316 I Analysis of the Voce Equation.

Data	T	$\dot{\gamma}$	A_L	C_L	B_L	n_L	R	$R_{lab,005}$	F	$F_{lab,005}$
	(K)	(s ⁻¹)	(MPa)	(MPa)	(MPa)					
15	10 ⁻⁷	2351	1245	0.7071	0.9998	0.780	8661	7.60		
18	10 ⁻⁶	265.7	1242	0.6828	0.9998	0.725	10221	6.68		
17	293	10 ⁻⁵	256.0	1249	0.6974	0.9997	0.742	7604	6.93	
16	10 ⁻⁴	282.2	1231.0	0.6622	0.9995	0.761	4720	7.23		
23	10 ⁻⁷	156.3	1351	0.7674	0.9995	0.652	6324	5.92		
20	470	10 ⁻⁶	143.9	1241	0.7182	0.9994	0.694	4415	6.30	
20	10 ⁻⁵	1591	1220	0.7071	0.9994	0.694	4425	6.30		
21	10 ⁻⁴	215.0	1128	0.7166	0.9990	0.679	2962	6.16		
19	10 ⁻⁷	111.0	1346	0.7338	0.9996	0.708	5938	6.48		
19	10 ⁻⁶	128.0	1336	0.7555	0.9996	0.708	6894	6.48		
22	10 ⁻⁵	117.5	1313	0.7401	0.9995	0.666	6597	6.03		
19	10 ⁻⁴	135.1	1247	0.7307	0.9993	0.708	3726	6.48		
15	10 ⁻⁷	144.2	1223	0.8108	0.9995	0.780	3824	7.60		
20	10 ⁻⁶	103.1	1301	0.7403	0.9995	0.694	5105	6.30		
17	770	10 ⁻⁵	120.3	1249	0.7426	0.9996	0.742	5366	6.93	
22	10 ⁻⁴	112.6	1208	0.7166	0.9995	0.666	5927	6.03		
18	10 ⁻⁷	98.4	1236	0.7378	0.9994	0.725	4054	6.68		
19	10 ⁻⁶	106.1	1258	0.7362	0.9994	0.708	4198	6.48		
17	820	10 ⁻⁵	112.1	1281	0.7809	0.9996	0.742	5102	6.93	
19	10 ⁻⁴	119.7	1156	0.7224	0.9993	0.708	3602	6.48		
21	10 ⁻⁷	109.4	1099	0.7183	0.9997	0.679	1025	6.16		
18	10 ⁻⁶	94.7	1160	0.7037	0.9995	0.725	4265	6.68		
19	870	10 ⁻⁵	98.0	1161	0.7195	0.9992	0.708	3097	6.48	
20	10 ⁻⁴	85.9	1066	0.6803	0.9992	0.694	3316	6.30		
15	10 ⁻⁷	67.5	175.0	0.2716	0.9923	0.780	234	7.60		
19	10 ⁻⁶	301	285.4	0.2101	0.9977	0.708	1060	6.48		
17	1070	10 ⁻⁵	38.7	424.5	0.3085	0.9970	0.742	715	6.93	
18	10 ⁻⁴	61.1	547.7	0.3999	0.9982	0.725	1274	6.68		

TABLE VI. AISI-316 I Analysis of the Ludwik Equation.

Data	T	$\dot{\gamma}$	A_L	C_L	B_L	n_L	R	$R_{lab,005}$	F	$F_{lab,005}$	
	(K)	(s ⁻¹)	(MPa)	(MPa)	(MPa)						
15	10 ⁻⁷	235.4	0.2530	1297	0.7749	0.9998	0.802	6188	7.34		
18	10 ⁻⁶	227.1	0.0944	1312	0.6883	0.9998	0.742	7125	6.68		
17	293	10 ⁻⁵	356.4	0.2387	1303	0.7505	0.9997	0.761	5341	6.93	
16	10 ⁻⁴	262.8	0.2174	1280	0.6703	0.9995	0.780	2998	6.68		
23	10 ⁻⁷	156.4	0.1741	1375	0.7703	0.9996	0.666	4502	5.92		
20	470	10 ⁻⁶	144.1	0.2570	1272	0.7208	0.9994	0.666	3262	6.30	
20	10 ⁻⁵	159.2	0.2473	1258	0.7122	0.9994	0.708	3124	5.803		
21	10 ⁻⁴	215.2	0.2543	1175	0.7241	0.9991	0.694	2104	5.638		
19	10 ⁻⁷	111.1	0.2376	1369	0.7333	0.9991	0.725	4175	5.998		
19	10 ⁻⁶	128.1	0.1903	1361	0.7542	0.9991	0.708	4841			
22	10 ⁻⁵	117.4	0.2442	1333	0.7431	0.9995	0.679	4660	5.497		
19	10 ⁻⁴	135.2	0.2455	1273	0.7347	0.9993	0.725	2619	5.998		
15	10 ⁻⁷	144.2	0.1171	1239	0.8125	0.9995	0.802	2612	7.343		
20	770	10 ⁻⁶	103.2	0.2097	1303	0.7428	0.9995	0.708	3598	5.803	
17	10 ⁻⁵	120.3	0.1676	1267	0.7465	0.9996	0.761	3721	6.521		
22	10 ⁻⁴	112.7	0.2729	1234	0.7206	0.9995	0.679	4222	5.497		
18	10 ⁻⁷	98.4	0.1824	1253	0.7400	0.9994	0.742	2828	6.234		
19	820	10 ⁻⁶	106.1	0.2446	1283	0.7392	0.9994	0.725	2950	5.998	
19	10 ⁻⁵	112.0	0.1795	1299	0.7830	0.9996	0.761	3540	6.521		
19	10 ⁻⁴	119.8	0.2571	1183	0.7266	0.9993	0.725	2532	5.998		
21	10 ⁻⁷	109.5	0.3427	1131	0.7335	0.9997	0.694	7315	5.638		
18	870	10 ⁻⁶	94.8	0.2904	1184	0.7076	0.9995	0.742	2985	6.234	
20	10 ⁻⁵	98.1	0.2711	1183	0.7333	0.9992	0.725	2176	5.998		
15	10 ⁻⁷	86.0	0.3378	1098	0.6848	0.9992	0.708	2343	5.803		
19	10 ⁻⁶	59.4	0.6334	254.5	0.2822	0.9956	0.802	548	6.521		
19	10 ⁻⁵	57.7	0.396	314.7	0.2822	0.9984	0.725	1100	5.998		
19	1070	10 ⁻⁴	48.3	1.205	463.3	0.3475	0.9973	0.761	548	6.521	
18	10 ⁻⁴	65.7	1.608	601.1	0.4297	0.9980	0.742	559	6.234		

TABLE VII. AISI-316 I Analysis of the Ludwik Equation.

Data	T	$\dot{\gamma}$	A_H	n_H	R	$R_{tab,005}$	F	$F_{tab,005}$
	[K]	[ms ⁻¹]	[MPa]					
22	10 ¹	10 ²	1052	0.2970	0.9571	0.652	104	7094
20	10 ¹	10 ⁵	1149	0.2980	0.9701	0.641	156	6987
20	293	10 ⁻⁵	1071	0.2659	0.9598	0.679	993	7354
19	10 ⁻¹	10 ⁻⁵	1081	0.2670	0.9766	0.684	165	7514
25	10 ¹	10 ⁻⁷	1035	0.2956	0.9782	0.619	244	6806
22	10 ⁻⁵	10 ⁻⁵	982.0	0.2593	0.9775	0.652	204	7094
22	473	10 ⁻⁵	918.0	0.3118	0.9673	0.641	146	6987
24	10 ⁻⁴	10 ⁻⁴	932.8	0.3579	0.9828	0.630	297	6891
23	10 ⁻⁷	10 ⁻⁷	1084	0.4164	0.9761	0.641	380	6987
19	10 ⁻⁶	10 ⁻⁶	1064	0.4147	0.9896	0.694	378	7514
19	673	10 ⁻⁵	1029	0.4096	0.9780	0.659	241	6806
20	10 ⁻⁴	10 ⁻⁴	1046	0.4451	0.9894	0.679	395	7354
21	10 ⁻⁷	10 ⁻⁷	1064	0.4393	0.9812	0.656	233	7215
19	773	10 ⁻⁵	1087	0.4492	0.9846	0.694	253	7514
24	10 ⁻⁴	10 ⁻⁴	1104	0.4195	0.9818	0.630	280	6891
21	10 ⁻⁴	10 ⁻⁴	1154	0.4924	0.9973	0.666	1673	7215
25	10 ⁻⁶	10 ⁻⁶	1048	0.4644	0.9794	0.619	258	6806
18	823	10 ⁻⁵	998.7	0.4234	0.9814	0.708	196	7701
22	10 ⁻⁵	10 ⁻⁵	970.7	0.4213	0.9802	0.652	233	7094
18	10 ⁻⁴	10 ⁻⁴	932.6	0.3993	0.984	0.708	230	7094
19	10 ⁻⁷	10 ⁻⁷	8374	0.3793	0.9806		200	
19	873	10 ⁻⁶	8602	0.3738	0.9761	0.694	176	7514
19	10 ⁻⁵	10 ⁻⁵	858.2	0.3722	0.9780		196	
19	10 ⁻⁴	10 ⁻⁴	911.6	0.4377	0.9920		476	
16	10 ⁻⁷	10 ⁻⁷	226.1	0.1246	0.9919	0.742	399	8187
21	10 ⁻⁶	10 ⁻⁶	317.1	0.1874	0.9951	0.666	906	7215
21	1073	10 ⁻⁵	410.6	0.2287	0.9932	0.652	609	7094
16	10 ⁻⁴	10 ⁻⁴	516.4	0.2744	0.9950	0.742	649	8187

TABLE VIII. AISI - 316 II Analysis of the Hollomon Equation.

Data	T	$\dot{\gamma}$	A_H	n_H	R	$R_{tab,005}$	F	$F_{tab,005}$	
	[K]	[ms ⁻¹]	[MPa]						
22	10 ¹	10 ²	1283	1307	2.473	0.9994	0.666	591	6028
23	10 ¹	10 ⁵	1289	1014	2.616	0.9991	0.652	3518	5916
20	293	10 ⁻⁵	1208	922.8	2.871	0.9996	0.649	7109	6303
19	10 ⁻¹	10 ⁻⁴	1083	1031	3.488	0.9990	0.708	2650	6476
25	10 ⁻⁷	10 ⁻⁷	1074	915.8	2.714	0.9998	0.630	1430	5730
22	10 ⁻⁵	10 ⁻⁵	1001	851.0	2.996	0.9998	0.666	1550	6028
22	473	10 ⁻⁵	1003	814.2	3.073	0.9997	0.652	3889	5916
24	10 ⁻⁴	10 ⁻⁴	943.4	780.6	3.416	0.9995	0.641	7292	5818
23	10 ⁻⁷	10 ⁻⁷	1220	1081	2.363	0.9997	0.652	1071	5916
19	10 ⁻⁶	10 ⁻⁶	981.0	845.0	3.244	0.9999	0.708	2024	6476
19	673	10 ⁻⁵	1050	907.4	2.763	0.9999	0.630	2335	5730
20	10 ⁻⁴	10 ⁻⁴	1005	865.6	2.759	0.9998	0.694	1488	6303
21	10 ⁻⁷	10 ⁻⁷	1199	1062	2.251	0.9999	0.679	2004	6356
19	10 ⁻⁶	10 ⁻⁶	1105	983.0	2.591	0.9998	0.708	1560	6476
24	773	10 ⁻⁵	1004	878.1	2.844	0.9997	0.641	1291	5818
21	10 ⁻⁴	10 ⁻⁴	815.2	725.7	4.661	0.9999	0.697	2263	6356
25	10 ⁻⁷	10 ⁻⁷	1037	921.9	2.627	0.9997	0.630	1154	5730
18	823	10 ⁻⁵	1066	948.1	2.545	0.9998	0.725	4983	6880
22	10 ⁻⁵	10 ⁻⁵	968.3	852.6	2.876	0.9998	0.666	13225	6028
18	10 ⁻⁴	10 ⁻⁴	883.6	746.1	3.203	0.9999	0.725	20589	6880
19	10 ⁻⁷	10 ⁻⁷	771.3	655.4	3.775	0.9997		7674	
19	873	10 ⁻⁶	795	678	3.728	0.9998	0.708	1037	6476
19	10 ⁻⁵	10 ⁻⁵	802.1	674.9	3.592	0.9999		18743	
16	10 ⁻⁴	10 ⁻⁴	826.7	715.1	3.203	0.9995		5004	
16	10 ⁻⁷	10 ⁻⁷					0.761		7226
21	1073	10 ⁻⁵	214.7	122.7	29.71	0.9966	0.679	834	6356
22	10 ⁻⁵	10 ⁻⁵	286.5	186.3	16.55	0.9978	0.666	1388	6028
16	10 ⁻⁴	10 ⁻⁴	315.7	239.2	11.87	0.9992	0.761	2440	7226

TABLE IX. AISI-316 II Analysis of the Voce Equation.

Data	T	$\dot{\gamma}$	A_L	B_L	n_L	R	$R_{tab,005}$	F	$F_{tab,005}$
	[K]	[ms ⁻¹]	[MPa]	[MPa]					
22	10 ¹	10 ²	227.5	1277	0.700	0.9998	0.666	8246	6028
20	10 ¹	10 ⁵	247.7	1277	0.675	0.9999	0.652	22158	5916
19	10 ⁻¹	10 ⁻⁵	2638	1261	0.6921	0.9997	0.694	8652	6303
20	10 ⁻⁴	10 ⁻⁴	2638	1259	0.6547	0.9986	0.708	7016	6476
25	10 ⁻⁷	10 ⁻⁷	1410	1386	0.7407	0.9995	0.630	7215	5730
24	10 ⁻⁶	10 ⁻⁶	1562	1205	0.7146	0.9995	0.666	5765	6028
23	10 ⁻⁵	10 ⁻⁵	1766	1246	0.7399	0.9993	0.652	4095	5916
24	10 ⁻⁴	10 ⁻⁴	1531	1161	0.6761	0.9993	0.641	4440	5818
23	10 ⁻⁷	10 ⁻⁷	1281	1405	0.7840	0.9997	0.652	1042	5916
19	10 ⁻⁶	10 ⁻⁶	1155	1248	0.6830	0.9995	0.708	5188	6476
25	10 ⁻⁷	10 ⁻⁷	1301	1262	0.7408	0.9997	0.630	10209	5730
20	10 ⁻⁴	10 ⁻⁴	1175	1203	0.7118	0.9996	0.694	692	6303
21	10 ⁻⁷	10 ⁻⁷	1270	1338	0.7708	0.9997	0.679	10943	6356
19	10 ⁻⁶	10 ⁻⁶	1100	1349	0.7541	0.9998	0.708	11303	6476
24	773	10 ⁻⁵	1125	1271	0.7814	0.9997	0.641	2343	5818
21	10 ⁻⁴	10 ⁻⁴	527.5	1224	0.5988	0.9996	0.679	6663	6356
25	10 ⁻⁷	10 ⁻⁷	1054	1286	0.7593	0.9994	0.630	5400	5730
22	10 ⁻⁶	10 ⁻⁶	1099	1291	0.7600	0.9996	0.725	6504	6880
18	823	10 ⁻⁵	105.7	1249	0.7472	0.9995	0.666	6550	6028
18	10 ⁻⁴	10 ⁻⁴	1223	1144	0.7158	0.9994	0.725	3196	6880
19	10 ⁻⁷	10 ⁻⁷	103.8	1103	0.7070	0.9996		6998	
19	873	10 ⁻⁶	106.2	1087	0.6888	0.9994	0.708	4152	6476
19	10 ⁻⁵	10 ⁻⁵	1143	1071	0.6944	0.9991		2637	
19	10 ⁻⁴	10 ⁻⁴	90.5	1072	0.6881	0.9996		5870	
16	10 ⁻⁷	10 ⁻⁷	470	264	0.0910	0.9922	0.761	254	7226
21	10 ⁻⁶	10 ⁻⁶	20.4	307	0.2177	0.9954	0.679	606	6356
22	1073	10 ⁻⁵	56.8	405	0.3418	0.9973	0.666	1116	6028
16	10 ⁻⁴	10 ⁻⁴	62.9	521	0.3958	0.9983	0.761	1147	7226

TABLE X. AISI-316 II Analysis of the Ludwik Equation.

Data	T	$\dot{\gamma}$	A_L	B_L	n_L	R	$R_{tab,005}$	F	$F_{tab,005}$	
	[K]	[ms ⁻¹]	[MPa]	[MPa]						
22	10 ¹	10 ²	227.7	0.2565	1310	0.7077	0.9998	0.679	13388	5497
23	293	10 ⁻⁵	281.1	0.1831	1319	0.6823	0.9999	0.666	16586	5375
20	10 ⁻¹	10 ⁻⁵	264.2	0.2806	1325	1.0701	0.9997	0.708	6134	5803
19	10 ⁻⁴	10 ⁻⁴	281.1	0.1402	1236	0.6607	0.9995	0.725	4919	5998
25	10 ⁻⁷	10 ⁻⁷	141.1	0.2165	1313	0.7443	0.9995	0.641	5223	5174
24	10 ⁻⁶	10 ⁻⁶	156.4	0.2604	1240	0.7199	0.9995	0.679	4112	5497
23	10 ⁻⁵	10 ⁻⁵	176.7	0.2226	1280	0.7443	0.9993	0.666	3348	5375
24	10 ⁻⁴	10 ⁻⁴	159.4	0.2594	1207	0.6830	0.9993	0.652	3184	5268
23	10 ⁻⁷	10 ⁻⁷	128.1	0.1582	1443	0.7656	0.9997	0.656	2719	5375
19	10 ⁻⁶	10 ⁻⁶	115.7	0.1560	1282	0.6826	0.9995	0.725	3667	5998
25	10 ⁻⁷	10 ⁻⁷	30.2	0.2249	1308	0.7440	0.9997	0.641	7331	5174
20	10 ⁻⁴	10 ⁻⁴	117.6	0.2348	1227	0.7178	0.9996	0.708	4893	5803
21	10 ⁻⁷	10 ⁻⁷	127.0	0.1724	1359	0.7731	0.9997	0.694	7746	6338
19	10 ⁻⁶	10 ⁻⁶	110.0	0.1887	1368	0.7563	0.9998	0.725	8356	5998
24	773	10 ⁻⁵	112.8	0.2235	1203	0.7444	0.9997	0.652	8828	5268
21	10 ⁻⁴	10 ⁻⁴	53.0	0.3710	1239	0.6017	0.9996	0.694	4718	6338
25	10 ⁻⁷	10 ⁻⁷	105.4	0.1914	1304	0.7616	0.9994	0.641	3863	5174
22	10 ⁻⁶	10 ⁻⁶	110.0	0.1952	1310	0.7624	0.9996	0.742	4542	6234
18	823	10 ⁻⁵	105.8	0.2274	1270	0.7500	0.9995	0.679	6564	5497
18	10 ⁻⁴	10 ⁻⁴	122.4	0.2888	1174	0.7205	0.9994	0.742	2744	6234
19	10 ⁻⁷	10 ⁻⁷	103.9	0.3291	1132	0.7117	0.9996		4859	
19	873	10 ⁻⁶	106.3	0.3469	1117	0.6928	0.9994		2930	
19	10 ⁻⁵	10 ⁻⁵	114.4	0.3463	1105	0.6998	0.9991	0.725	1861	5998
19	10 ⁻⁴	10 ⁻⁴	90.7	0.2426	1091	0.6917	0.9996		4118	
16	10 ⁻⁷	10 ⁻⁷	51.9	0.3039	261.3	0.2578	0.9945	0.780	246	6881

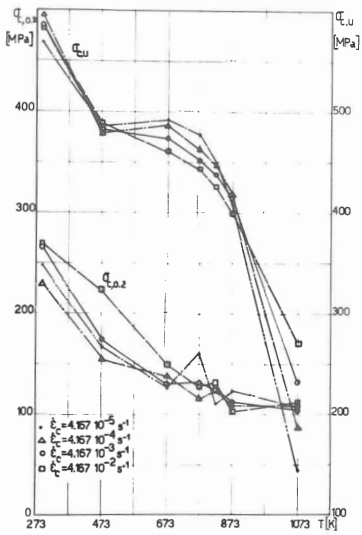


Fig. 1. AISI-316 I
Conventional Stresses as a
Function of Temperature.

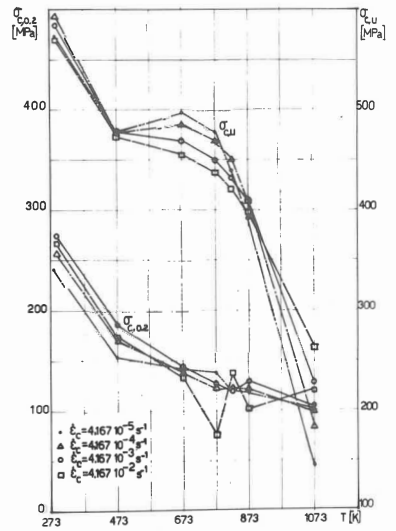


Fig. 2. AISI-316 II
Conventional Stresses as a
Function of Temperature.

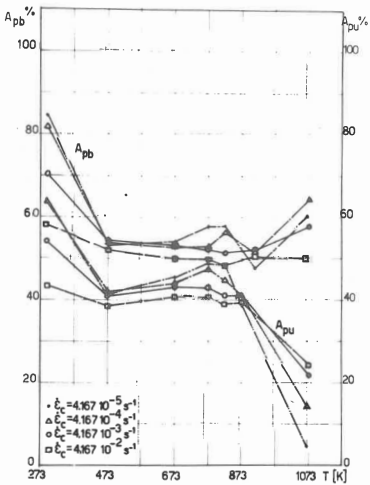


Fig. 3. AISI-316 I
Conventional Elongations as a
Function of Temperature

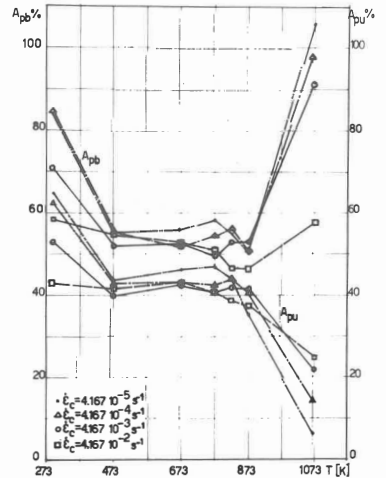


Fig. 4. AISI-316 II
Conventional Elongations as a
Function of Temperature.

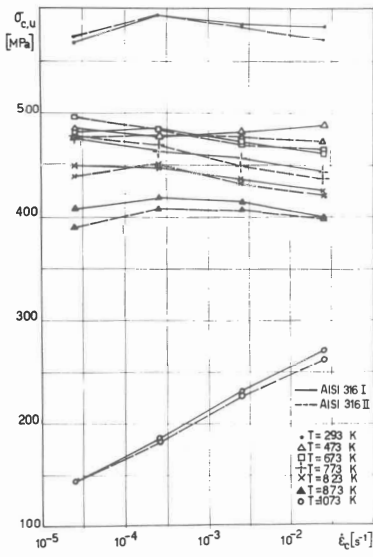


Fig. 5. Conventional Ultimate Stress as a Function of Strain Rate.

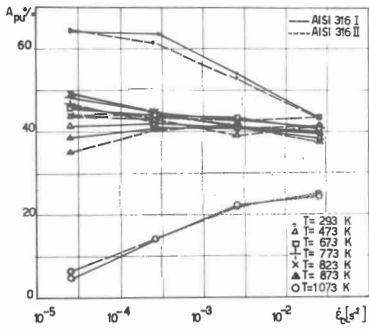


Fig. 7. Uniform Plastic Elongation as a Function of Strain Rate.

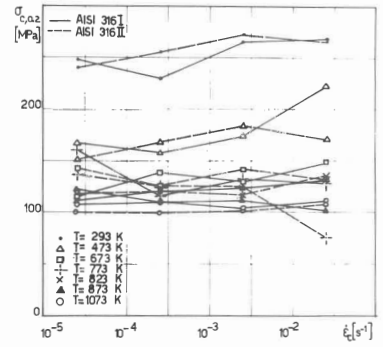


Fig. 6. Conventional Yield Stress at 0.2% as a Function of Strain Rate.

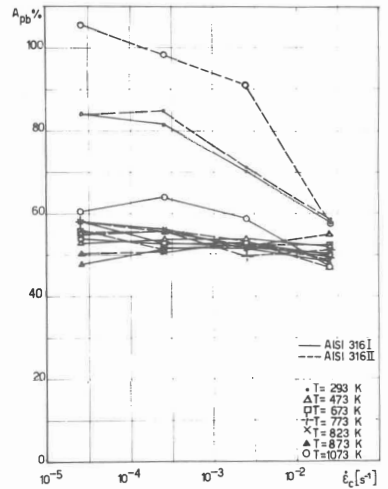


Fig. 8. Plastic Elongation at breaking Point as a Function of Strain Rate.