SIMPLE ANALYSIS OF STRESS-STRAIN-TEMPERATURE-TIME BEHAVIOUR AND ITS CHARACTERIZATION IN METALS AND ALLOYS

S.T. QUAASS,

Nuclear Power Assessment Division,
Australian Atomic Energy Commission, Coogee, N.S.W., Australia

ABSTRACT

The well-known lack of any general relationships between stress, strain and temperature-time in materials is a great handicap to the completion of a firm bridge between two disciplines - metallurgy and engineering stress analysis, in particular those who prepare property data and those who use it.

The work presented here, which has been done over a number of years, shows that there are adequate general functions. It is important to note that the functions presented describe the general behaviour of a real metal or alloy. No relationship to physical models is claimed. The approach adopted allows use of the vast amount of tabular data, already available, to prepare characteristic constants. Much more refined functions may be found but the approach adopted uses two basic functions:

1. The generalised stress-strain relationship

$$\frac{\sigma}{\sigma_r} = \tanh\,(k_\epsilon \cdot \epsilon_{tot})$$

for all temperature-time values.

2. The generalised rupture stress relationship

$$\sigma_r = \sigma_{crit}\left[1 - \tanh\left\{\frac{1}{K_p} \cdot (P - P_{crit})\right\}\right]$$

where σ is stress to give total strain ϵ_{tot}

σ_r is rupture stress at temperature-time P

k_ϵ is a material constant (strain hardening)

K_p is a material constant (temperature resistance)

P is $(T^\circ C + 273)(20 + \log_{10} t \text{ hours})$

P_{crit} is a material constant termed critical temperature-time or critical P

σ_{crit} is a material constant and is the rupture stress at critical P

By substituting the rupture stress (2) into (1) a general relationship can be found and by inversion, of course, one can obtain the complete functions. These are listed in conventional mathematical terms and also in conversational computer language using acceptable symbols. The functions should be regarded simply as a tool to assist the stress analyst in the solution of his many problems, in particular time dependent inelastic problems. Characteristic constants for many alloys are listed.

1. INTRODUCTION

There is no very general function available to describe the stress-strain-temperature-time behaviour of metals and alloys and this creates a considerable problem for the stress analyst and, indeed, the metallurgist. The analyst usually calculates stress using elastic theory, analysis of behaviour of stress and strain, and then applies a failure stress criterion, analysis of failure. The first half of his approach, analysis of stress itself, requires a knowledge of stress and strain relationships and when his particular problem involves non-linearity, or temperature and time, his stress calculation becomes uncertain. If the first half of the calculation is inaccurate, then the second half, the examination of failure, will also be uncertain, even if the failure criterion is correct. These short-comings are common knowledge in the disciplines represented at this conference.

What is available to the analyst and metallurgist is a vast amount of tabular data. Available functional relationships are limited in application. Some stress-strain formulae are available but predominant is the use of a power function with constants to handle material, temperature, etc. Analytically this creates problems with derivatives. Yield stress, secant or tangent moduli relationships are available to handle non-linearity but only in quite specific cases. One (if not the only one) tool available is the creep rate formulae available from the physical metallurgist exploring creep. These expressions for plastic strain rate involve temperature and time and sometimes stress. The analyst uses these knowing they apply only in the creep range but it is all he has available. Further there existed no bridge between short time tensile and long time creep data. He resorts to incorporation of elastic strains to obtain total strains and for this he has no elastic modulus functions.

The failure criterion used has linear expressions involving log rupture stress which again arise from studies in the creep range.

This paper presents a summary of the progress made in a study of these problems. The approach adopted was to examine generally as many materials as possible and not to bias the choice of functions with existing models, e.g. based on rate theory. Consequently it should be noted that the functions presented herein empirically describe the general behaviour of a real metal or alloy. The approach allows use of the tabular data, already available, to prepare characteristic constants.

2. BASIS OF THE CHARACTERISATION

Simple graphical analysis[1-5] is used to examine inelastic time dependent thermal stress, high strain fatigue lives, bolt-retightening stresses and lives, and other related design problems. This technique was used some time ago without evidence of its validity[5]. It consisted of plotting stress-total strain curves on a carpet plot, the distance between the origins of the stress-total strain curves being to a scale of temperature-time. The Larson and Miller parameter was used for this scale. Later, evidence showed that creep, tensile and relaxation data became compatible on this cross plot if care was taken to use total strain[6]. This was done for a series of nickel-based alloys simply because many short time and long time data existed for these materials. Unpublished work[7] has shown that the graphical analysis was successful in handling the both short and long time data for other materials. Some evidence for this compatibility in the form of reduced graphs is given in this paper in Figures 1-12. Since this compatibility was found, the graphs themselves showed no discontinuities, and indeed, the graphs had general characteristic shapes; it was concluded that metals and alloys could be characterised by simple mathematical functions with certain characteristic constants.

Functions are now proposed whose sole advantage is that they describe the behaviour of materials over the widest range of the variables; stress, strain, temperature and time. No attempt is made to demonstrate their relationship to physical metallurgical models although this is being studied. Further, extreme local accuracy is not claimed. Table I summarises the functions, symbols and units.

The basis of the mathematical approach is as follows. A function is adopted for the stress-total strain curve

$$\text{stress} = f_1\,(\text{total strain})$$

This is standardised by referring the stress (to give a total strain) to the rupture stress for the same <u>temperature-time</u>

$$\frac{\text{stress}}{\text{rupture stress}} = f_1\,(\text{total strain}) \qquad \ldots(1)$$

All that is then required is to replace the rupture stress by temperature-time using a second function

$$\text{rupture stress} = f_2\,(\text{temperature-time}) \qquad \ldots(2)$$

When the functions have been chosen, equation (2) is substituted in equation (1)

$$\frac{\text{stress}}{\text{rupture stress}} = f_1\,(\text{total strain})$$

$$\frac{\text{stress}}{f_2\,(\text{temperature-time})} = f_1\,(\text{total strain})$$

$$\text{stress} = f_2\,(\text{temperature-time})\cdot f_1\,(\text{total strain})$$

If inversions exist, explicit functions can be obtained for either strain, temperature or time in terms of the other variables.

The choice of the stress-total strain function has occupied the attention of workers for some time[5]. In this work the tanh function was adopted because:

(a) It fits the data well.

(b) It is linear at low strains and has a finite slope; the power functions, most commonly used, do not have this property, nor does the hyperbola.

(c) It approaches a constant value at high strains; the sinh function does not have this property. The property is extremely convenient since it enables the standardisation of the stress-strain curve to be effected by reference to the rupture stress. Fixing values would have to be assigned to other functions.

(d) The tanh function is available in most sets of mathematical tables.

(e) It reverses about zero; hence it can deal with stress and strain reversal from tension to compression.

(f) It can be inverted and this is necessary if strain has to be expressed explicitly in terms of stress, temperature and time.

(g) The tanh function and its inversion can be replaced by exponential and logarithmic functions respectively.

Choice of a rupture relationship has been a problem and a universal equation of accuracy has yet to be found[8-15]. The rupture relationships shown by a wide variety of metals and alloys are presented later. The Larson-Miller temperature-time parameter has been used to reduce the three variable problem to a two variable problem. The Larson-Miller parameter was chosen because it is well-known, easy to use and contains one constant. For all metals and alloys considered here the value of the Larson-Miller constant was taken as 20. However, minor changes in this constant make very little real difference to the outcome on a macro scale. The Larson-Miller parameter is given by

$$P = (T°C + 273)(20 + \log_{10} t \text{ hours})$$

Examination of many rupture graphs shows three distinct forms of rupture relationships (see Figure 1(a)):

(i) A simple reverse ogive curve familiar to statisticians; the cumulative frequency or probability integral.

(ii) A hyperbola added at the low temperature-time portion of the graph in (i).

(iii) A combination of (i) and (ii) with a "bump" added at intermediate temperature-time values.

Of course, these three are indeed only one case functionally, e.g. (i) and (ii) can be handled by a relationship of the form $x^5 y + x y^5 = 4$. This however, can express explicitly neither x nor y, and thus is of little use.

All the cases can be handled with the mathematics of system stability, and perhaps other functions could be used, but the real benefits gained have to be considered in relation to the complexities added. For the purposes of initial stress analysis, it was considered sufficient to handle the "three" cases mentioned bearing in mind the interest in macro behaviour and material scatter itself by the use of

regularised rupture stress = -tanh (regularised temperature-time)

Whether this approach can or cannot average the hyperbola and bump depends on the choice of a suitable value of critical stress. Hence it is important to decide which values of the constants are adopted. Here the constants were not averaged.

It was decided to use the -tanh function because:

(a) It fits the data well.

(b) We already use it for the stress-strain curve.

(c) Its use pinpoints some critical constants, the so-called critical P, and the so-called critical σ, and these mean something in simple terms to the engineer.

(d) It can be inverted and this is a great advantage in order to calculate temperatures and times.

(e) It is accurate in the creep range, i.e. in the region of critical P, and in most cases this is where the time dependent behaviour is being explored.

Recently, it was demonstrated using the probability integral[4], that some metals can show the more general rupture behaviour. (The probability integral and -tanh function are really the same after a simple arithmetic standardisation of the variables.)

Here the standardisation of the variables is effected simply by referring the -tanh function to a new zero at (σ_{crit}, P_{crit}), using $(\sigma - \sigma_{crit})/\sigma_{crit}$; and for the argument of tanh $6(P - P_{crit})/(P_{plat} - P_{pc})$ or simply $(P - P_{crit})/K_p$.

3. RESULTS

3.1 General

Some examples of reduced graphs are presented in Figures 1 to 12. These are conventional Cartesian graphs (as opposed to the cross plotting employed earlier). In the upper graph are plotted the rupture stress on the ordinate and the temperature-time on the abscissa. The temperature-time parameter used in all cases is:

$$P = (T°C + 273)(20 + \log_{10} t \text{ hours})$$

In the lower graph are plotted, as the ordinate, the stress to give a total strain divided by the rupture stress for the same temperature-time, and as the abscissa, the total strain value at that temperature-time for that stress. Changes in scale of graphs are not made from material to material so that engineers and analysts are enabled to appreciate visually the differences between the various alloy bases. Not all the graphs prepared are presented in this paper but Table II lists the characteristic constants obtained to date for a number of materials. It should be noted immediately that the data available on which some of these constants are based are extremely limited. Furthermore, the rapid methods used in the determination of the constants are far from precise. Notwithstanding data limitations, the stress/rupture stress-total strain data for a number of materials obviously forms a distinct common pattern and the relationship to the tanh function can be seen.

The rupture stress/temperature-time graphs have the characteristics discussed earlier (2). When the characteristic constants are examined, several illuminating points emerge:

(a) A great many alloys are available, which from the stress-strain-temperature-time point of view are not very different at all. Real benefits to be obtained from minor changes in composition are in some cases marginal to say the least.

(b) The constants for a material indicate well-known characteristic properties, e.g.

σ_{crit} indicates strength generally
P_{crit} indicates hot strength
k_ϵ indicates strain hardening
K_p indicates temperature resistance

If σ_{crit} is multiplied by two it approaches the room temperature strength. The higher σ_{crit} is, the higher the strength. If P_{crit} is large the strength of the alloy is retained to higher temperatures. A high k_ϵ indicates a high rate of strain hardening. If K_p is high it means the material tends to retain its strength more at its softening temperature.

(c) It seems that minor amounts of alloying elements and precipitates, heat treatment, etc. increase only σ_{crit}.

(d) Large amounts of alloying elements or changes in the base material are necessary to increase P_{crit}.

(e) k_ϵ and K_p seem to be fairly consistent. k_ϵ is 1, 2 or 3 and K_p is 2 to 3 x 10^3.

Some may question the need for four constants, but as explained above they have some physical meaning and at this stage they seem to be necessary. Future work may reveal correlations between some of them, making some redundant.

Of course many will see that graphical analysis using the reduced graphs is much more convenient than using a carpet plot and they can be used to complement analysis which uses the functions listed later in this report in Table III.

3.2 <u>More Exact Rupture Relationship</u>

Apart from the soft alloys (low alloy mild steels etc.) which show the hyperbola and bump, the most common rupture relationship consists of a small hyperbola added to the -tanh function at low P values.

This can be catered for simply by adding a hyperbola term

$$\sigma = \frac{h_p}{P} + \sigma_{crit}\left[1 - \tanh\left\{\frac{1}{K_p}(P - P_{crit})\right\}\right]$$

Values of h_p are given in the tables of characteristic constants.

In stress analysis this is sufficient but if inversion is required we can use the device:

$$P = \frac{h_\sigma}{\sigma} + P_{plat}\left[1 - \tan\left\{\frac{1}{K_\sigma}(\sigma - \sigma_{plat})\right\}\right]$$

Here the low stress area is handled by a hyperbola and the high stress end by a tanh function. Values of h_σ and K_σ are not given in this graph. The constants σ_{plat}, P_{plat} refer to the plateau in the rupture graph.

3.3 Failure

There is an elementary point about fracture that requires emphasis. Much of the description here has concerned relationships between stress, strain and temperature-time. Although rupture was invoked to assist in the solution, the failure relationships are not the same as the behaviour relationships.

This is best demonstrated by considering the elementary creep curve, that is, creep strain as ordinate, and time as abscissa. The creep curve function has no limit. Any point on it can in principle be obtained by a particular value of stress, temperature and time, using the behaviour relationships.

Rupture is described by a different functional relationship. This applies particularly to the expressions for rupture strain.

It appears from experimental data, some old[16], some new[17], that

(a) if a material is strengthened, either by cold work, precipitation hardening, or tempering slightly, the strain at failure is low until a critical value of temperature-time is reached, then it increases;

(b) if a material is in a soft condition due to annealing, over-ageing or over-tempering the ductility, originally high, decreases markedly near a critical value of temperature-time to very low values and then rises again.

Glen[16] has attributed these ductility troughs to carbide precipitation. However, Siegfried[16], at the same time as Glen's work was published, demonstrated that the ductility trough occurred in a simple non-ferrous alloy. For zirconium alloys the existence or absence of ductility trough has been confirmed[18]. In hard zirconium alloys the strain at failure is low until critical P is reached and then it rises. In soft zirconium alloys there is definitely a trough.

This phenomenon requires more thought and study. Obviously at certain values of σ_{crit} a change in failure ductility characteristics takes place.

However one general statement can be made. Consider the stress ratio-total strain curve. If σ/σ_r increases because of σ alone (the tensile test) the failure strain is high. If σ/σ_r increases because of σ_r decreasing (the creep test) the failure strain decreases. If σ/σ_r is increased because σ decreases but σ_r decreases faster (the relaxation test) the failure strain practically disappears; it is about 1 per cent.

To illustrate this, if a stress criterion for failure is explored, $\sigma=\sigma_r$, in which case, since $\sigma/\sigma_r = \tanh(k_\epsilon \epsilon_{tot})$, the value of $k_\epsilon \epsilon_{tot}$ can be any figure above about 3 per cent.

If k_ϵ is about 3, ϵ_{tot} at failure is any value above about 1 per cent. For a design basis therefore, it would be unwise to choose too high a strain as a failure criterion.

3.4 The Functional Relationships

If the reduced graphs are accepted and the tanh functions are accepted as describing the graphs, one arrives at the basic functions listed in Table I.

The various specific relationships can be arrived at by simple mathematics and these are listed in Table III. Computer symbols are given in basic conversational language since desk top programmable calculators are becoming increasingly popular.

The expressions, which involve plastic strain as an independent variable, have used a hyperbola since it is not possible to find a simple inversion for

$$\epsilon_{pl} = \frac{1}{k_\epsilon}\left[\operatorname{arctanh}\left(\frac{\sigma}{\sigma_r}\right) - \frac{\sigma}{\sigma_r}\right]$$

It will be noted that new functions are not required for elastic strain since at linearity

$$\frac{\sigma}{\sigma_r} = k_\epsilon\,\epsilon_{tot} = k_\epsilon\,\epsilon_{el}$$

And thus, since ϵ is here expressed as a percentage, the elastic modulus

$$E = 100\,\frac{\sigma}{\epsilon} = 100\,k_\epsilon\,\sigma_r$$

$$= 100 \cdot k_\epsilon \cdot \sigma_{crit} \cdot \left[1 - \tanh\frac{1}{K_p}(P - P_{crit})\right] \quad \text{in stress units.}$$

A computer programme has been written to deal with each and all of the specific functions and gives excellent agreement and predictions[19].

To obtain an expression for creep rate, one simply derives the expression for total strain with respect to time. This reveals the interaction between the variables stress and temperature. This is being studied to check physical models.

4. CONCLUSIONS

(1) A mathematical relationship between stress, strain, temperature and time adequate for describing mechanical behaviour is available.

(2) The adequacy of the relationship depends upon its end use. For preliminary stress analysis it is quite sufficient.

(3) The essential components of the specific relationships are:

$$\sigma/\sigma_r = \tanh(k_\epsilon\,\epsilon_{tot})$$

$$\sigma_r = \sigma_{crit}\left[1 - \tanh\left\{\frac{1}{K_p}(P - P_{crit})\right\}\right]$$

(4) The specific relationships are given in Table III.

(5) The four characteristic constants measure four properties,

σ_{crit} strength generally
P_{crit} retention of strength to temperature
k_ϵ strain hardening
K_p retention of strength at temperature

(6) Characteristic average constants for common materials are given in Table II.

(7) For failure analysis, the continued use of stress as a criterion seems to be essential. The magnitude of the strain at failure can be quite inexact.

5. RECOMMENDATIONS

(1) The following should be determined:

(i) The effect of multiaxial conditions upon the constants.

(ii) The ability of the expressions to handle time dependent shear stress and strain.

(iii) Agreement upon the values of the characteristic constants for average data.

(iv) Agreement upon the incorporation of a safety factor to handle scatter.

(v) Agreement upon sources of data on which characteristic constants are based.

(vi) Values of characteristic constants based on allowable stresses in codes, e.g. A.S.M.E.

(2) Since use of the technique effects considerable reduction it may prove to be of assistance in studying effects such as irradiation. For example, are k_ϵ and K_p, in particular, changed by neutron flux?

(3) Examination should be made of the integrals $\int \sigma \, d\epsilon$ and $\int \sigma\epsilon \, d\epsilon$ used in inelastic analysis.

ACKNOWLEDGEMENTS

Certain phases of this study were carried out in research institutions in the United States, Britian and Australia. I wish to acknowledge the assistance of the staff of the Australian Atomic Energy Commission in particular.

Many government and private organisations have most willingly continued to supply data as it became available. Without it the analysis would not be possible.

REFERENCES

[1] Hill, G.J., Thornton, D.V. and Quaass, S.T., J. Inst. Metals 93, 451, 1964.

[2] Quaass, S.T., J. Inst. Metals 95, 160, 1967.

[3] Quaass, S.T., Discussion of Glenny and Taylor's Paper, J. Inst. Metals 89, 437, 1960.

[4] Quaass, S.T. and Rotsey, W.B., "Design Against High Temperature Fracture", p.51. "Fracture, Second Tewksbury Symposium", Butterworth and Co., Australia, 1969.

[5] Gatewood, B.E., "Thermal Stresses: with Applications to Airplanes, Missiles, Turbines and Nuclear Reactors", McGraw-Hill Book Co. Inc. Publications in Aeronautical Sciences. New York, Toronto, London, 1957. p.134.

[6] Quaass, S.T., J. Inst. Metals 96, 129, 1968.

[7] Quaass, S.T., Unpublished Work 1960-1970.

[8] Finnie, I. and Heller, W.R., "Creep of Engineering Materials". McGraw-Hill, London,1959.

[9] Lubahn, J.D. and Felgar, R.P., "Plasticity and Creep of Metals", 1961, (Wiley).

[10] Siegfried, W. and Zimering, S., Progress Reports, U.S.A.E.C. and Euratom, Battelle, Geneva, 1964-1966.

[11] Conway, J.B., "Stress Rupture Parameters, Origin, Calculation and Use". Gordon and Breach Science Publishers. New York, London, Paris. 1969.

[12] Conway, J.B., "Numerical Methods for Creep and Rupture Analysis", Gordon and Breach Science Publishers. New York, London, Paris, circa 1967.

[13] Garofalo, Frank, "Fundamentals of Creep and Creep Rupture in Metals". MacMillan Series in Materials Science, the MacMillan Co., New York and London, second printing 1966.

[14] Van Leeuwen, H.P., "Predicting Material Behaviour Under Load Time and Temperature Conditions", NATO-AGARD Report 513, 1965.

[15] Thomson, A.G.R., "The Potential Use of Mathematical Models in Materials Data, Presentation with particular reference to the AGARD Materials Properties Handbooks". NATO-AGARD 510, 1966.

[16] "Symposium on Strength and Ductility of Metals at Elevated Temperatures", Amer. Soc. Test. Mat. STP 128, 1952, U.S.A. Papers by Brown et al., Glen and Siegfried.

[17] "Joint Conference on High Temperature Properties of Steels". BISRA I.S.I. Publication 97, 1967, I.S.I. London.

[18] Shober, F.R. et al., "The Mechanical Properties of Zirconium and Zircaloy-2", BMI 1168 1957.

[19] Barry J., unpublished work, A.A.E.C. 1971.

TABLE I - SUMMARY OF THE FUNCTIONS, SYMBOLS AND UNITS

$$\frac{\sigma}{\sigma_r} = \tanh(k_\epsilon \epsilon_{tot})$$

$$\sigma_r = \sigma_{crit}\left[1 - \tanh\left\{\frac{1}{K_p}(P - P_{crit})\right\}\right]$$

$$\sigma = \sigma_{crit}\left[1 - \tanh\left\{\frac{1}{K_p}(P - P_{crit})\right\}\right] \cdot \tanh(k_\epsilon \cdot \epsilon_{tot})$$

$$P = P_{crit} + K_p \cdot \operatorname{arctanh}\left[1 - \left\{\frac{\sigma}{\sigma_{crit}} \cdot \frac{1}{\tanh(k_\epsilon \cdot \epsilon_{tot})}\right\}\right]$$

$$\epsilon_{tot} = \frac{1}{k_\epsilon} \operatorname{arctanh}\left[\frac{\sigma}{\sigma_{crit}}\left\{\frac{1}{1 - \tanh\left(\frac{1}{K_p}(P - P_{crit})\right)}\right\}\right]$$

VARIABLES

Behaviour		Failure			UNITS
σ	S1	σ_r	S10	Stress	tons inches^{-2} (t.s.i.)
ϵ_{tot}	A1		A10	Strain Total	per cent
ϵ_{pl}	L1		L10	Strain Plastic	per cent
ϵ_{el}	E1		E10	Strain Elastic	per cent
T	T1	T_r	T10	Temperature	°C
t	H1	t_r	H10	Time	hours
P	P1	P_r	P10	Temperature-Time	°K log t or P units
E	M1			Modulus	

CONSTANTS

σ_{crit}	S7	Critical Stress	t.s.i.
P_{crit}	P7	Critical P	P units
k_ϵ	K1	Strain Hardening	per cent^{-1}
K_p	K2	Strength Retention	P units
h_p	K3	Hyperbolic term constant	P units (t.s.i.)
K_σ	K4	Inversion Device	tons inches^{-2}
h_σ	K5	Inversion Device	P units (t.s.i.)
σ_{plat}	P_{plat}	Plateau Values	t.s.i. and P units

TABLE II - CHARACTERISTIC CONSTANTS FOR VARIOUS METALS AND ALLOYS

Material Common Name Composition	S7	P7	K1	K2	K3	Remarks Form, Heat Treatment, Data Source
		Alloy Base: Aluminium U.S.				
1100-0	3	8.5	2	3.0	9	
1100-H14	4	9	3.5	1.4	9	
1100-H18	5.5	8.5	3.5	1.1	7.5	
2011-T3	12.5	8.0	2	1.4	?	
2014-T6	16	8.2	2.5	1.8	9	
2017-T4	14	8.4	2	1.6	10	
2024-T3	16	8.4	2	1.85	12	
2024-T4	15	8.4	2	1.7	12	
2024-T81	15.5	8.5	2	1.8	10	
2025-T86	17.5	8.4	3	1.45	9	
3003-0	3.7	8.5	2	1.85	10	
3003-H14	5	9.4	3	1.65	9	
3003-H18	6.5	9	3	1.85	9	
3004-0	5.5	9.2	2	2.2	12	
3004-H34	7.5	9.5	2.5	2.5	11	
3004-H38	9	9	2.5	2.3	12	
5050-0	4.7	9.5	2.5	2.3	11	
5050-H34	6.2	9.2	4	1.25	11	
5050-H38	7	9	4	1.65	12	
5052-0	6.3	9.5	2	2.5	11	
5052-H34	8	9.3	2.5	1.4	12	
5052-H38	9	9.4	2.5	1.8	12	
5454-0	8	9.6	2	2.5	12	
5454-H32	9	9.4	2	2.2	12	
5454-H34	10	9.4	2.5	2.0	12	
7075-T6	20	7.7	3	1.0	12	
7075-T73	17	7.8	2.5	1.0	12	
		Alloy Base: Aluminium U.K.				
Al-Si	14	10.1	2.5	2.0		
DTD 324 Al-Si	11.5	10.3	3	1.65		
DTD 324 Al-Si	11.5	10.2	3	1.65		
DTD 364 L65 Al-Cu	15	10.2	2.5	1.65		
DTD 130 RR56 Al-Cu	13.5	10.2	2.5	1.9		
RR57 Al-Cu	15	10	2.5	3.0		
RR58 Al-Cu	15	10.2	2.5	2.5		
RR59 Al-Cu	13	10.2	3	1.85		
Al-Ni-Cu	11.5	10.2	3	1.7		
Al-Ni-Cu	15	10.2	3	1.9		

continued ...

TABLE II (continued) (ii)

Material Common Name Composition	S7	P7	K1	K2	K3	Remarks Form, Heat Treatment, Data Source
		Alloy Base: Complex High Temperature				
G19	20.5	20.5	1.5	3.3	77	
G32	30	20	3	5.0	55	
G38 Worm-worked	22	19.6	3	3.0	77	
G38 Solution treated	19	19.6	1	3.0	55	
G39	16	20.6	1	5.0	0 to 10	
		Alloy Base: Austenitic Steel				
FDP/11	16	19.8	1	2.1	45	
304	14	19.2	0.7	2.8	45	
304L	12.5	19.2	0.8	2.8	60	
316	16	19.7	1	2.7	22	
316L	14	19.6	0.8	3.3	45	
321	13	19.3	1	2.7	60	
FCBT	14	20.2	1.5	2.8	77	
347	15	19.7	0.8	2.9	55	
555	14	20.2	1	3.3	32	
548	13.5	21	1	4.35	47	
ESSHETE 1250	16	21	1.5	3.3	44	
309	16.5	19.6	0.7	2.8	0 to 10	
310	17	19	1	3.3	0 to 10	
R22	19	19.5	1	2.5	56	
R23	19	19.5	1	2.5	39	
	Alloy Base: Ferritic Steels* (Plain Carbon and Manganese)					
Semi killed C	15	16	1.5	2.5		
Full killed C low residuals	16	16	1.5	2.5		
Full killed C high residuals	17	16	1.5	2.5		
Aluminium killed C high residuals	16	16	1.5	2.5		
AS 135A	16	16	1.5	2.5		
AS 135B	17	16	1.5	2.5		* Special cases: hyperbola plus bump h_p is less than 10
AS 149	17	16	1.5	2.5		
AS 157:24	16	16	1.5	2.5		
Semi killed C-Mn low residuals	16	16	1.5	2.5		
Full killed C-Mn low residuals	17	16	1.5	2.5		
Al-treated C-Mn	15	16	1.5	2.5		
Semi killed C-Mn-Nb	17	16	1.5	2.5		

continued ...

TABLE II (continued) (iii)

Material Common Name Composition	S7	P7	K1	K2	K3	Remarks Form, Heat Treatment, Data Source
			Alloy Base: Ferritic Steels (Low Alloy)			
½ Mo	17	17.3	1.5	3.3	*	N only
½ Mo	16	17.3	1.5	3.3	*	N and T
1 Cr Mo	22	17.8	2	2.5	*	N only
1 Cr Mo	22	18	2.5	2.0	*	N and T
2-1/4 Cr Mo	15.5	17.5	1.5	2.0	30	A only
2-1/4 Cr Mo	21	17.1	2.5	2.0	30	N and T
Mo V (i)	21	17.5	2.5	3.3	*	A - Annealed
2-3/4 Cr Mo V W	24	17.7	3	2.5	40	N - Normalised
H40	29	18.4	2.5	3.6	40	T - Tempered
			Alloy Base: Ferritic Steels (High Alloy)			
12 Cr	16	17.5	1.5	2.5	40	
12 Cr Mo	19	17.5	2.5	3.1	40	
12 Cr Mo V	22	17.5	2.5	3.3	40	
12 Cr Mo V Nb	28	18	2.5	3.7	40	
10 Cr 6 Co	32	18.8	2	2.5	40	
H46	28	18.3	2	3.6	55	
R1	19	17	1.5	2.9	55	
			Alloy Base: Magnesium			
ZRE1 RE Zn Zr	5	11	2	2.0	20	Cast Annealed Magnesium Elektron
RZ5 Zn RE Zr	4.5	11	-	2.0	20	Cast Heat-treated Magnesium Elektron
HK31 Th Zr	5	-	1.3	2.0	20	"
ZT1 Th Zn Zr	4.5	11	2.5	2.0	25	"
ZTY	6.5	11	-	2.0	20	"
			Alloy Base: Nickel			
Nimonic 75	25	19	1.3	2.9	25	
Nimonic 80A	31	20.5	3	3.0	30	
Nimonic 90	35	20.5	2.5	3.3	45	
Nimonic 105	40	21	2.5	3.7	0 to 10	
			Alloy Base: Zirconium			
Zircaloy II	5	16.3	1.5	2.5	50	Annealed Transverse Longitudinal BMI
Zircaloy II	11	16.0	1.0	2.8	80	Cold Worked Transverse Longitudinal BMI
Zircaloy II	7	16.3	1.0	2.9	80	Cold Worked Longitudinal KAPL
Zircaloy II	6.5	16.3	1.0	2.7	45	Cold Worked Transverse KAPL
2½% Nb	20	15	1.5	2.2	70	Heat Treated AECL Cold Worked 10%

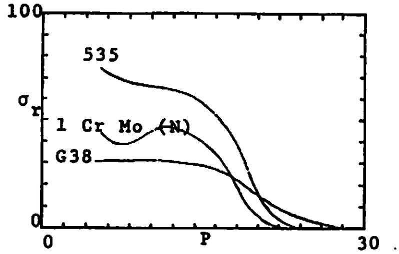
TABLE III - SPECIFIC FUNCTIONAL RELATIONSHIPS

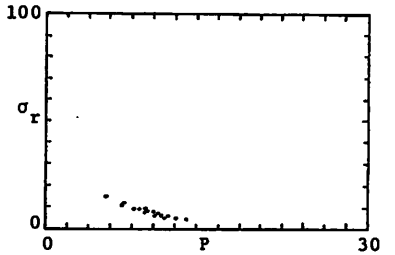
	Unknown	Known	Function No.
		Temperature-Time Combined	
	Stress	Total Strain, Temperature-Time	(1)
		Plastic Strain, Temperature-Time	(2)
		Elastic Strain, Temperature-Time	(3)
	Temperature-Time	Total Strain, Stress	(4)
		Plastic Strain, Stress	(5)
		Elastic Strain, Stress	(6)
	Total Strain	Stress, Temperature-Time	(7)
	Plastic Strain	Stress, Temperature-Time	(8)
	Elastic Strain	Stress, Temperature-Time	(9)
	Modulus		(10)
		Temperature-Time Separated	
		Total Strain, Temperature, Time	(11)
BEHAVIOUR:	Stress	Plastic Strain, Temperature, Time	(12)
		Elastic Strain, Temperature, Time	(13)
	Temperature	Total Strain, Stress	(14)
		Plastic Strain, Stress	(15)
		Elastic Strain, Stress	(16)
	Time	Total Strain, Temperature, Stress	(17)
		Plastic Strain, Temperature, Stress	(18)
		Elastic Strain, Temperature, Stress	(19)
	Total Strain	Stress, Temperature, Time	(20)
	Plastic Strain	Stress, Temperature, Time	(21)
	Elastic Strain	Stress, Temperature, Time	(22)
	Modulus		(23)
		Temperature-Time Combined	
	Stress	Temperature-Time	(24)
	Temperature-Time	Stress	(25)
		Temperature-Time Separated	
FAILURE:	Stress	Temperature, Time	(26)
	Temperature	Stress, Time	(27)
	Time	Stress, Temperature	(28)
	Total Strain		(29)
	Plastic Strain		(30)
	Elastic Strain		(31)

continued ...

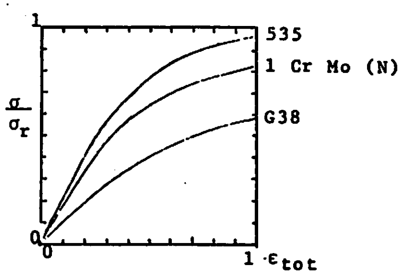
TABLE III (continued) (ii)

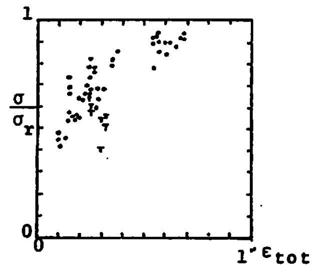
```
                                                                                  Nos.
S1=S7*(1-TANH((P1-P7)/K2))*(TANH(K1*A1))                                          (1)
S1=S7*(1-TANH((P1-P7)/K2))*(1-((0.05)/(K1*L1)))                                   (2)
S1=S7*(1-TANH((P1-P7)/K2))*(K1*E1)                                                (3)

P1=P7+K2*(HATAN(1-((S1/S7)/(TANH(K1*A1)))))                                       (4)
P1=P7+K2*(HATAN(1-((S1/S7)*((K1*L1)/(K1*L1-0.05)))))                              (5)
P1=P7+K2*(HATAN(1-((S1/S7)/(K1*E1))))                                             (6)

A1=(HATAN((S1/S7)/(1-TANH((P1-P7)/K2))))/K1                                       (7)
L1=(HATAN((S1/S7)/(1-TANH((P1-P7)/K2)))-((S1/S7)/(1-TANH((P1-P7)/K2))))/K1        (8)
E1=((S1/S7)/(1-TANH((P1-P7)/K2)))/K1                                              (9)
M1=K1*S7*(1-TANH((1/K2)+(P1-P7)))*100                                             (10)

S1=S7*(1-TANH((1/K2)*((T1+273)*(20+((ALOG(H1))/(2.303)))-P7)))*(TANH(K1*A1))      (11)
S1=S7*(1)TANH((1/K2)*((T1+273)*(20+((ALOG(H1))/(2.303)))-P7)))*(1-(0.05)/(K1*L1)) (12)
S1=S7*(1-TANH((1/K2)*((T1+273)*(20+((ALOG(H1))/(2.303)))-P7)))*(K1*E1)            (13)

T1=(((P7+K2*(HATAN(1-((S1/S7)/TANH(K1*A1))))))/(20+(ALOG(H1))/2.303))-273         (14)
T1=((P7+K2*(HATAN(1-((S1/S7)*((K1*L1)/(K1*L1-0.05))))))/(20+(ALOG(H1))/2.303))-273 (15)
T1=((P7+K2*(HATAN(1-((S1/S7)/(K1*E1))))))/(20+(ALOG(H1))/2.303))-273              (16)

H1=EXP((((P7+(HATAN(1-((S1/S7)/(TANH(K1*A1)))))*K2)/(T1+273))-20)*2.303)          (17)
H1=EXP((((P7+(HATAN(1-((S1/S7)*((K1*L1)/(K1*L1-0.05)))))*K2)/(T1+273))-20)*2.303)  (18)
H1=EXP((((P7+(HATAN(1-((S1/S7)/(K1*E1))))*K2)/(T1+273))-20)*2.303)                 (19)

A1=(HATAN((S1/S7)/(1-TANH((1/K2)*(((T1+273)*(20+((ALOG(H1))/(2.303))))-P7)))))/K1  (20)
L1=((HATAN((S1/S7)/(1-TANH((1/K2)*((T1+273)*(20+(ALOG(H1))/2.303)-P7)))))/K1)
  -(((S1/S7)/(1-TANH((1/K2)*((T1+273)*(20+((ALOG(H1))/(2.303)))-P7))))/K1)         (21)
E1=((S1/S7)/(1-TANH((1/K2)*(((T1+273)*(20+((ALOG(H1))/(2.303))))-P7))))/K1         (22)
M1=K1*S7*(1-TANH((((T1+273)*(20+(ALOG(H1))/2.303))-P7)/K2))*100                   (23)

S10=S7*(1-TANH((1/K2)*(P1-P7)))                                                   (24)
P10=P7+K2*(HATAN(1-(S1/S7)))                                                      (25)

S10=S7*(1-TANH((1/K2)*((T1+273)*(20+(ALOG(H1))/2.303)-P7)))                       (26)
T10=((P7+K2*HATAN(1-(S1/S7)))/(20+(ALOG(H1))/2.303))-273                          (27)
H10=EXP((((P7+K2*(HATAN(1-(S1/S7))))/(T+273))-20)2.303)                           (28)
A10=(3to∞)/K1                                                                     (29)
L10=(2to∞)/K1                                                                     (30)
E10=1/K1                                                                          (31)
```

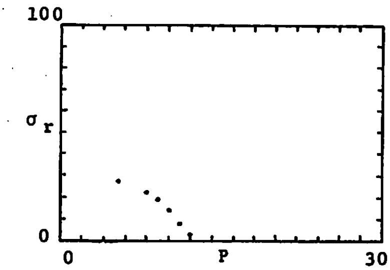


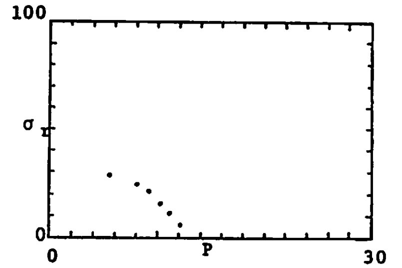


Figures 1(a) and (b) Figures 2(a) and (b)

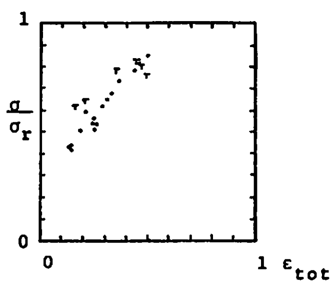


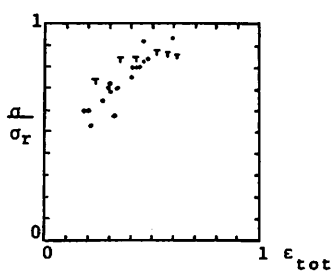




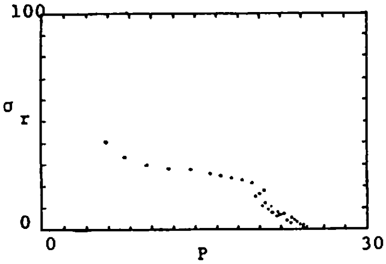


Figures 3(a) and (b) Figures 4(a) and (b)

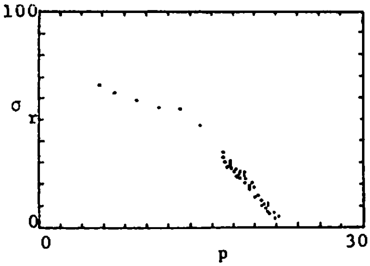




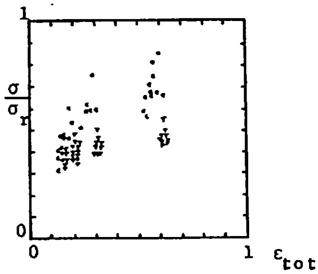
Figures 1(a) and (b) Typical reduced graphs.
Figures 2(a) and (b) Reduced graphs for magnesium alloy ZT1.
Figures 3(a) and (b) " " " aluminium-silicon alloy.
Figures 4(a) and (b) " " " aluminium-copper alloy.

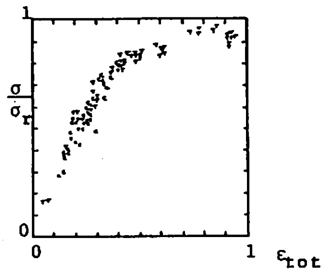


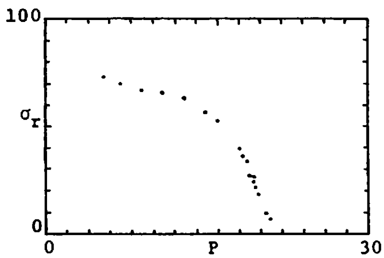
Figures 5(a) and (b)



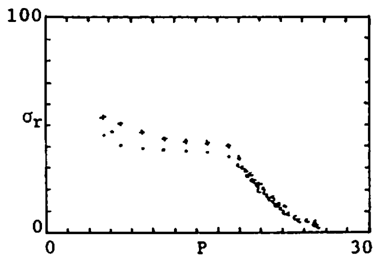
Figures 6(a) and (b)



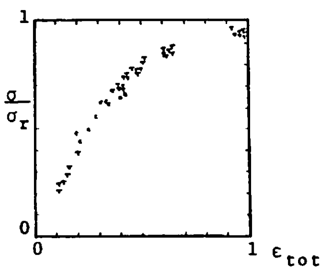


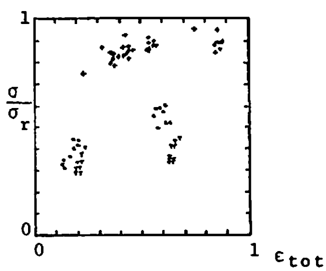


Figures 7(a) and (b)

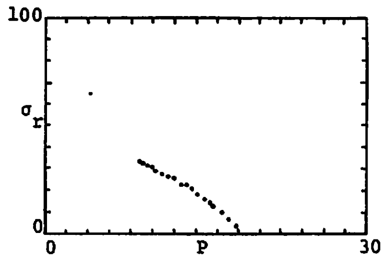


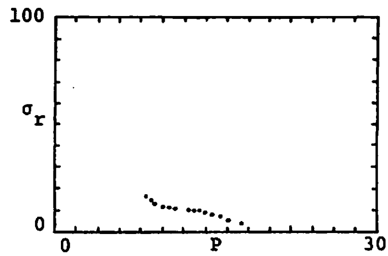
Figures 8(a) and (b)





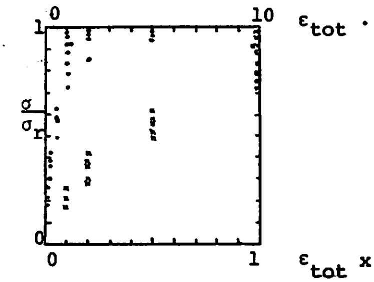
Figures 5(a) and (b) Reduced graphs for austenitic steel FCB(T).
Figures 6(a) and (b) " " " ferritic steel 448.
Figures 7(a) and (b) " " " " " 535.
Figures 8(a) and (b) " " " high temperature alloy G38.
(+ warm worked, . solution-tested)

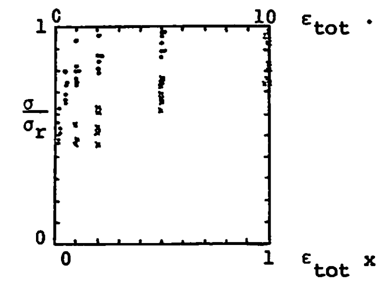


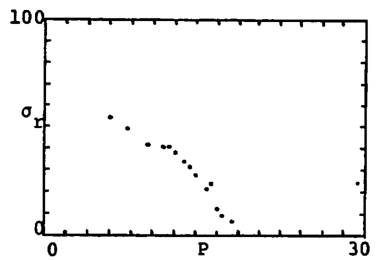


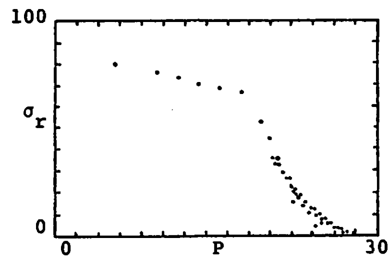
Figures 9(a) and (b)

Figures 10(a) and (b)



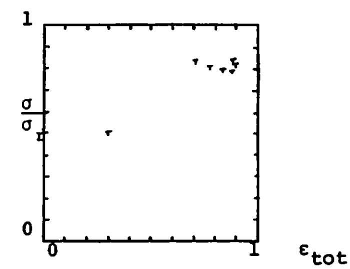


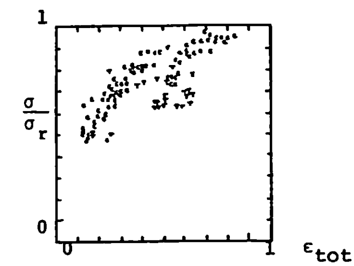




Figures 11(a) and (b)

Figures 12(a) and (b)





Figures 9(a) and (b)	Reduced graphs for Zircaloy II cold worked.
Figures 10(a) and (b)	" " " " annealed.
Figures 11(a) and (b)	" " " zirconium niobium alloy.
Figures 12(a) and (b)	" " " nickel alloy Nimonic 90.