DELAYED YIELD IN STEELS (REVIEW)

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Delayed yield has been explained in terms of dislocation theory [1-5]. An atmosphere of free atoms is formed around a dislocation and is very closely coupled to the latter. Cottrell and Bilby [3] and Nabarro [2] have examined the motion of a dislocation within an atmosphere and the conditions under which a dislocation can break away from an atmosphere, which are determined by the temperature and the applied force. They showed that a small loop appears first, while the dislocation itself is held by the atmosphere and starts to move only at a certain time after the application of the stress σ. This time t_0 decreases as T and σ increase.

A moving dislocation that has left its atmosphere moves to the grain boundary. Passage through this boundary requires a force substantially greater than that for release from the atmosphere. Macroscopic yield starts when the dislocations accumulated at a boundary start to move through it. Fisher [6] used Cottrell's theory to derive the formula

$$\log t_0 = -A + BG^2 / \tau T.$$

Here A and B are constants to be determined by experiment, which are dependent on the internal parameters of the material (energy per unit length of dislocation, number of possible sequences of loop formation, etc), while G is the shear modulus and τ is shear stress.

However, this equation gives incorrect results for very low and very high T, and also for very short t_0, which Fisher ascribed to unsuitability of the dislocation model under these conditions.

Campbell [7, 8] also proposed a criterion for dynamic yield based on the Cottrell-Bilby theory, and this criterion is very widely used in the literature on delay. Yield starts at the time t_0 defined by

$$\int_0^{t_0} \exp\left(\frac{U}{kT}\right) dt = C. \qquad (1)$$

Here U is the activation energy (a function of the applied stress), k is Boltzmann's constant, and C is a constant.

This expression may be transformed in accordance with the loading $\sigma(t)$ and the form of $U(\sigma)$, which may [9, 10] be taken as linear:

$$U(\sigma) = \sigma / \sigma_0. \qquad (2)$$

as a polynomial [11]:

$$U(\sigma) = 0.9\ (1 - \sigma / \sigma_0)^3,$$

in which σ_0 is some characteristic stress, or as a logarithmic relation [12, 13]:

$$U = E_0 \ln (\sigma / \sigma_y), \qquad (3)$$

in which E_0 is a constant and y is the yield point at T = 0.

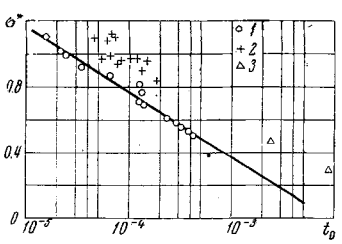

Fig. 1

In (1), the integral contains an exponential function of σ, while (3) transforms this to a power law. We need $\sigma(t)$ also in order to calculate the integral of (1). It is usual to put $\sigma(t)$ = const in studying delay (rectangular stress pulse); a stress known to exceed the yield point is applied to the specimen, and the time for plastic flow to start is considered as the delay time.

Square-pulse loading gives from (1) that

$$t_0 = C \exp\ (-\sigma / \sigma_0) \qquad (4)$$

if U (σ) is taken as in (2), and that

$$t_0 = C(\sigma / \sigma_y)^{-\alpha},\ (\alpha = E_0 / kT) \qquad (5)$$

if (3) is used.

These formulas both agree well with experiment. The power-law expression is more convenient, so all subsequent calculations will be performed for (5).

Several papers [14-18] deal with delay on loading at a constant rate of increase in deformation or stress ($\dot{\varepsilon}$ = const or $\dot{\sigma}$ = const). Replacement of σ by $\dot{\sigma}t$ in (1) and use of (3) gives

$$t_0 = C(\alpha + 1)\ \ (\sigma_{yd} / \sigma_y)^{-\alpha}. \qquad (6)$$

Here σ_{yd} is the dynamic yield point. The t_0 for a triangular loading pulse is α +1 times that for the square pulse of (5).

Kotlyarevskii [14] considered loading that can become σ = const or $\dot{\sigma}$ = const under the corresponding conditions; $\sigma(t)$ was linearized by approximating it by the three straight lines

$$\sigma = \dot{\sigma}_1(t) \quad (0 < t < t_1),$$
$$\sigma = \dot{\sigma}_2(t - t_1) + \sigma_1 \quad (t_1 < t < t_2),$$
$$\sigma = \dot{\sigma}_2(t_2 - t_1) + \sigma_1 = \sigma(t_0) \quad (t_2 < t < t_0).$$

Here $\dot{\sigma}_1$ and $\dot{\sigma}_2$ are the rates of stress increase on the first and second parts. Kotlyarevskii applied Campbell's criterion to get

$$t_0 = t_2 + C^*\left[\frac{\sigma_{ys}}{\sigma(t_0)}\right]^{\alpha} + \frac{t_1}{\alpha+1}\left\{\left[\frac{\sigma_1}{\sigma(t_0)}\right]^{\alpha}\left(\frac{\dot{\sigma}_1}{\dot{\sigma}_2}\right)^2\left(\frac{\dot{\sigma}_1}{\dot{\sigma}_2} - 1\right) - \frac{\sigma(t_0)}{\dot{\sigma}_2 t_1}\right\}$$
$$\left(C^* = C\frac{\sigma_y^{\alpha}}{\sigma_{ys}^{\alpha}}\right)$$

Here σ_{ys} is the static yield point. This expression takes the following forms in the cases $\dot{\sigma}$ = const and σ = const:

$$t_0 = C(\alpha + 1)\ (\sigma_{yd} / \sigma_y)^{-\alpha},\ \ t_0 = C(\sigma / \sigma_y)^{-\alpha}.$$

Kotlyarevskii's formulas coincide with those above for $\dot{\sigma}$ (or $\dot{\varepsilon}$) = const and for an instantaneously applied load.

There is also the form of loading in which the load increases and then decreases, e.g.,

$$\sigma = \sigma_m \sin \omega t.$$

Then Campbell's criterion is

$$\left(\frac{\sigma_m}{\sigma_0}\right)^{\alpha} \int_0^{t_0} \sin^{\alpha}(\omega t)\, dt = C.$$

Sinusoidal stress has been considered several times [19-22]. Belsheim [19] derived the following empirical relation for t_0 as a function of σ_{yd} for mild steel at a loading frequency of about 360 Hz:

$$t_0 = 513 \exp\ (-0.000139\ \sigma_{yd}).$$

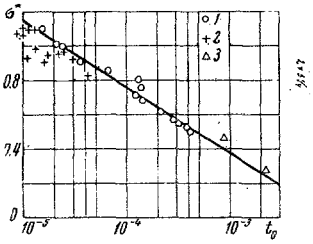

Fig. 2

Here t_0 is the time from the point $\sigma > \sigma_{ys}$ to the onset of yield. It is clear that this t_0 as so defined should substantially exceed that for other types of loading for certain σ, as is found. Taylor [20–22] found that Campbell's criterion applies for an arbitrary type of loading:

$$\int_0^{t_0} \sigma(t)\, dt = C$$

However, Taylor does not state how he defined t_0 for an oscillatory load (there are various possibilities), and his graphs have few points and a large spread; it is difficult to draw any definite conclusion. Costello [23] examined the case

$$\sigma(t) = \kappa t^{\beta}$$

He assumed that β lies between 0.5 and 2 under the usual experimental conditions. Campbell's criterion gives

$$t_0 = C^{\circ}\sigma^{-\alpha}$$

The factor C° is dependent on β, whereas α is fixed for a given T and given material. Plots of $\log\sigma$ against $\log t_0$ are parallel straight lines (for different β) falling within a comparatively narrow range. The t_0 calculated for the different methods of loading differ very considerably, and the following relation has been proposed [16, 17] for the purpose of comparing them:

$$\int_0^{t_0} \exp\left[\frac{U(\sigma)}{kT}\right] dt = \int_0^{t_p} \exp\left[\frac{U(\sigma)}{kT}\right] dt = t_p \exp\left[\frac{U(\sigma)}{kT}\right]. \quad (7)$$

Here t_0 and σ are for an arbitrary form of loading, while t_p and σ_p apply for a rectangular pulse. If $\sigma(t)$ is known, (7) gives t_0.

Figure 1 [17] gives experimental results for different methods of loading, the ordinate being $\sigma^* = (\sigma_{yd} - \sigma_{ys})/\sigma_{ys}$, which corresponds to the dynamic yield point (or the applied stress in the case of a rectangular pulse), while t_0 is in sec (here taken as the time to onset of yield). Figure 2 [17] shows the same experimental results converted via (7), and here the results can be compared for different methods of loading, since the points all lie near a single straight line. The symbols in Figs. 1 and 2 are as follows: 1) points for σ = const, 2) $\dot{\sigma}$ = = const, 3) $\dot{\sigma} = \sigma_m \sin\omega t$.

In general, it is very difficult to make such comparisons because the results of different workers generally relate to different steels. It is shown below that t_0 is much affected not only by the composition but also by the grain size, the surface treatment, and the experimental conditions, in particular T.

In general, Campbell's criterion describes closely the curves for small t_0 and high σ, but there are large discrepancies for $\sigma \to \sigma_{ys}$. Campbell's criterion in the form of (1) cannot cover the part that deviates from the straight line corresponding to σ_{ys}, so Campbell and Duby [15] modified (1) to give the best fit for high and low σ. They supposed that rapid diffusion of carbon atoms allowed these to link up again with dislocations when t_0 was fairly large, which gave a modified yield criterion as

$$\exp(-bt_0)\int_0^{t_0} \exp\left(bt + \frac{U}{kT}\right) dt = C, \quad (8)$$

and which becomes

$$\exp(-bt_0)\int_0^{t_0} \sigma^{\alpha}\exp(bt)\, dt = C \quad (9)$$

if (3) is used for U. Here 1/b is the mean time required for a dislocation to link up again with atoms; b may be deduced from the limiting values for $t_0 \to \infty$, when (8) and (9) become

$$\exp\left(\frac{U_{ys}}{kT}\right) = bC, \qquad \sigma_{ys}^{\alpha} = bC, \quad (10)$$

in which U_{ys} is the activation energy corresponding to σ_{ys}. The observed σ_{ys}, α, and C may be used with (10) to find b; Campbell and Duby obtained $b = 10.1\ \text{sec}^{-1}$ for mild steel, which they used in (9) to relate σ to t_0 for $\dot{\sigma}$ = const. Campbell's experiments showed that (9) takes account of the approach to σ_{ys} with a maximum deviation of 7% from the observed points. However, here we will use Campbell's criterion in the form of (5), as this is much simpler; the region of the static straight line is not of great interest.

Although there are fairly many papers on delayed yield, relatively few experiments have been done, partly because there are difficulties and partly because the results have a very great spread. The results can be processed only if numerous points are available; but some Krafft curves have been plotted only from two or three points, and it is clear that such experiments cannot give reliable quantitative evidence on t_0. In view of the experimental difficulties, many authors have used the results of others, usually those of Wood and Clark [9, 10], which are the most reliable, since they obtained numerous points throughout the range of t_0 (0.3 to 1.0 msec) and five different T (394, 296, 214, 141, and 77° K). Figure 3 shows t_0 (sec) as a function of σ (kg/mm^2); the solid lines are those calculated from (5). Here only α(T) takes account of the T dependence of t_0, it being assumed that C is independent of T. The calculated curves fit the experimental results well at 296° K (+23° C) and above, but there is some deviation at 214° K (−59° C), and this becomes considerable at 77° K (−196° C), which shows that the T dependence in (5) is not reliable for all T.

Table 1 gives the parameters of (5) derived from the results [9, 10, 24–30] for various steels.

The α and $\log c$ (where $c = C\sigma_y^{\alpha}$) were determined as functions of T by least squares for the various compositions, grain sizes, and ranges in t_0.

Figures 4 and 5 show some of the α(T) and $\log c$(T) curves, in which the numbers on the curves correspond to the numbers in the table. From about 273° K (0° C) upwards, α and $\log c$ vary little with T, and this is the region where (5) gives good results. At 250–300° K (−23 to 27° C) there are kinks in α(T) and $\log c$(T), and these quantities acquire a substantial temperature dependence at low T. Curves 6 [9, 10] indicate that this kink lies at 180° K (−93° C). It is difficult to judge the behavior at low T because very few measurements have been made. It is not clear why α and c have negative temperature coefficients.

Another interesting effect occurs at low T. If σ is large (the precise σ varies with T) there is an upper limiting σ at which brittle frac-

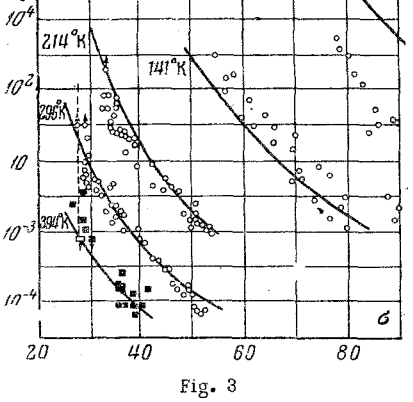

Fig. 3

Table

№	Source	Composition, %	Treatment	t_0, sec	T° K	lg c	α
1	[10]	0.12C, 0.98Mn	Annealing	$3\cdot10^{-3}$—$1\cdot10^{2}$	213	26.3	16.9
					297	16.7	12.1
2	[10]	0.12C, 0.98Mn	*	$3\cdot10^{-3}$—$1\cdot10^{2}$	213	16.8	12.2
					297	12.9	11.3
3	[10]	0.12C, 0.98Mn	**	$3\cdot10^{-3}$—$1\cdot10^{2}$	213	24.2	16.2
					297	25.9	19.3
4	[10]	0.12C, 0.98Mn	***	$3\cdot10^{-3}$—$1\cdot10^{2}$	213	16.7	11.8
					297	13.1	10.9
5	[24]	0.19C, 0.43Mn	Annealing	$5\cdot10^{-3}$—$5\cdot10^{0}$	296	22.4	15.7
6	[9]	0.17C, 0.39Mn	Annealing	$3\cdot10^{-4}$—$1\cdot10^{3}$	77	86.5	44.1
					141	45.1	24.5
					214	28.3	17.6
					296	23.2	15.9
					394	17.3	13.4
7	[25]	0.17C, 0.39Mn	Annealing	$3\cdot10^{-5}$—$3\cdot10^{-1}$	296	23.0	15.7
					339	8.2	7.0
					394	17.5	13.6
8	[26]	0.204C, 0.84Mn	Annealing	$2\cdot10^{-6}$—$1\cdot10^{-4}$	198	23.2	14.5
					248	13.9	9.8
					298	12.7	9.5
					373	9.7	8.2
9	[26]	mild steel	Annealing	$2\cdot10^{-6}$—$4\cdot10^{-5}$	296	4.6	5.2
				$4\cdot10^{-5}$—$1\cdot10^{0}$	296	27.9	18.7
10	[27]	0.01C, 0.99Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	213	30.2	20.1
					253	24.6	16.9
					298	14.9	11.5
11	[27]	0.11C, 0.62Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	213	18.3	12.2
					253	15.9	11.3
					298	12.3	9.8
					394	24.8	17.8
12	[27]	0.16C, 0.69Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	204	32.6	19.3
					228	23.0	14.7
					252	21.6	14.1
					276	18.7	12.7
					300	14.8	10.8
					324	18.4	13.1
					348	14.6	11.1
					372	9.1	8.0
					394	11.4	9.6
13	[27]	0.22C, 0.36Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	228	23.1	14.2
					252	26.9	16.6
					300	17.2	11.9
					324	16.9	11.9
					348	16.5	11.9
					372	16.4	11.9
					394	14.8	11.2
14	[27]	0.22C, 0.98Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	253	28.1	17.6
					298	21.4	14.4
					338	19.2	13.5
					394	24.3	17.1
15	[27]	0.31C, 1.01Mn	—	$5\cdot10^{-6}$—$5\cdot10^{-3}$	298	19.4	13.4
					338	18.0	12.9
					394	21.0	15.2
16	[27]	—	—	$2\cdot10^{-6}$—$1\cdot10^{-3}$	213	29.5	18.1
					253	24.5	15.7
					298	15.9	11.5
					338	9.3	8.0
					394	14.1	11.1
17	[30]	0.19C, 0.54Mn	—	$1\cdot10^{-3}$—$2\cdot10^{-4}$	296	25.2	17.1
18	IMAsh	steel 3	Annealing	$2\cdot10^{-2}$—$1\cdot10^{0}$	296	17.3	11.7
19	IMAsh	steel 45	Annealing	$2\cdot10^{-2}$—$1\cdot10^{0}$	296	21.2	13.9
			n | d mm				
20	[29]	0.09C, 0.45Mn	3150 | 0.0178	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	11.2	8.1
21	[29]	0.09C, 0.45Mn	2030 | 0.0222	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	13.4	9.7
22	[29]	0.09C, 0.45Mn	773 | 0.0360	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	11.8	9.2
23	[29]	0.09C, 0.45Mn	495 | 0.0450	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	8.8	7.2
24	[29]	0.09C, 0.45Mn	346 | 0.0540	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	11.6	9.3
25	[29]	0.10C, 0.55Mn	5250 | 0.0138	$1\cdot10^{-3}$—$1\cdot10^{0}$	296	12.3	8.8

*Steel treated with liquid hydrogen.

**Steel treated with liquid hydrogen and carburized.

***Steel treated with liquid hydrogen and nitrided.

Note. The numbers 18 and 19 correspond to experiments done in the Laboratory of Machine Materials Strength at the Institute of Machine Research; N = grains/mm^2, d = grain diameter.

ture occurs, with no delay, as Fig. 3 shows from points for 77° K (−196° C). Others [26, 27] have found this, and the effect has been confirmed in the Laboratory of Machine Materials Strength at the Institute of Machine Research.

Clark and others [17, 31, 32] have examined the effects of aging on delayed yield for repeated dynamic loading. Macrodeformation does not always occur during the first loading cycle, although the maximum σ exceeds the yield point. It has been found [4, 32] that repeated loading to $\sigma > \sigma_y$ will cause the specimen to behave as elastic for a time t_2 such that $t_1 + t_2 = t_0$ if it has first been loaded with $\sigma > \sigma_y$ for a time $t_1 < t_0$, which does not allow plastic deformation to occur. The same occurs in a long sequence of loading cycles.

Clark examined the effects on t_0 from heat treatment between successive loading cycles. If the specimen after loading is aged at 66° C for 100 min and is loaded for $t = 3t_0/5$, no yield occurs. The same occurs on aging at 93° C for 12 min. Maintenance at 21° C does not

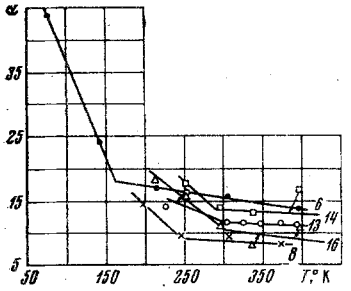

Fig. 4

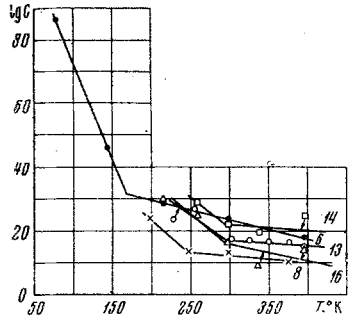

Fig. 5

affect t_0. Clark and Wood concluded that proper choice of T and aging time produces some recovery; repeat loading does not cause yield if the recovery time at a given aging temperature is less than the aging time. It was considered [4] that the recovery is related to the diffusion of carbon and nitrogen atoms.

Results have been given [9, 10, 27] on the effects of C and N contents on t_0. It was found that the σ for a given t_0 increases with the C and N contents.

Other studies [26–29] deal with the effects of grain size on t_0. Campbell found that this is

$$t_0 = \frac{A}{d^3} \exp\left(\frac{U}{kT}\right).$$

He supposed that the grains all have the same diameter d and that the dislocations are uniformly distributed in the material. The larger d the less the σ needed to make the material yield in a given time, which explains the effects of heat treatment on t_0. However, it is also necessary to take account of microstructural parameters (size of ferrite grains, free distance between perlite inclusions in the ferrite, and size of the perlite inclusions).

Table 1 gives the results from least-square processing, which do not reveal any definite trend in α and log c with the contents of C, N, and Mn, or with d. The reason is that each worker recorded too few points, so least-squares processing does not allow one to establish quantitative characteristics. Moreover, the authors themselves mostly drew their curves by eye. Finally, the results were obtained on various steels, which differed in composition, heat treatment, test conditions (in particular, T), and methods and levels of loading (different ranges in t_0).

However, it would seem that the % C and Mn substantially affects the results. For instance, steels have been used [27] all containing 0.22% C and with Mn contents of 0.36 and 0.98%. The corresponding α for normal T were 11.9 and 14.4, while the log c were 17.2 and 21.4. The contents of all other components would appear significant, as would the type of heat treatment.

Our results were obtained for steels differing in heat treatment and having 0.01 to 0.31% C, as well as 0.39 to 1.01% Mn. The room-temperature α was 9-16, and the log c was 12-22.

The published evidence does not provide exact values for the coefficients of (5) for any class of material, and this is evidently impossible, because the delay is much affected by factors such as grain size and heat treatment, as well as chemical composition and test conditions. Independent tests are needed for each particular material in order to obtain quantitative results.

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