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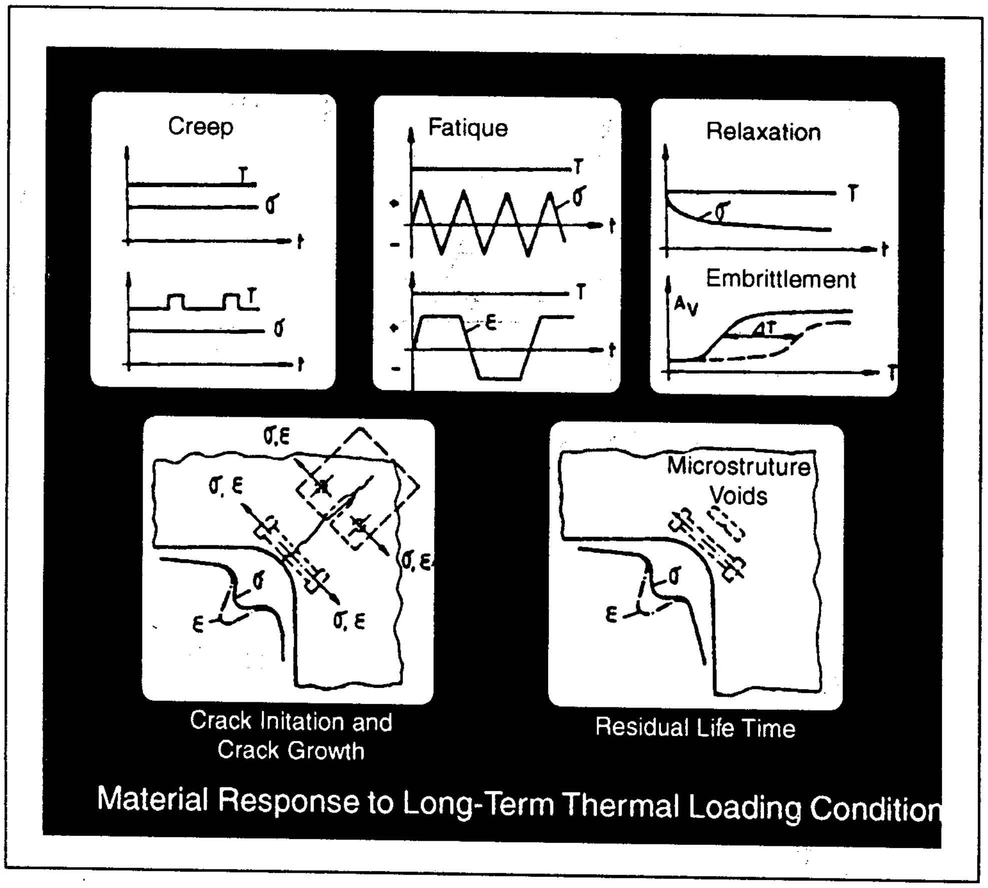

Material Response to Long-Term Thermal Loading Conditio

Verein Deutscher Eisenhüttenleute VDEh)
German Iron and Steel Institute

Evaluation of Long term Creep Data and Application of Results in Lifetime Assessment in East Europe

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1. INTRODUCTION

Progress in the computational methods of design and life time evaluation offers the possibility of more detailed modelling of both the development and time dependency of stress/strain processes in materials of machine parts. At the same time, however, these progressive methods require detailed description of material properties, e.g. in the form of the creep strength and/or strain characteristics in the case of creep of material. In addition, effective use of these computational methods demands description of the material properties not only in a form corresponding to the computing procedure used but also the statistical confidence of the data must be on a level adequate for full utilisation of the accuracy of the method.

This concerns especially the long term material properties: creep strength for 10^5 to $2x10^5$ hours. It is therefore not sufficient to base the mathematical description of a material behaviour exclusively on the numerical results of the experiments, but also the trends underlying the data as well as the processes under way in materials at long term exposure in conditions of high temperature must be incorporated into the models in maximum possible measure.

2. METHODS OF CREEP STRENGTH ESTIMATION AND EXTRAPOLATION

2.1 State of the art and review of East-European co-operation

The objective of a data assessment of creep test results is to generate a matrix for temperature and time, to put this into a material specific standard, like DIN, ASME or others. The two possible ways to do this are graphical assessment or computer aided regression analysis.

In 1992, the Working group 1 of the European Creep Collaborative Committee (ECCC-WG1) was established to develop and recommend the procedures to be used by ECCC for the generation, collation and assessment of creep deformation, stress rupture and stress relaxation data [1]. For the data assessment the group also defined so-called “PAT”s (Post Assessment Acceptability Criteria). For a valid assessment it is desirable to fulfil as much criteria as possible.

In the former East-European working group of COMECON (participants from Bulgaria, Czechoslovakia, German Democratic Republic, Soviet Union, Hungary, Romania) 15 years earlier was developed a unit procedure to assess data from creep tests. The problem was the existence of three different relationships used in standards in three different countries. The group decided to use these relationships separately and to use the average values for generation of material specific creep or rupture strength matrix.

2.2 Equations for regression analysis

The methods were detailed described in [2]. The first equation (East German procedure) used the Larson-Miller-parameter

$$P_{LM} = [C + \log(t_r)] \cdot T \cdot 10^{-4} \qquad (2.1).$$

The master curve is described by a parable of the logarithmic stress as follows:

$$\log(\sigma) = B_1 + B_2 \cdot P_{LM} + B_3 \cdot P_{LM}^2 \qquad (2.2).$$

where t_r is time to rupture,
T is temperature,
σ is stress.

The second solution from Soviet Union was fixed in the national standard [3]

$$P_A = [A_4 + \log(t_r) - 2 \cdot \log(T)] \cdot T \cdot 10^{-4} = A_1 + A_2 \cdot \log(\sigma) + A_3 \cdot \sigma \quad (2.3)$$

Czechoslovakia presented a complex equation with 6 free coefficients

$$\log(t_r) = C_1 + C_2 \cdot F + C_3 \cdot G + C_4 \cdot F \cdot G \qquad (2.4)$$

with
$$F = \log\left|\frac{1}{T} - \frac{1}{C_5}\right| \qquad (2.5)$$

and
$$G = \log[\sinh(C_6 \cdot \sigma \cdot T)] \qquad (2.6)$$

For all solutions were fixed limits for the definition range:

(2.1/2.2) has a extreme in σ and limits for σ and P,

(2.3/2.4) can have a extreme in P and must have a limit for σ, P and eventually for T,

(2.5/2.6) have 2 or 3 T-singularities.

In principle the three separate solutions obtain good interpolation results. They are differing in extrapolation for larger extrapolation factors.

The validation rules were therefore fixed as follows:

1. all three solutions obtain admissible results,
2. all data are within the definition range of solutions,

3. the single solution result does not differ more than 2% from the average of the three solutions.

In 1983, at Technological University Dresden a Fortran-based computer program "KDA" was finished [4], which included all three solutions and calculated the time and temperature dependent creep strength values from given data set.

2.3 Assessment of working example

For a working example was used a P91- (X10CrMoVNb9-1) creep rupture dataset from ECCC (table 2.1).

An assessment was done in 1995 by ECCC and the results were published in [5]. In 1999, an assessment was done by Siempelkamp, using the KDA-program on one hand to demonstrate the quality of the assessment procedure and beside this to compare the results with the already available results from ECCC-assessment. The results of the KDA-assessment compared with the ECCC-assessment are given in table 2.2. The ECCC-values are the average of the results of two different assessments, the ISO 6303 procedure and the German graphical cross-plotting and averaging technique. The KDA-values are the average of the results of the three separate solutions of the East European countries.

The comparison of results shows slightly different values of the rupture strength, especially at lower temperatures. In the common service temperature range of 550 to 600 °C and time range of 100.000 to 200.000 hours for P91-steel the differences are smaller than 5%, but the KDA-assessment in all cases has lower values.

3. MATHEMATICAL MODELS OF HEAT RESISTANT MATERIAL PROPERTIES

The following paragraphs are aimed to demonstrate a mathematical model of the process of creep based on both certain physical principles of the process and its statistical properties the purpose of which is to systematically model the mutual relationships of a number of technical quantities, among this being the time to creep rupture, the deformation relationship (creep curve) and the limit deformation.

3.1 Basic principles and relationships of the general model of strain dependence

The process of constitution of the strain dependence model will be based upon the principles of the dislocation mechanism and stochastic behaviour of the material during the course of the strain mechanism.

Initiation of deformation can be seen as a random process of discrete stochastic character. This interpretation is possible as the movement velocity of dislocations through material is finite, and thus the time interval, during which dislocations move through the metal (crystalline phase) before they will have accumulated to their critical number, is relatively large in comparison with the interval during which the external manifestation of the process in the form of permanent strain takes place [6].

To proceed with the description it is necessary to find general properties typical of the creep processes of various materials. These can be derived from a series of repeated measurements of the creep curve. These properties can be summarised as follows [7]:

a) time increments of the logarithmically transformed creep deformation

$$\Delta y(t) = y(t_2) - y(t_1),$$

where $y(t)=\ln\varepsilon_c(t)$ and $\varepsilon_c(t)$ represents the total creep deformations at time t, are not stochastically dependent on the magnitude of the deformation $\varepsilon_c(t)$ or $y(t)$,

b) the process of development of deformation at times $t>t_o$ is sufficiently determined by the deformation $\varepsilon_c(t_o)$ at time t_o,

c) the mean rate of the $y(t)$ process is independent of the initial value $y(t_o)$.

Summarily the mathematical model of creep strain characteristics is given by the following equations (3.1)–(3.5) [8-12].

Creep strain ε_{cs}:

$$\varepsilon_{cs}(t|\sigma,T) = \varepsilon_{os}.\left[\frac{\varepsilon_{ms}}{\varepsilon_{os}}\right]^{g[p(t)]} \tag{3.1}$$

where t, σ, T are time, stress and temperature, respectively

ε_{os} is instantaneous strain

ε_{ms} is creep limit strain

$g[p(t)]$ is damage function

instantaneous strain ε_{os} (for elastic deformation):

$$\varepsilon_{os} = \varepsilon_{el} = \frac{\sigma}{E(T)}.10^2 \tag{3.2}$$

$E(T)=E_1+E_2.\exp(-E_3/T)$ is the modulus of elasticity

limit creep strain ε_{ms}:

$$\varepsilon_{ms} = \exp\left[M_1 + M_2.\mathrm{tgh}\left[\frac{\ln t_{rs} - M_3 - M_4T}{M_5}\right]\right] + \frac{\sigma}{E(T)}.10^2 \tag{3.3}$$

time to rupture t_{rs}:

$$\log t_{rs} = A_1 + A_2\log\left|\frac{1}{T}-\frac{1}{A_5}\right| + A_3\log\left|\frac{1}{T}-\frac{1}{A_5}\right|.\log\left[\sinh(A_6\sigma T)\right] + A_4\log\left[\sinh(A_6\sigma T)\right] \tag{3.4}$$

$$\ln t_{rs} = \ln 10.\log t_{rs}$$

or any relationships given by rel. (2.2) or (2.3)

damage function $g[p(t)]$

$$g[p(t)] = [p(t)]^N\left[\frac{1+\exp\left[-2[p(t)]^K\right]}{1+\exp(-2)}\right]^M \tag{3.5}$$

where $$p(t) = \exp\left[[\ln t - \ln t_{rs}][1 - N(\Theta)] + \frac{\delta(\ln t_r)}{\sqrt{(2\pi)}}.\exp(-\frac{1}{2}\Theta^2) \right]$$

$$\Theta = \frac{1}{\delta(\ln t_r)}\left[\ln t - \ln t_{rs}\right],\ \ln t_{rs} \ \text{ see rel. (3.4)}$$

$\delta(\ln t_r)$ is the standard deviation of logarithmic time to rupture

$N(\Theta)$ is Gauss normalised probability distribution function

3.2 Application of the creep process complex model for evaluation of low alloyed steels properties

In this paragraph a verification of the model validity will be demonstrated and some applications mentioned. The steels in question are of the types:

- Cr0.5 Mo0.5V0.25 (according to the Czech Standard ČSN 41 5128),
- Cr2.25Mo1 (ČSN 41 5313),
- Cr2.25Mo1Nb (ČSN 41 5418),
- Cr1.25Mo0.65V0.75W0.55 (ČSN 41 5335).

Firstly we shall estimate the creep process of the steel Cr0.5Mo0.5V0.25 [8]. A comparison of several experimental creep curves and the mathematical model is presented for temperature 575°C and 600°C in Fig. 1a,b.

If this model is used together with the creep strength regression relationship according to ČSN 41 5128 creep curves of the corresponding grade of steel should be obtained. For evaluation of validity of this statement we use the mathematical formalisation of the creep strength data presented in this standard which will be compared with values of stress computed by means of the mathematical model of the creep process, the parameters of which are given in Table 3.1. From the comparison of both sets of values shown in the Table 3.2 the adequacy of agreement is apparent.

In a similar manner the creep tests of the steel Cr2.25Mo1 and Cr2.25Mo1Nb were evaluated [9-12]. A comparison of several experimental creep curves and mathematical model is presented in Fig.2. This model has been further transformed to the corresponding normatively declared creep strength (the parameters are presented in Table 3.3 and 3.4).

Let us now treat the Cr1.25Mo0.65V0.75W0.55 steel. In this case a set of data obtained from creep tests of material of steam turbine rotors has been evaluated [13]. The material parameters are in Table 3.5.

4. DISCUSION

The progress in computation methods leading to more detailed modelling of the stress/strain states of materials and even to description of their redistribution in time during the creep process requires also more detailed description of the properties of materials. Not only the mathematical model itself is involved but also its reliability, as for system consisting of components with operational life times ranging between 10^5 and 2.10^5 hours the long term material properties must be extrapolated from relatively short term tests. Thus the confidence of prediction of these properties depends also on the extent to which the mathematical model is reliable and adequate. These were the reasons for which the derivation on the mathematical model of the creep process has been based upon principles founded not only on the statistical evaluation of data and on application of the theory of probability but also on the physics of the process. Moreover the presented model of the process of creep provides a complex description of the mutual relationships between a number of quantities (time to creep fracture, initial and limit deformations) and the creep curve itself.

For application purposes the proposed model has been used for evaluation of the heat resistance and of the deformation dependencies of steels of the types Cr0.5Mo0.5V0.25, Cr2.25Mo1, Cr2.25Mo1Nb and Cr1.25Mo0.65V0.75W0.55 (their parameters are given in Tables 3.1, 3.3-3.5).

Results have been widely used in a practice. As an example it is possible to mention an estimation of residual life of critical components in fossil fired power plants where calculated operational life 10^5 hrs was exceeded. An attention was given to high-pressure rotors of turbines, made of low-alloy steels, with an output 55 and 110 MW which were in operation from $1{,}1.10^5$ up to $1{,}8.10^5$ hrs [14]. Another example is a residual life-time estimation of steam pipe-lines of power plants [15-17].

5. CONCLUSION

The aim of this contribution was to inform about activities in creep data assessment in East Europe. Already about twenty years ago existed in frames of former COMECON close co-operation of experts interested in creep processes. The activity resulted in procedures for estimation of creep strength data (see eqs (2.1)-(2.6)). This approach was used for formation of national standards.

Except of this, for designers an original model describing relationship between creep strain, stress and temperature (see eqs (3.1)-(3.5)) was developed. This model has been used for many technical applications, mainly in case of structural machine parts where exist ununiform stresses, magnitude of which redistributes with time. An one of the most simple application is calculation of relaxation curves from creep curves.

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Table 2.1: **Quantity and duration of P91-data used in assessment [5]**

Temperature [°C]	No. of heats	Test duration [h]						
		$<10^4$	10^4 to 2.10^4	2.10^4 to 3.10^4	3.10^4 to 5.10^4	5.10^4 to 7.10^4	7.10^4 to 10^5	$>10^5$
		Number of tests points available						
500	27	66 (6)	6 (4)	2		1 (3)	(2)	
525	8	6 (3)	1	1 (2)		1 (2)	(2)	
538/540	12	18	4	(2)	(1)	(5)		
550	69	194 (12)	31 (3)	20 (4)	7 (3)	1 (1)	1 (1)	
575	32	68 (1)	12 (2)	1			1	
593	15	39 (1)	9	3	3 (1)			
600	104	405 (17)	57 (2)	13 (8)	10 (6)	4 (5)	(1)	
625	24	64 (1)	1 (1)				(1)	
649/650	93	334 (9)	35 (4)	11 (2)	3	2		
675/677	17	32		1				
700	16	34	3					
Totals	141	1260	159 (16)	52 (18)	23 (11)	9 (16)	2 (7)	

( ) Figures in parentheses denote unbroken tests

Table 2.2 Rupture strength values of P91-data assessment

Temperature [°C]	10.000 h [N/mm^2]		100.000 h [N/mm^2]		200.000 h [N/mm^2]	
	ECCC (1995)	KDA (1999)	ECCC (1995)	KDA (1999)	ECCC (1995)	KDA (1999)
500	289	277	258*	237*	246*	225*
510	271	259	239*	219*	227*	207*
520	252	241	220*	202*	208*	190*
530	234	224	201	185	189*	174*
540	216	208	183	170	171*	158*
550	199	191	166	154	154*	144*
560	182	176	150	140	139*	130*
570	166	161	134	126	124*	117*
580	151	146	120	114	110*	105*
590	136	133	106	102	97*	93*
600	123	120	94	91	86*	83*
610	110	108	83	80	75*	73*
620	99	97	73	71	65*	64*
630	89	86	65	62	57*	56*
640	79	77	56	54	49*	48*
650	70	68	49	47	42*	42*
660	62	60	42	41	35*	36*
670	55	56	36	36	-	31*

* Values which have involved extended time extrapolation

Table 3.1.: Parameters of mathematical model for the creep process of the steel of Cr0.5Mo0.5V0.25 type – relation (1)

Instantaneous elastic strain – relation (3.1) Modulus of elasticity – temperature dependence		
E_1=0.21425030E+06	E_2=-0.45038420E+06	E_3=0.19371090E+04
Creep strength – time to rupture – relation (3.4)		
A_1=0.71731900E+02	A_2=0.20508200E+02	A_3=0.14641980E+01
A_4=0.36334340E+01	A_5=0.11730000E+04	A_6=0.57287390E-04
Limit creep strain – relation (3.3)		
M_1=0.14492690E+01	M_2=0.00000000E+00	M_3=0.00000000E+00
M_4=0.00000000E+00	M_5=0.00000000E+00	
Damage function – relation (3.5),		
N=0.26069590E+00	M=-0.80546550E+00	K=0.60000000E+00

Material parameters are valid for
temperature T [K], stress σ [MPa], instantaneous strain ε_o [%], creep limit strain ε_m [%], total creep strain ε_c[%], time to rupture t_r[h].

Table 3.2 .: Creep strength for 1% creep strain – steel of Cr0,5Mo0,5V0,25 type

Temperature [°C]	Time [h]	According to ČSN 415128.5 [MPa]	According to math. model [MPa]	Strength rate
480	10^4	232	251	0.92
	10^5	183	184	0.99
	$2x10^5$	169	167	1.01
520	10^4	162	162	1.00
	10^5	115	108	1.06
	$2x10^5$	101	95	1.06
560	10^4	105	104	1.01
	10^5	61	63	0.97
	$2x10^5$	49	54	0.91

Table 3.3.: Parameters of mathematical model for the creep process of the steel of Cr2.25Mo1 type – relation (3.1)

Instantaneous elastic strain – relation (3.2) Modulus of elasticity – temperature dependence		
E_1=0.21190810E+06	E_2=-0.38008711E+06	E_3=0.17781250E+04
Creep strength – time to rupture – relation (3.4)		
A_1=0.44449631E+02 A_4=0.18797710E+02	A_2=0.11249189E+02 A_5=0.11730000E+04	A_3=0.62106867E+01 A_6=0.25000001E-04
Limit creep strain – relation (3.3)		
M_1=0.24490228E+01 M_4=0.00000000E+00	M_2=0.73595409E+00 M_5=0.18781336E+01	M_3=0.88359375E+01
Damage function – relation (3.5),		
N=0.26077857E+00	M=0.10745522E+00	K=0.78557402E+00

Table 3.4.: Parameters of mathematical model for the creep process of the steel of Cr2.25Mo1Nb type – relation (3.1)

Instantaneous elastic strain – relation (3.2) Modulus of elasticity – temperature dependence		
E_1=0.21190810E+06	E_2=-0.38008711E+06	E_3=0.17781250E+04
Creep strength – time to rupture – relation (3.4)		
A_1=0.33392560E+02 A_4=0.38516710E+01	A_2=0.78463220E+01 A_5=0.11823700E+04	A_3=0.13845440E+01 A_6=0.61764510E-04
Limit creep strain – relation (3.3)		
M_1=0.24490228E+01 M_4=0.00000000E+00	M_2=-0.73595409E+00 M_5=0.18781336E+01	M_3=0.88359375E+01
Damage function – relation (3.5),		
N=0.24632310E+00	M=-0.10041890E+00	K=0.84000000E+00

Table 3.5.: Parameters of mathematical model for the creep process of the steel of Cr1.5Mo0.55V0.75W0.55 type – relation (3.1)

Instantaneous elastic strain – relation (3.2) Modulus of elasticity – temperature dependence		
E_1=0.21200285E+06	E_2=-0.51559443E+06	E_3=0.21378906E+04
Creep strength – time to rupture – relation (3.4)		
A_1=0.12088409E+02 A_4=0.74835526E+02	A_2=0.27704468E+01 A_5=0.72300000E+03	A_3=0.21288342E+02 A_6=0.20000002E-05
Limit creep strain – relation (3.3)		
M_1=0.12534423E+01 M_4=-0.50620005E-01	M_2=-0.59145725E+00 M_5=0.84640968E+00	M_3=0.49449265E+02
Damage function – relation (3.5),		
N=0.22900703E+00	M=-0.24125764E+00	K=0.5060000000E+01

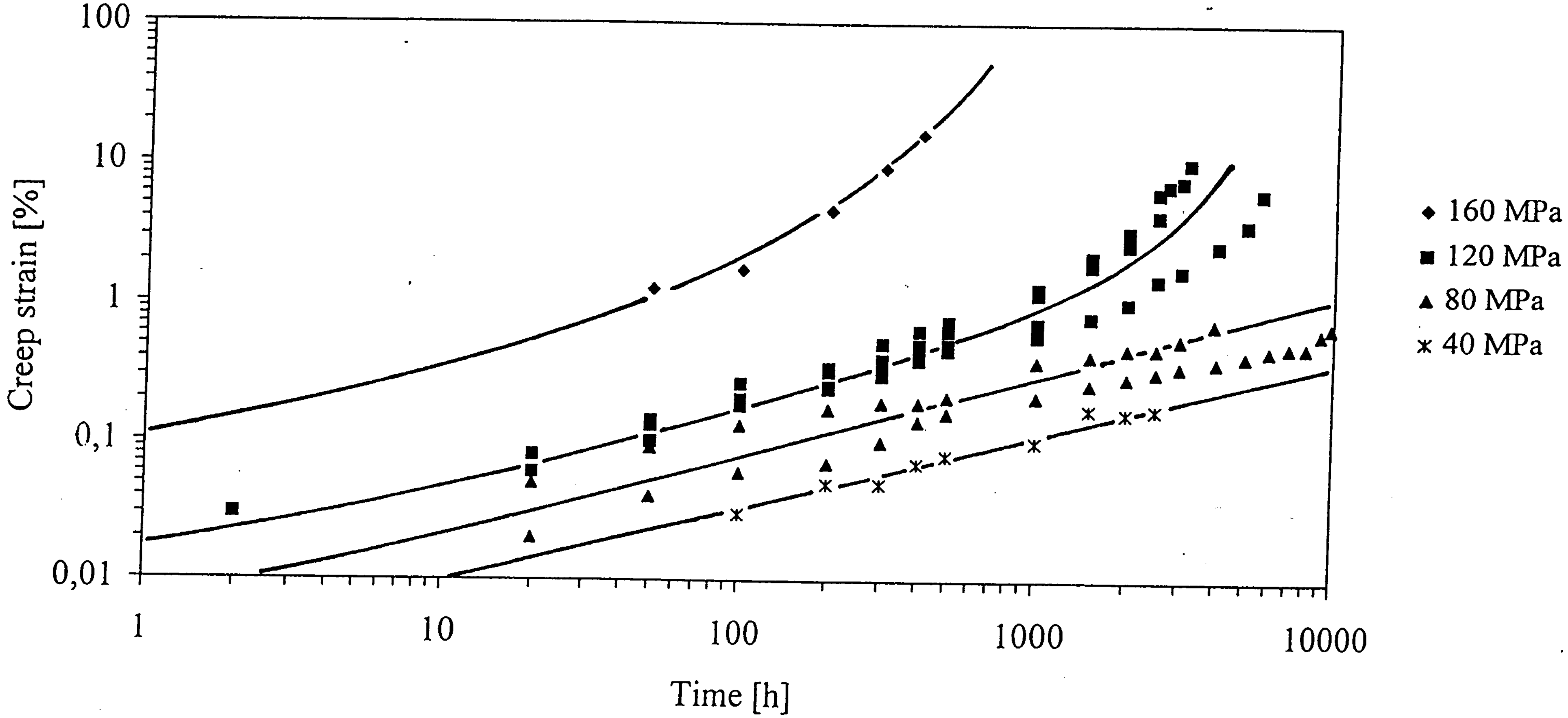

Fig. 1a. **Fitness of the experimental creep curves with the constitutive equations for the creep process - low alloy steel Cr0,5Mo0,5V0,25, 575 °C**

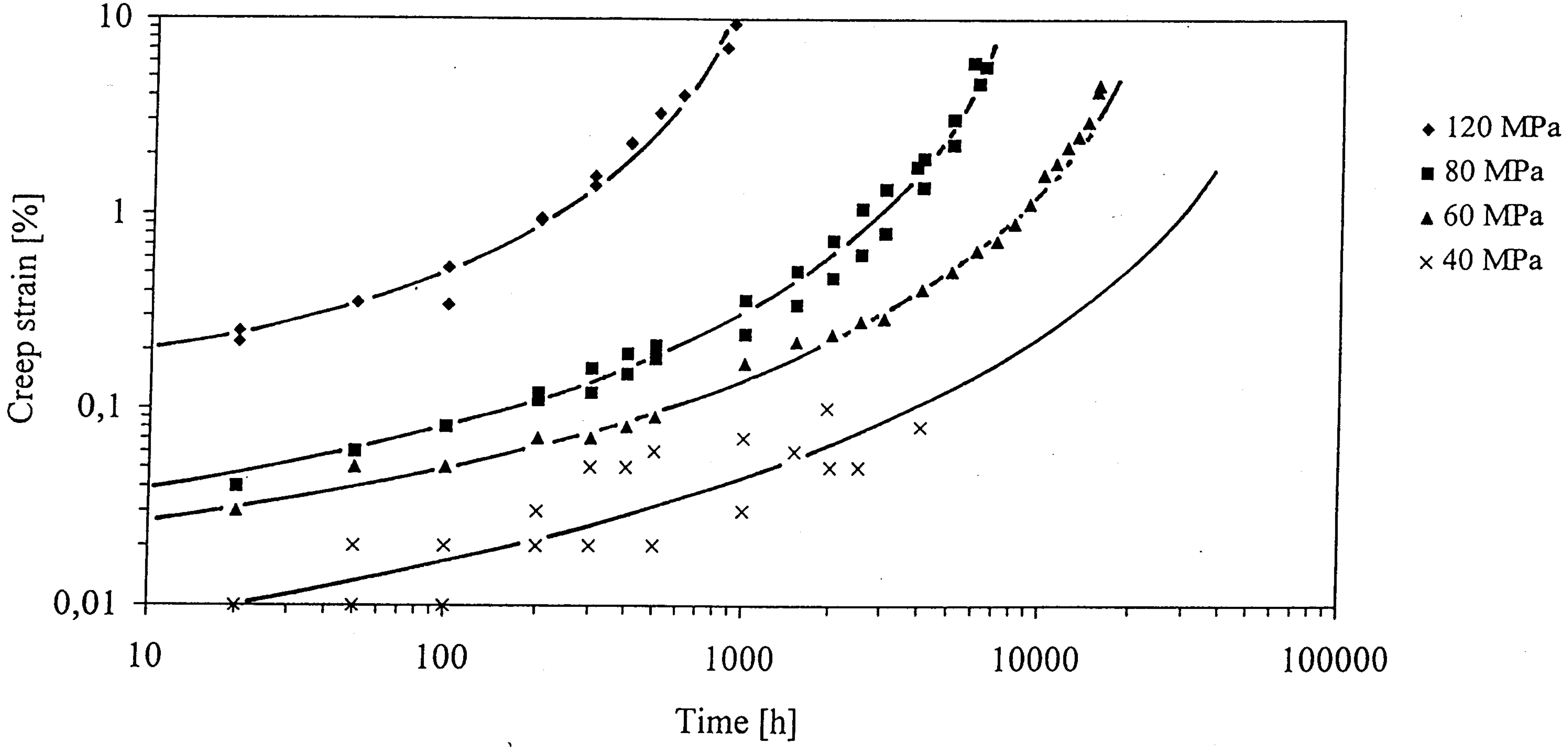

Fig. 1b. **Fitness of the experimental creep curves with the constitutive equations for the creep process - low-alloy steel Cr0,5Mo0,5V0,25, 600 °C**

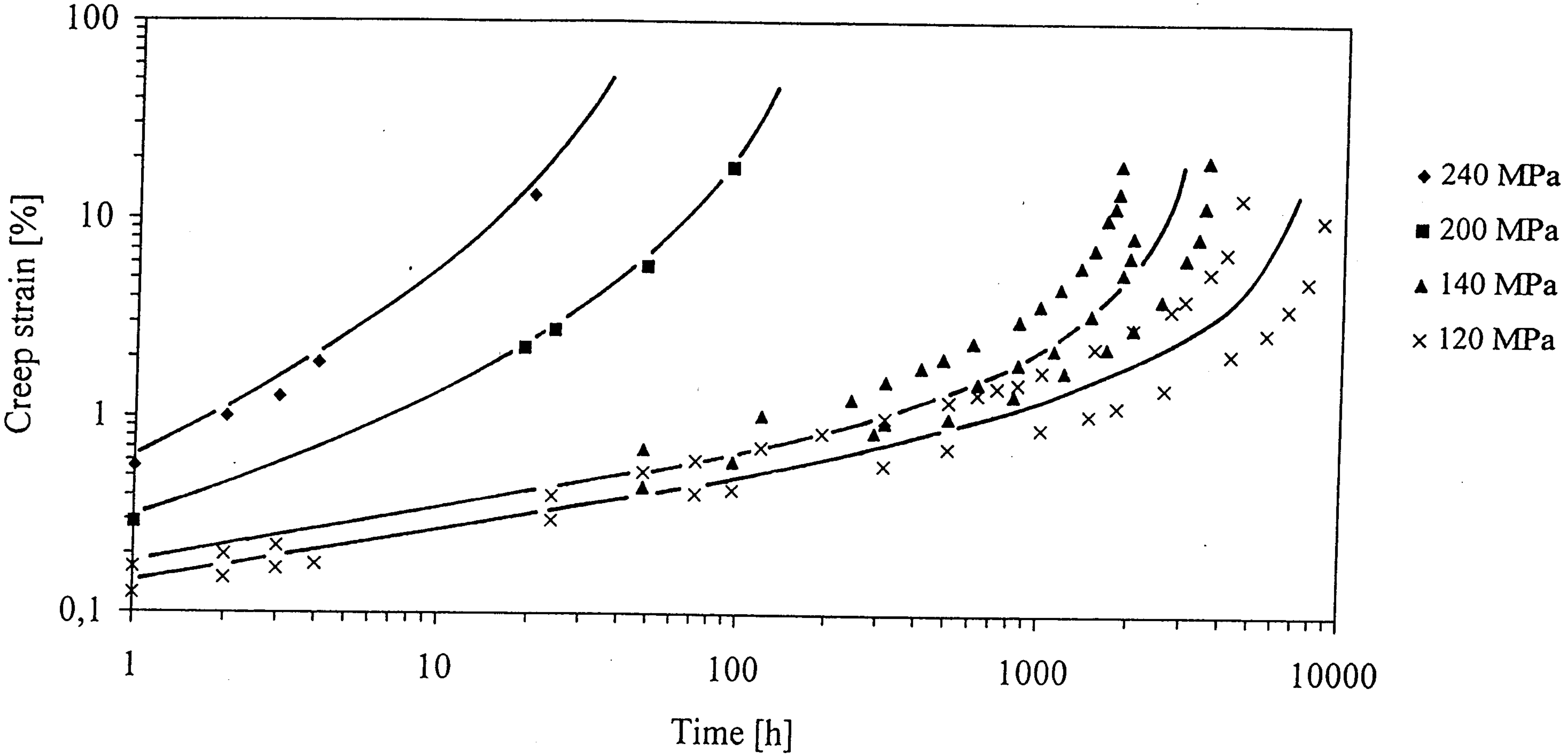

Fig 2. Fitness of the experimental creep curves with the constitutive equations for the creep process - low-alloy steel Cr2,25Mo1Nb1, 575 °C