THE SPREAD IN CREEP CURVES

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Allowance for the spread in creep curves in creep calculation leads to a sounder choice of calculated values for the time and stress, while in some instances the spread may be a source of initial perturbations [1] or considerable unevenness of the stress over the cross section, which can lead to a substantial change in the approach to creep problems. Here we give test results on the spread from 293 creep curves recorded with D16T alloy under fixed test conditons: 207°C and stress 18 kgf/mm². We examined the reason for the spread and derive a formula enabling one to describe the creep curves as random functions of time.

The threaded specimens were turned from 18-mm rods as supplied; the working part was 100 mm long and 8 mm in diameter, while the test time was 20 hr.

We used 13 specimens from the same batch to determine the mechanical characteristics at normal temperature. The arithmetic mean for the limiting temporary stress was $\sigma_b = 54.1$ kgf/mm², with the least and largest values, respectively, 49.3 and 56.4. At 200°C, the mean σ_b for D16T rod is [2] 41 kgf/mm². Our measurements were therefore made at about 0.45 σ_b for the given temperature.

The creep tests were done with four machines, each of which had three independent two-section ovens for loading specimens with constant forces. The constant temperature in the ovens was provided by a dilatometer control. The temperatures varied around the mean by only ± 2°C, with a period of variation of about 15 min, but the variations were approximately the same in all the runs, so they should not influence the spread in the curve. The temperature difference along the length of a specimen during test did not exceed 1°C. A specimen mounted up with its extensometer was inserted in the heated oven and was heated to the set temperature for about an hour and then was kept for two hours at the temperature, after which the tensile load was smoothly applied. The initial reading of the indicator was then taken to record the extension, and then at set intervals further readings were taken to determine the creep. All the machines employed indicators of dial type with a scale division of 0.002 mm.

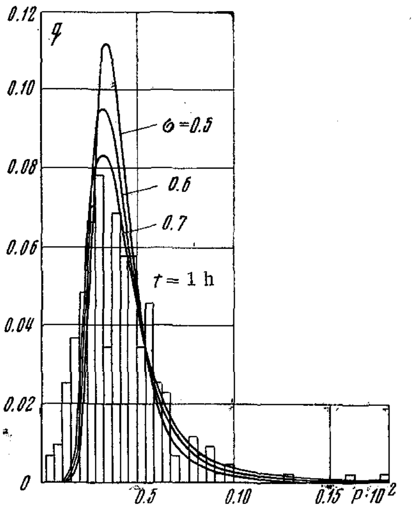

Fig. 1

The temperature was measured systematically with a manual potentiometer type PP of 0.5 class; the temperature transducers were chromel–alumel thermocouples, whose maximum error according to the calibration was 2.2°C at 200°C; the overall error in determining the temperature was thus not more than 3.2°C.

The calibration showed that the error was not more than 0.3 kgf/mm² in determining stresses at 18 kgf/mm².

When we used coordinates of time t and creep strain p, the curves for the different specimens were not completely identical, although most of them by the 20th hour had reached the region of steady-state creep. This state had already been reached after 10-15 hr in certain instances.

Figures 1-4 give histograms for the distribution of the creep strains after 1, 5, 10, and 20 hr of test. To construct each histogram we divided the complete range of strains into 40 equal intervals Δp_i, and the results were used to calculate the frequencies in

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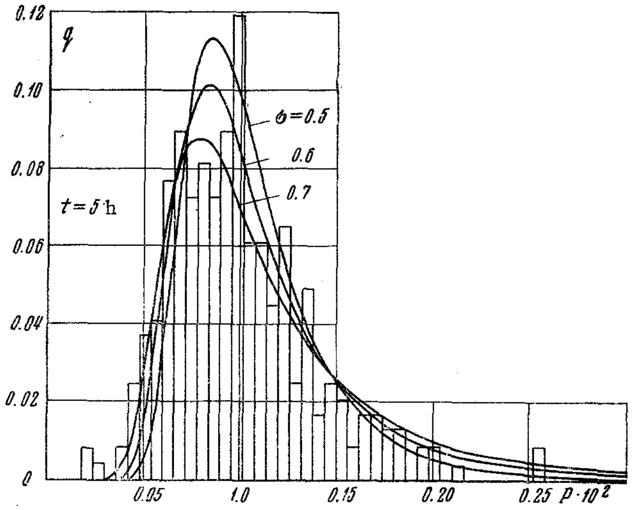

Fig. 2

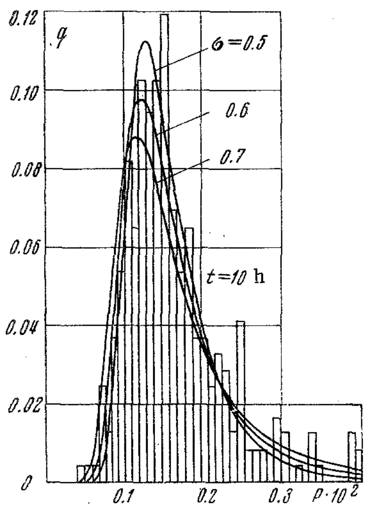

Fig. 3

each of the intervals. The height of a column for an interval was proportional to the number of instances encountered. The histograms show that the distribution is not normal and has positive skewness.

Figure 5 shows curves constructed from different characteristics: from the arithmetic mean (1), from the median (2), and from the mode (3). The median divides the range into halves, and we consider it the most convenient for constructing average curves if the number of tests is restricted and the spread in the creep curves is large. The median can be determined without calculation and one can take into account all the observed curves without discarding any before the averaging. The median can also be constructed when part of the specimens have already broken, because the lack of individual curves has little effect on the position of the median.

We examined the magnitude and causes of the spread. We found that a large spread persisted when we tested specimens from a single rod and on testing with a single apparatus and oven, while deviations of the average curves from the general mean are completely explained by the considerably smaller number of specimens, since from a single rod we tested from 7 to 18 specimens, whereas with one apparatus we tested from 17 to 33 specimens.

The curves constructed in these cases from the medians deviate less from curve 2 than do curves constructed from the arithmetic means, which deviate from curve 1. In the second case the deviations at 20 hr lay within the limits from -0.09×10^{-2} to 0.10×10^{-2}, while in the first case they lay within the limits -0.07×10^{-2} to 0.08×10^{-2}.

We examined the possible errors due to the variation in the longitudinal loading and in the temperature by making tests with small deviations from the set values; 86 specimens were tested at 205°C and 18 kgf/mm², and 93 at 200°C. At 207°C we tested 93 specimens at 18.5 kgf/mm² and 77 at 17.5 kgf/mm². Figure 6 shows the resulting arithmetic-mean curves (solid lines for various stresses, broken line for different temperatures, heavy lines for curve 1 of Fig. 5). These curves enable one to determine the approximate spread caused by deviations in the load and temperature. We also examined whether the surface treatment of the specimens affected the creep and spread; the tests were done on the same specimens of D16T material, but with rods of diameter 22 mm. We tested 162 specimens at 207°C and 18 kgf/mm²; of these, 74 had polished surfaces, while the rest had surfaces treated with a cutting tool on a lathe. Figure 7 shows the curves constructed from the arithmetic means and the limits of the spread; the solid line is for the unpolished specimens, while the broken line is for the polished ones. It is clear that surface polishing has no effect on the creep or on the spread.

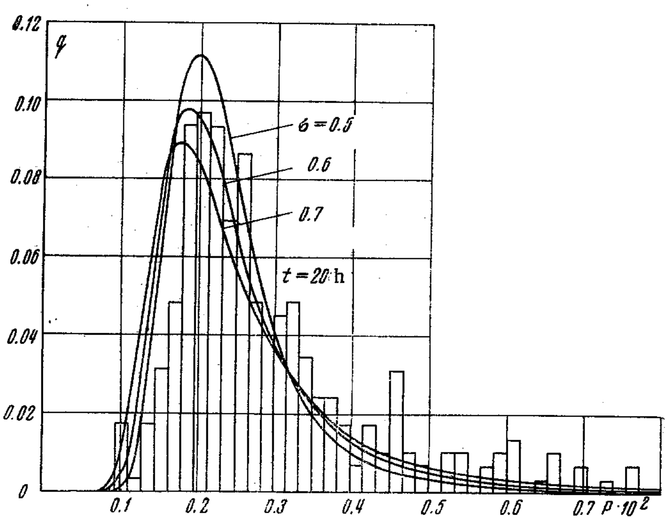

Fig. 4

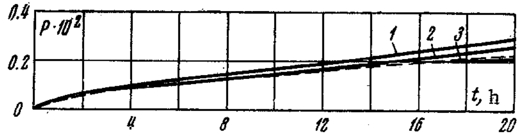

Fig. 5

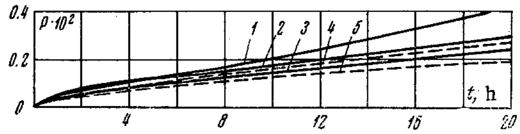

Fig. 6

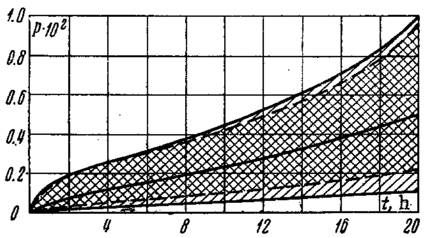

Fig. 7

The batch of rods 22 mm in diameter differed somewhat from the main batch as regards chemical composition, and it was possible to evaluate the effect on the creep of D16 of the small changes in composition permitted by the state standard. As the plasticity of duralumin increases with the ratio of copper to magnesium at normal temperature, it was natural to compare the two batches via the Cu/Mg ratio. The main batch of rods contained 4.15% copper and 1.50% magnesium (Cu/Mg = 2.77), while the batch of 22 mm diameter rods had 4.10% copper and 1.27% magnesium (Cu/Mg = 3.23). This is probably why the creep of the second batch was larger.

At 6 kgf/mm² and 270°C we tested 18 specimens that had been annealed at 360°C and left to cool in the oven. The creep was greatly increased, while the spread in the curves remained equally large.

These results show that the surface treatment does not affect the creep rate; the chemical composition greatly affects the creep rate, but the spread in these tests cannot be explained as due to differences in chemical composition, since all the specimens were made from one batch.

It remains to evaluate the effects on the spread from errors in the load and temperature, on the assumption that small deviations result in the linear dependence of the creep strain on temperature and stress. The above shows that the temperature error did not exceed ± 3.2°C, while the load error did not exceed ± 0.3 kgf/mm². We assume also that errors due to incorrect adjustment of the equipment were absent. The curves of Fig. 7 show that the maximum spread on account of errors in the temperature was ± 12%, while the spread due to error in the longitudinal loading ranged from + 25 to − 10%. Taken overall, if we assume that the effects of these factors are independent, we get a spread from + 37 to − 22%, which is somewhat greater than the spread of the average curves obtained after processing the data for each apparatus separately. The residual part of the spread (from 130 to − 45%) is probably due to the internal structure of the material and to indefiniteness of the eccentricity when applying the load; this part of the spread is not reduced even if there are no errors in the longitudinal loading and in the temperature.

We did not examine the effects of the eccentricity on the spread on account of lack of a satisfactory method; but measurement of the strain by means of four strain gauges attached to the surface on opposite sides showed that the strains on opposite sides of a specimen differed by not more than 10% in any of the machines, so we assume that the effects of the eccentricity on the spread are not decisive.

We assume that the spread in the creep curves is determined by the spread in σ_b; to describe the curve for constant temperature and constant load we use the formula

$$p = B \operatorname{sh} \frac{\sigma}{n} t^m \tag{1}$$

where $B = 2.94 \times 10^{-5}$ hr^{-1}, $m = 0.58$, and n was taken in accordance with [3] as 5.5 kgf/mm^2, since the tests there were done on the same batch of specimens. The curve calculated from (1) is shown as the broken line in Fig. 5 and closely coincides with the observed curve 3. We transform (1) to give

$$p = B \operatorname{sh} \left(\frac{\sigma}{\sigma_0} \frac{\sigma_b}{n} \right) \tag{2}$$

We varied σ_0 within the limits 49.3 to 56.4 kgf/mm^2, in accordance with the above test results, which gave strains at 20 hr varying from 0.165×10^{-2} to 0.253×10^{-2}, which is much less than the strain actually recorded. It has been suggested [1] that one should take into account the spread in the curves no matter what the cause of the stress by introducing into the formula some random quantities as well as the constants; we attempted to describe the set of curves via the formula

$$p^* = B \operatorname{sh} \frac{\sigma}{n^*} t^m \tag{3}$$

(where B and m are constant and only n* is a random quantity), assuming on this basis that the curves intersect nowhere apart from the origin. We assumed a normal distribution for n* and a probability density given by

$$g(n) = \frac{1}{\sigma \sqrt{2\pi}} \exp \frac{(n - 5.5)^2}{2\sigma^2} \tag{4}$$

where σ is the standard deviation of n.

The functional relationship of (3) between n* and p* was used in accordance with [4] to calculate the density of the distribution q(p); one can select values for σ and equate the area under the histograms to the area under the q(p) curves for various values of time to get the best agreement between the histograms of Figs. 1-4 and the density distribution q(p), which occurs for $\sigma = 0.6$.

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