AAEC/E381

AAEC/E381

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

HIGH STRENGTH STEELS - STRESS RELAXATION AND DERIVED CREEP CHARACTERISTICS AT ROOM TEMPERATURE

by

J.T.A. POLLOCK
S.G. BARTON

May 1976

ISBN 0 642 99744 6

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

HIGH STRENGTH STEELS - STRESS RELAXATION AND DERIVED CREEP CHARACTERISTICS AT ROOM TEMPERATURE

by

J.T.A. POLLOCK
S.G. BARTON

ABSTRACT

The room temperature tensile strength and stress relaxation characteristics of 301 stainless, 431 stainless and Vascomax 300 maraging steels in the form of thin strip have been determined. On the basis of Ultimate Tensile Strength (UTS), the maraging and 431 steels (UTS ~ 1.8 GPa) are marginally superior to the 301 steel (UTS ~ 1.75 GPa). Relaxation data show that plastic deformation occurs at ~ 45% UTS in the 301 steel, ~ 60% UTS in the 431 steel and ~ 65% UTS in the 300 steel. These stresses, which define the lower limit above which creep will certainly occur, are significantly lower than 0.1% proof stresses measured directly from stress/strain data. The relaxation data were used to estimate logarithmic creep rates under constant load for these materials. There is a comparative superiority of the maraging steel over the two stainless steels in the range 80-90% UTS.

National Library of Australia card number and ISBN 0 642 99744 6

The following descriptors have been selected from the INIS Thesaurus to described the subject content of this report for information retrieval purposes. For further details please refer to IAEA-INIS-12 (INIS: Manual for Indexing) and IAEA-INIS-13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

CREEP; COMPARATIVE EVALUATIONS; DEFORMATION; ELASTICITY; MEDIUM TEMPERATURE; STAINLESS STEEL-301; STAINLESS STEEL-431; STEELS; STRESS RELAXATION; TENSILE PROPERTIES

CONTENTS

1. INTRODUCTION

Materials having a high strength to weight ratio are necessary for the fabrication of many structural components for ambient temperature operation. Although fibre reinforced composites are obvious contenders for this purpose, a more sophisticated understanding of the operational characteristics of composites has diminished the early enthusiasm for their use. High strength steels lack the optimum strength to weight ratio of composites, but have the advantages of nearly isotropic strength, well-established forming processes and relatively low cost. Unfortunately, there is little information available on the long-term mechanical behaviour of these steels at ambient temperatures. In particular, the creep characteristics are virtually unknown and it is difficult to predict, from simple tensile tests, the creep behaviour of very strong materials which exhibit very little elongation before fracture.

The aim of this work is to provide relevant design information and, if possible, to make pertinent suggestions for improvement in the desired properties. The first part of the study compares the room temperature mechanical properties in tension of a type 301 stainless steel with some other steels which are of interest because of their lower cost or better properties. The second stage of the work develops the technique of stress relaxation in an effort to establish a short-term method for characterising the long-term deformation properties of any steel (or alloy) of interest.

2. MECHANICAL PROPERTIES IN TENSION

The chemical compositions and fabrication schedules for the materials selected for comparison with the 301 stainless steel are listed in Table 1. Type 431 stainless steel is cheaper than type 301 because of a lower nickel content. The maraging steel has the advantage that it is easily formed and welded to very close tolerances before developing optimum strength by ageing at 760 K. Negligible changes in dimension accompany this strengthening treatment.

Round-shouldered tensile samples having gauge dimensions 20 mm long x 4 mm wide were stamped from thin sheets of the various steels. These samples were loaded in tension at a constant strain rate in an Instron Testing Machine until fracture occurred. A typical load versus time curve is shown in Figure 1(a). A summary of the data measured for the four types of steel is presented in Table 2. As a result of the small quantity of material available, only a few samples of the steels to be compared with the commercially fabricated 301 were tested. However, scatter among the Ultimate Tensile Stress (UTS) values for a given steel was ~ ± 5% and it is believed that the differences apparent in Table 2 are real. The 1% C spring steel was the weakest and will not be discussed further. Both the maraging and 431 stainless steels were stronger than the 301 sample. Ductility, as measured by elongation at fracture, was about 1%, which is similar to that of the 301 sample.

3. STRESS RELAXATION

Stress relaxation is an effective method for characterising the dislocation dynamics of materials under load. Relaxation tests may be performed using tensile samples. Essentially, the sample is deformed at a constant strain rate as for a normal tensile test. At a preselected loading point, the crosshead is stopped. The specimen continues plastic deformation, its plastic strain replacing the elastic strain of the system (including the elastic strain of the sample). Hence, the load is recorded to drop as a function of time at a rate which depends on the stress dependence of the plastic strain rate of the material. A series of relaxation curves obtained with a 301 sample is presented in Figures 1(b-e). The enhanced load sensitivity of these curves is obtained by using zero suppression units.

The relaxation data may be analysed by several methods which are derived from three basic equations. The plastic strain rate, $\dot{\varepsilon}_p$, is given by the Orowan relationship [Orowan 1940]

$$\dot{\varepsilon}_p = \phi \rho \bar{v} \bar{b} \quad , \qquad (1)$$

where ϕ is a geometric factor, ρ is the density of mobile dislocations, $\bar{b}$ is the dislocation Burgers' vector and $\bar{v}$ is the average dislocation velocity. If ρ remains constant during relaxation, then the strain rate is proportional to the average dislocation velocity. During relaxation, the elastic displacement of the testing system is replaced by the continuing plastic deformation of the sample. Thus, the plastic and elastic displacement rates (*i.e.* strain rates) are related as follows:

$$\dot{\varepsilon}_p = -\dot{\varepsilon}_e = -\frac{1}{E'} \dot{\sigma} \quad , \qquad (2)$$

where $\dot{\varepsilon}_e$ is the elastic strain rate of the sample and the test rig, E' is the combined modulus of the sample and test rig, and $\dot{\sigma}$ is the observed rate of change of stress with time.

Johnson & Gilman [1959] have shown that the applied stress, σ, and the average dislocation velocity may be related as follows:

$$\bar{v} = B(\sigma - \sigma_{\mu})^{m^*} \qquad (3)$$

where B is a constant equal to the average velocity at unit effective stress, σ_{μ} is the internal or athermal stress, and m* is the dislocation velocity/stress exponent. The term $(\sigma - \sigma_{\mu})$ in Equation (3) is known as the effective or thermal stress, σ^*, and is the fraction of the acting stress given most consideration in many treatments of dislocation dynamics. These three equations may be combined in a variety of ways [Guiu & Pratt 1964; Li 1967; Kelly & Round 1969] to allow the determination of the characteristic σ_{μ}, σ^* and m* values from the stress relaxation data.

The constancy of ρ (*i.e.* unchanging structure during relaxation), is the assumption upon which the relevance of the data analysis rests. However, as the strains introduced during typical stress relaxation tests are small (< 0.1%), the assumption of constant dislocation density is reasonable.

The stress relaxation of each sample was determined by loading specimens in an identical manner to stress levels in the range 70-90% UTS and allowing the stress to relax. The variation in stress with time was interpreted using several analytical methods based on Equations 1 to 3. The parameters of σ^*, m* and σ_{μ}, which are descriptive of the dislocation dynamics of the materials, were calculated and the results are given in Table 3. The strain rate sensitivity of the flow stress, λ, is also included. The derivation and usefulness of this parameter will be described later. Considerable variation in the dislocation velocity/stress exponent m* is noted between values calculated by the method of Li [1967] with its emphasis on longer relaxation times, and the method of Kelly & Round [1969] which employs the entire relaxation curve but makes special use of the early stages. Not unexpectedly, these variations are less marked with the maraging steel, which has a simple b.c.c. structure, than they are with the stainless steels.

4. DERIVED CREEP DATA

The relaxation data were used to extract information concerning the creep rates to be expected with these materials under conditions of constant stress. This was a difficult task, strewn with pitfalls and requiring considerable qualification. Nevertheless, it was hoped that any information extracted, although not absolute in a quantitative sense, would serve to provide an order of preference among the contending materials and an order of magnitude value for creep at various load levels.

Relaxation creep values were calculated using the relationship introduced earlier, $\dot{\varepsilon}_p = -\dot{\sigma}/E'$ (Equation 2). Stress rates measured directly from the relaxation curves were converted into relaxation strain (*i.e.* creep) rates. The relaxation curves used were those analysed to provide the data in Table 3. A typical group of relaxation creep rates is shown as a function of stress drop in Figure 2. The stress to which each material had been loaded was approximately 85% UTS. These curves provide a comparative statement of the creep behaviour of the three materials during relaxation. Initially, the maraging steel has the higher creep rate. However, the relative positions of the curves change rapidly and, after the load has relaxed about 40 MPa (~ 1.5 min relaxation time), the maraging steel is much superior to the type 301 sample and slightly better than the 431 sample.

The relaxation creep data were derived under conditions of decreasing stress. It is apparent that the maraging steel, although inferior at short times, improves to a superior position with respect to the other steels at long relaxation times. It will be demonstrated that this relative order was maintained when the relaxation creep data were converted to creep data under conditions of constant stress.

Feltham [1961] outlined a possible method for converting relaxation creep data to constant stress creep data. The method is applicable to situations where

(a) the total strains involved during both relaxation and creep are small;

(b) the relationship between relaxed time and stress is logarithmic; and

(c) a logarithmic relationship holds between creep strain and time during the creep process.

Conditions (a) and (b) are satisfied by the present experimental data. High strength steels operating under load at ambient temperatures and satisfying condition (a) are expected to obey the relationship contained in (c). Thus, it seemed reasonable to apply the following modified version of Feltham's approach to our data.

Since $\dot{\varepsilon}_p = -\dot{\sigma}/E'$ (Equation (2)) and $d\sigma^* = d\sigma$ ($d\sigma_\mu = 0$ in the absence of work hardening), the strain rate sensitivity parameter $\lambda = d\sigma^*/d \log \dot{\varepsilon}_p$ may be expressed as

$$\lambda = \frac{d\sigma}{d \log(-\dot{\sigma})} \quad . \qquad (4)$$

Note: Since the steels investigated exhibit considerable work hardening, the simple equality $d\sigma^* = d\sigma$ used above requires modification [Sargeant 1965] to the form $d\sigma^* = d\sigma\,(1 + W)$. W may be expressed in terms of E', the combined elastic modulus, and the gradient of the stress/strain curve at the stress from which relaxation occurred. For the high strength steels investigated, the term (1 + W) ranged from ~ 2 for the maraging steel to ~ 6 for the 301 stainless steel. Thus, to get the correct value for λ in the presence of work hardening, values of $d\sigma/d \log(-\dot{\sigma})$ have been multiplied by the appropriate value of (1 + W).

The relaxation data may also be fitted to an expression having the form

$$\sigma - \sigma_o = \lambda \log C - \lambda \log (t + c) \quad , \qquad (5)$$

where t is the time during which the stress has relaxed from σ_o to σ and c is a constant. From Equation (5) it follows that

$$d\sigma/d \log (t + C) = d\sigma^*/d \log (t + c) = -\lambda \quad . \qquad (6)$$

Feltham [1961] has also shown experimentally that the relationship between strain, ε, and time during the creep process has a form similar to Equation (5), namely

$$\varepsilon - \varepsilon_o = -\delta \log g + \delta \log (t + g) \quad . \qquad (7)$$

For creep, $d\sigma = 0$ and it follows that

$$d\sigma^* = -d\sigma_\mu \quad . \qquad (8)$$

If a work hardening coefficient, θ, is defined as $\theta = \frac{d\sigma_\mu}{d\epsilon}$, then it follows from Equation (8) that

$$d\epsilon = -d\sigma^*/\theta \quad . \qquad (9)$$

From Equation (7),

$$\frac{d\epsilon}{d \log(t + g)} = \delta \qquad (10)$$

which, combined with the relation expressed in Equation (9), leads to

$$\frac{d\sigma^*}{d\log(t+g)} = -\theta\,\delta \quad . \tag{11}$$

Equations (6) and (11) are conjugates, from which it follows that

$$\lambda = \theta\,\delta \quad . \tag{12}$$

This result simply states that the strain rate sensitivity measured from a relaxation test is the same as that measured from a creep test. It may be expected to hold if the strains involved are small and similar deformation processes occur in both cases.

Substituting for δ in Equation (7) and making the reasonable assumption that g is approximately 1-3 s, Equation (7) takes the useful form

$$\varepsilon - \varepsilon_o = \frac{\lambda}{\theta}(\log t - 1) \quad , \tag{13}$$

where θ may be taken as the slope of the stress/strain curve at the stress under consideration. Using expression (13), values of the logarithmic creep increment have been calculated for the various stresses listed in Table 3. These creep strains are plotted as a function of stress (expressed as a percentage of UTS) in Figure 3. The data fit a linear relationship and confirm that the maraging steel has superior creep properties at all but the highest applied loads. (Its superiority improves as the applied stress decreases, confirming the elastic limit determinations (see Section 5 and Table 4), which implies that plastic deformation occurs in the 431 and 301 samples at much lower fractions of the UTS than indicated by the elastic limits defined as 0.1% proof stress.)

At 85% UTS, each of the materials creeps logarithmically with a yearly strain of $\sim 10^{-3}$. It should be noted, however, that the above derivation of constant load strains from stress relaxation data tends to predict lower strains than those encountered in practice, perhaps by an order of magnitude.

Finally, it should be noted that these creep strains occur during the logarithmic part of the creep process and do *not* include the strain taking place as the sample is loaded or during the minutes at maximum load before logarithmic conditions are attained. The latter portion of the strain is represented by ε_o in Equation (13). A rough estimation of the strain occurring as the sample is loaded may be obtained from Figure 4, which was constructed from data measured on stress/time tensile curves. These nominal stress/strain curves show that maraging steel exhibits the greatest dimensional change on loading, a strain of 3 x 10^{-3} occurring on loading to 85% UTS (roughly 1.70 GPa).

5. DETERMINATION OF ELASTIC LIMIT

The analysis of the relaxation data presented in Section 4 was difficult because of the structural complexities of the materials investigated. However, the relaxation method can be applied in another way to derive information on the likelihood of small dimensional changes under stress at long times. When the crosshead is stopped in a tensile test, a fall in load (*i.e.* relaxation) will only be noted if the specimen *continues* to undergo plastic deformation. This criterion of prior plastic deformation means that within its elastic limit the material will not exhibit relaxation behaviour; the technique may thus be used to determine this limit. This is an important determination because although it gives no information as to the creep rates to be expected at loads in excess of the elastic limit, the stress below which creep should not occur is defined. The elastic limit is difficult to assess by other means for materials which do not exhibit a yield point. Usually a 0.1% proof stress is determined, but this parameter is of questionable usefulness with materials having about 2% elongation before fracture.

The determination of the elastic limit by stress relaxation may be explained using the experimental curves for a commercial 301 sample reproduced in Figure 1. Figure 1(a) shows a typical load/time curve obtained with this material. The elastic limit for this specimen as defined by the 0.1% proof stress would be ~ 1.3 GPa (*i.e.* ~ 75% UTS). Figures 1(b-e) are a selection from a series of curves at 5 kg intervals and describe the relaxation behaviour obtained with a similar commercial 301 sample. Machine relaxation curves obtained using a large cross section test sample loaded to stress levels within its elastic limit have been superimposed. It is apparent that the commercial 301 sample has started to relax at loads of < 40 kg (*i.e.* < 45% UTS) and shows substantial relaxation at loads of 60% UTS. Series of curves confirming this early onset of plastic deformation at < 45% UTS were observed with other commercial 301 samples.

A similar comparative analysis of relaxation curves obtained with the 300 and 431 steels indicated that plastic deformation in these materials was occurring at loads equal to ~ 65 and 60% UTS, respectively. Substantial relaxations were measured at loads of ~ 75% UTS. Interestingly, the elastic limit defined in this manner for the maraging steel agrees fairly well with the 0.1% proof stress value (~ 70% UTS, Table 2). The 0.1% proof stress figure for the 431 stainless steel is ~ 80% UTS, substantially higher than the value determined by relaxation. Table 4 summarises the elastic limit data.

6. SUMMARY AND CONCLUSIONS

(1) Tensile tests at room temperature have shown that the UTS of 431 stainless steel and 300 maraging steel (~ 1.8 GPa) are marginally superior to the 301 stainless steel (UTS ~ 1.75 GPa) under consideration (Table 2). The maraging steel has the additional advantage that it can be easily formed and welded.

(2) Stress relaxation studies have demonstrated that plastic deformation occurs at ~ 45% UTS in the 301 steel, ~ 60% in the 431 steel and ~ 65% UTS in the maraging steel (Table 4). These stresses define the loading stress above which creep will definitely occur. In the case of the 301 and 431 stainless steels, they are substantially lower than the 0.1% proof stress.

(3) The relaxation data have been used to derive an estimate of the logarithmic creep strain occurring under constant load for the three steels of interest (Figure 3). Although the absolute values should be treated with care, owing to the assumptions made in applying the analysis, the relative superiority of the maraging steel over the 431 and the 301 stainless steels is evident.

(4) In determining the dimensional change under load, it is necessary to consider both the instantaneous deformation, which takes place as the steel is loaded, and the long-term deformation process, *i.e.* creep. Rough estimates of this instantaneous deformation indicate strain values of the order of 10^{-3} in the stress range 1.5 to 1.55 GPa (~ 85% UTS) for the three steels (Figure 4).

7. ACKNOWLEDGEMENT

The authors wish to thank Dr. P.M. Kelly for advice and encouragement during the course of the work and helpful discussion during the preparation of the manuscript.

8. REFERENCES

Feltham, P. [1961] - *J. Inst. Met.*, 89 : 210.

Guiu, F. & Pratt, P.L. [1964] - *Phys. Status. Solidi A.*, 6 : 111.

Johnson, W.G. & Gilman, J.J. [1959] - *J. Appl. Phys.*, 30 : 129.

Kelly, P.M. & Round, J.M. [1969] - *Scr. Metall.*, 3 : 85.

Li, J.C.M. [1967] - *Can. J. Phys.*, 45 : 493.

Orowan, E. [1940] - *Proc. Phys. Soc.* (London), 52 : 8.

Sargeant, G.A. [1965] - *Acta. Metall.*, 13 : 603.

TABLE 1

COMPOSITION AND CONDITION OF TEST MATERIALS

301 STAINLESS STEEL 18 Cr, 8 Ni, 2 Mn, 1 Si, 0.15 C Supplied by manufacturers as 0.125 mm strip 'fully hard' condition.
431 STAINLESS STEEL 15.5 Cr, 2.36 Ni, 0.72 Mn, 0.43 Si, 0.16 C Supplied as 12.5 mm dia. rod and hot forged (1320 K) before rolling to 0.425 mm strip. (Intermediate anneal at 920 K.) Austenitised at 1370 K and oil quenched. Finally pack rolled to 0.25 mm.
VASCOMAX 300, MARAGING STEEL 18 Ni, 8 Co, 5 Mo, 0.6 Ti Supplied as 0.3 mm strip and aged for 3 hours at 760 K to produce maximum strength.
1% SPRING STEEL As received, fully hardened, 0.125 mm strip.

TABLE 2

ROOM TEMPERATURE MECHANICAL PROPERTIES IN TENSION

Material	Strain Rate (min^{-1})	UTS (GPa)	0.1% Proof Stress (GPa)	0.2% Proof Stress (GPa)	Elongation at Fracture (%)	Number of Tests
301 stainless	0.0500	1.76	1.30	1.50	~ 1	6
431 stainless	0.0625	1.84	1.49	1.65	~ 1	3
Maraging 300	0.0625	1.81	1.30	1.50	~ 1	4
1% C spring steel	0.0625	1.57	1.21	1.26	3	6

TABLE 3

VALUES OF THE PARAMETERS m^*, σ_o^*, σ_μ DERIVED FROM THE RELAXATION DATA

Material	Relaxation stress	Li's method			Kelly & Round's method			Strain rate sensitivity of stress
		m^*	σ_o^*	σ_μ	m^*	σ_o^*	σ_μ	
	(GPa)		(GPa)	(GPa)		(GPa)	(GPa)	(GPa), λ
301 s.s.	1.66	18.0	0.56	1.10	4.8	0.20	1.46	0.03100
	1.06	21.0	0.51	0.45	4.4	0.12	0.94	0.02485
	1.21	15.0	0.49	0.72	9.0	0.30	0.91	0.03200
	1.02	15.0	0.35	0.67	11.0	0.26	0.76	0.0230
	1.61	16.0	0.48	1.13				0.0300
431 s.s.	1.54	13.0	0.44	1.10	9.0	0.31	1.23	0.0340
	1.63	20.0	0.54	1.09	8.0	0.22	1.41	0.0260
	1.80	16.0	0.36	1.44	7.0	0.20	1.60	0.0230
300 maraging steel	1.65	3.0	0.04	1.61	1.5	0.02	1.63	0.0105
	1.70	3.1	0.04	1.66	3.0	0.03	1.67	0.0111
	1.78	3.9	0.045	1.735	2.7	0.03	1.75	0.0105
	1.86	5.7	0.09	1.77	4.1	0.06	1.80	0.0150

TABLE 4

COMPARATIVE VALUES OF THE ELASTIC LIMITS

Material	0.1% Proof Stress		Relaxation Limit	
	(GPa)	(% UTS)	(GPa)	(% UTS)
301 stainless steel	1.30	75	0.7	42
431 stainless steel	1.49	82	1.1	62
300 maraging steel	1.30	72	1.2	67

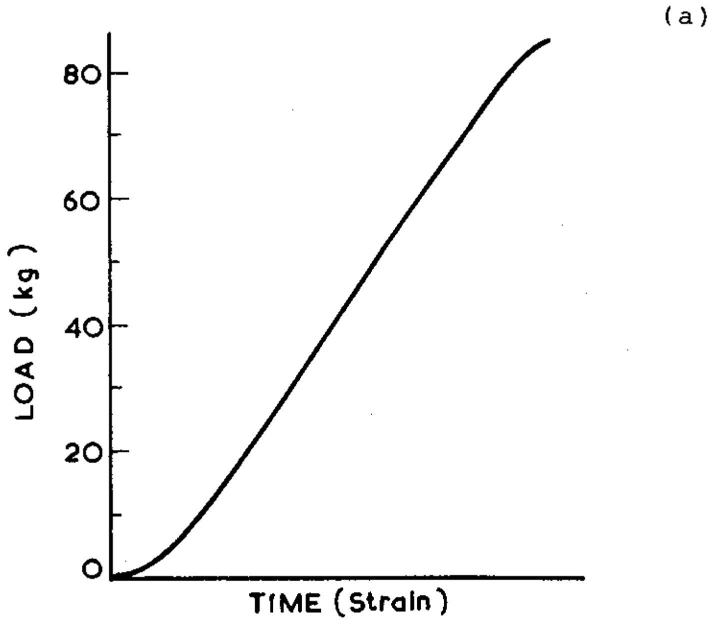

FIGURE 1(a) TYPICAL LOAD-TIME TENSILE CURVE FOR COMMERCIAL 301

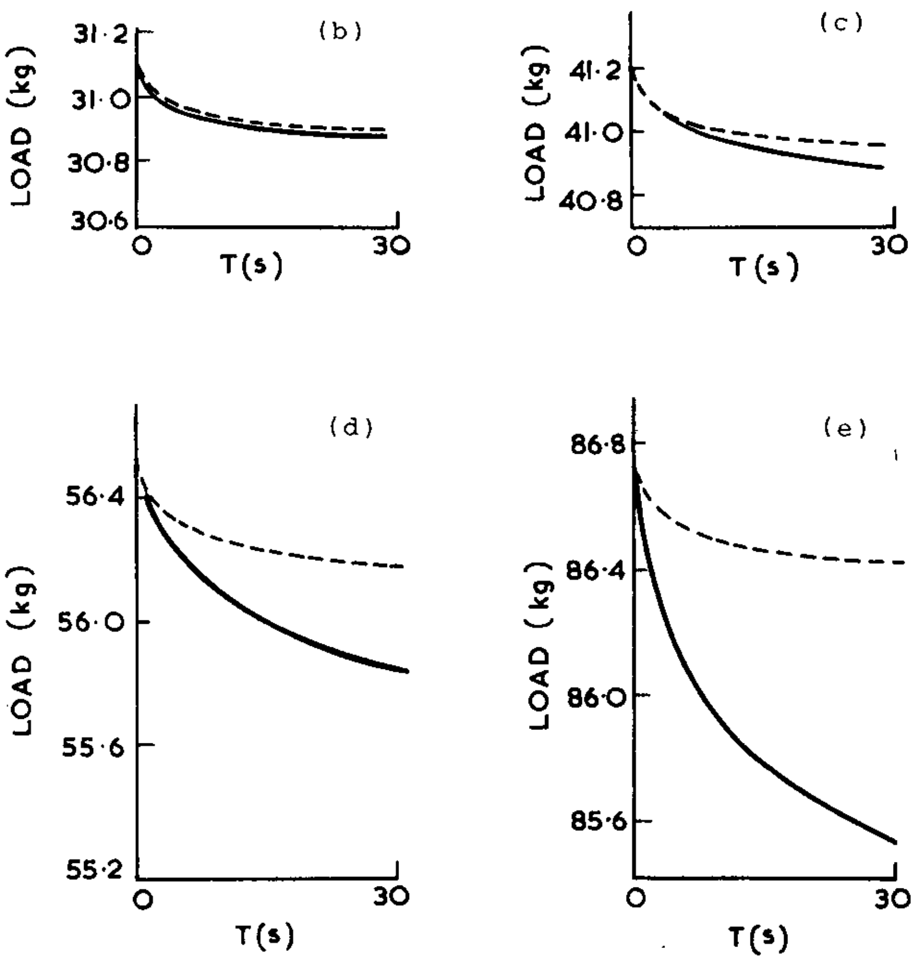

FIGURE 1(b-e) RELAXATION CURVES FOR COMMERCIAL 301 (SOLID LINE) AND TESTING SYSTEM (BROKEN LINE)

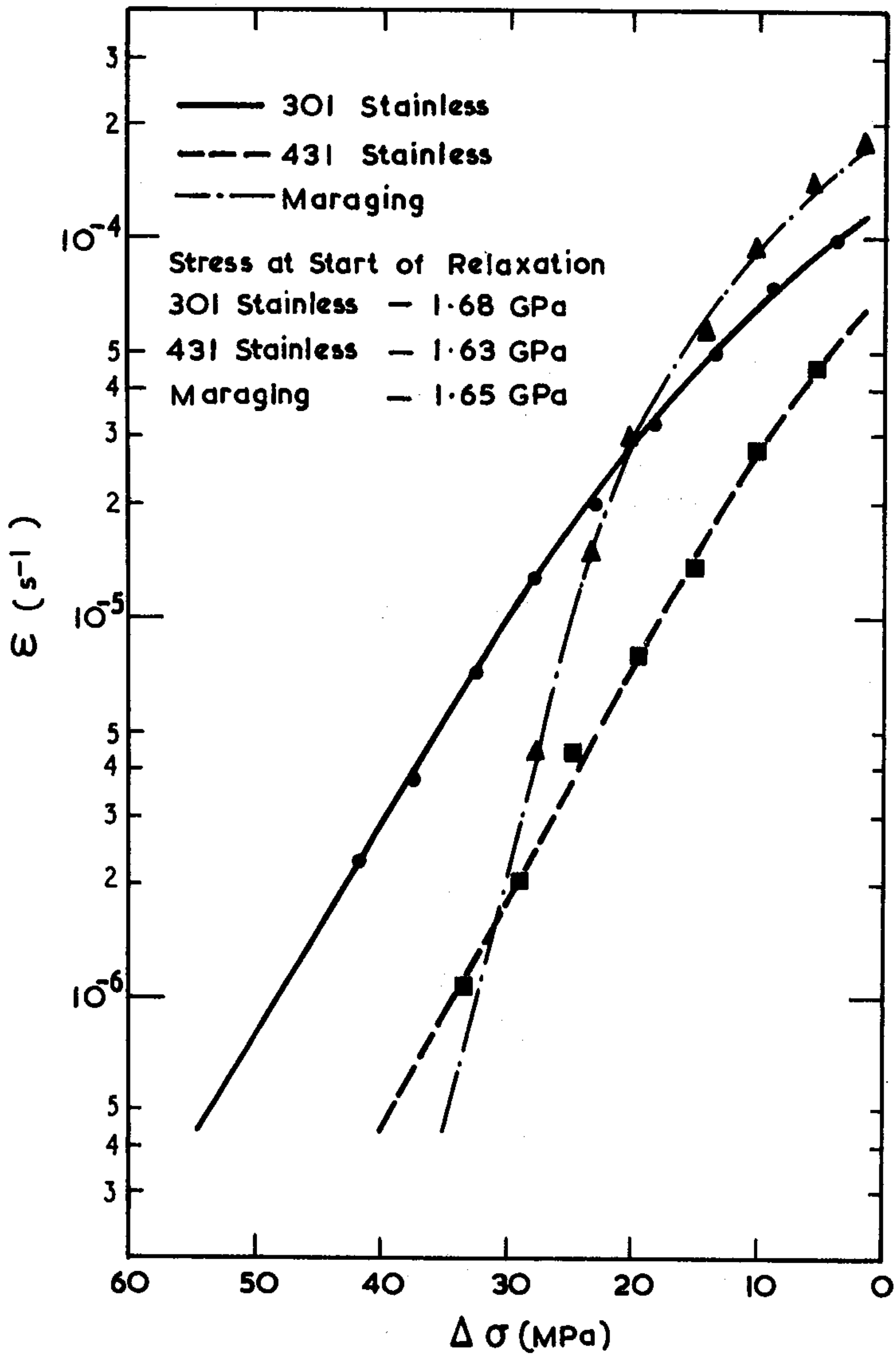

FIGURE 2. RELAXATION CREEP RATE AS A FUNCTION OF RELAXED STRESS

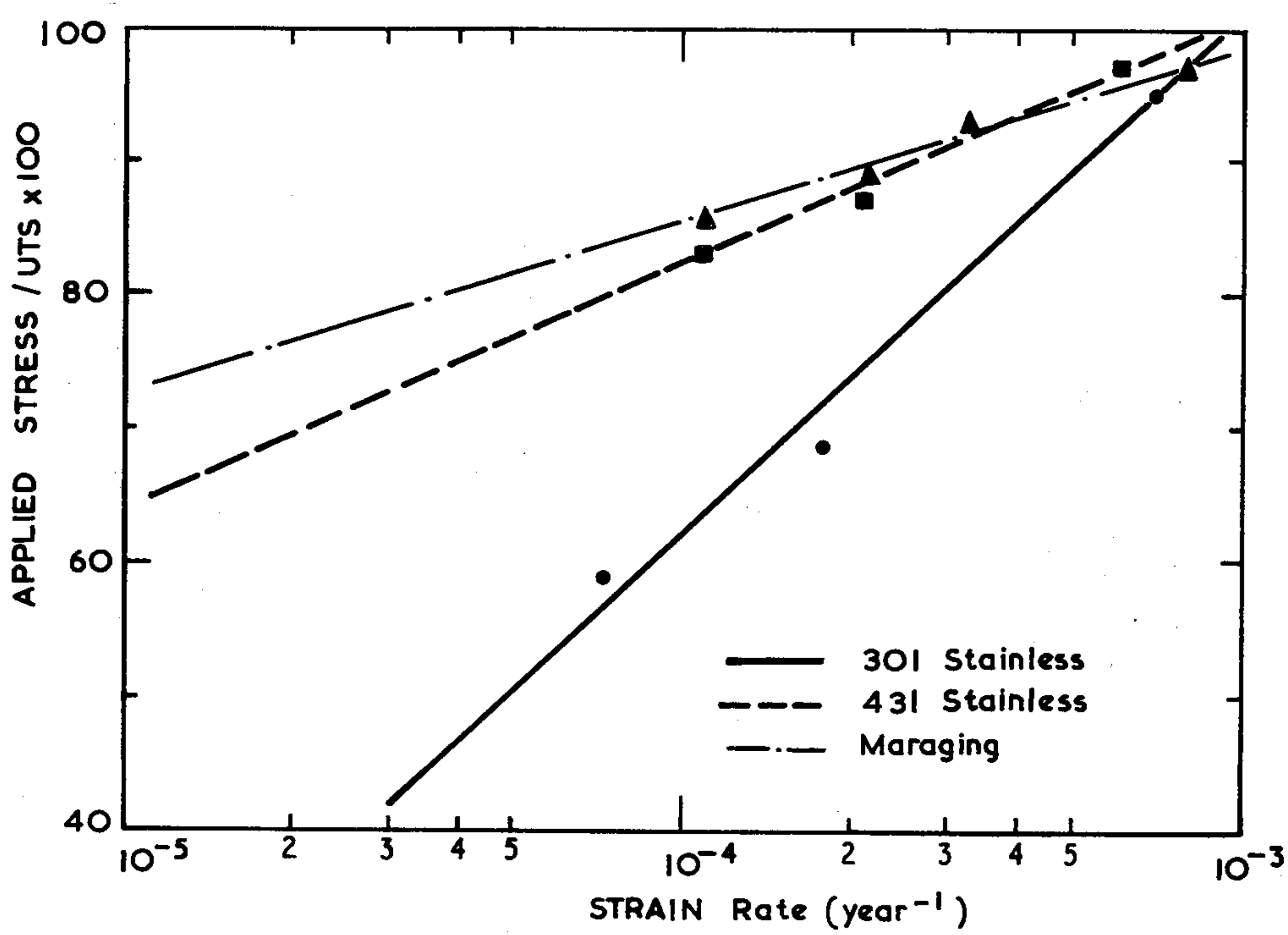

FIGURE 3. DERIVED CREEP RATES AS A FUNCTION OF CONSTANT STRESS (EXPRESSED AS PER CENT OF UTS)

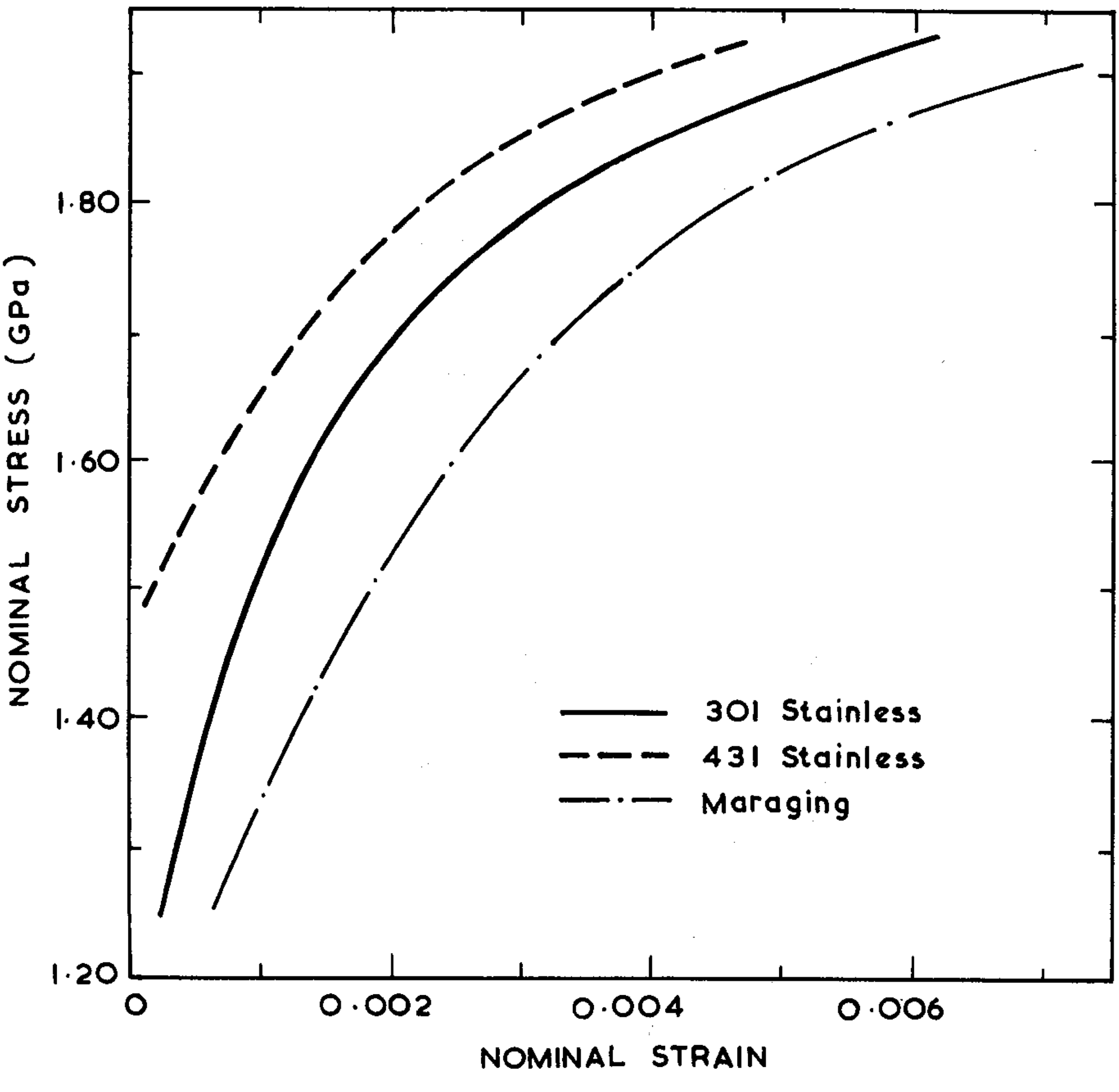

FIGURE 4. NOMINAL STRESS/STRAIN CURVES FOR COMMERCIAL 301 STAINLESS STEEL, 431 STAINLESS STEEL AND MARAGING STEEL