

high elongation were used to keep this change in force to 5% or less. Pressure has an effect on the spring constant through its effect on the shear modulus.²⁶ This effect in steel is of the order of a percent or two at the pressures used here and so has been neglected. A fuse wire was employed to hold the load off the sample until the desired temperature and pressure were obtained, at which time the creep was commenced by fusing the wire.²⁷

The sample deflection was measured by a differential transformer wound on a polyethylene core. The primary coil was composed of 600 turns of 38 gauge copper magnet wire. Each of the secondaries consisted of 3000 turns of the same wire. The entire assembly was approximately 4 cm in length, 1.75-cm outside diameter, and 1-cm inside diameter. It was mounted in the stressing apparatus as shown in Fig. 3. The core was soft iron, slightly smaller than the inside diameter of the coil spring. The surface of the core was carefully polished and the end rounded to avoid interference with motion of the spring. This core was rigidly attached to the upper end of the spring and center knife edge.

The primary coil was driven at 1000 to 2000 cps by a Hewlett Packard 200T precision telemeter test oscillator. The signals from the secondary coils were demodulated and their difference recorded on a Leeds and Northrup 10-mV Speedomax recorder, modified to read 10 mV, 100 mV, etc. up to 300-V full scale. Most of these studies were made on the 100-mV scale. Calibration with a soft iron core mounted on a micrometer, and visual inspection of a deforming sample showed the differential transformer output to be linear with core displacement for a region slightly greater than 1.25 cm in length. The output was approximately

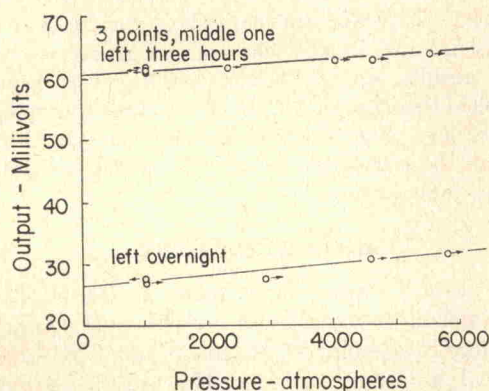


FIG. 4. Pressure calibration of displacement gauge. Lower curve shows pressure dependence of output using porcelain sample, the upper curve indicates output with knife edge rigidly held above the beam. A pressure dependence of displacement reading would cause a deviation from parallelism.

²⁶ P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **64**, 39 (1929).

²⁷ For a time the experiments were harrassed by transversal fractures of the inner die of the pressure vessel, initiated when a free end of the 12-V fuse wire shorted out there.

5 V per cm which resulted in a sensitivity with the present measuring system of at least 5×10^{-5} cm. A number of the experiments were made with the driving voltage lowered to give a sensitivity of 1 V per cm to facilitate recording over very long times.

To determine the effect of pressure on the voltage-displacement characteristics of the differential transformer, the core was securely fixed in one position with the fuse wire, and the lead sample was replaced by a porcelain beam. With the core so fixed, the pressure was varied and the effect on output noted. The fuse wire was then broken, allowing the core to drop a few millimeters, being supported in this position by the porcelain beam. The results are shown in Fig. 4. It can be noted that the curves are nearly parallel, indicating a very small effect of pressure on the displacement

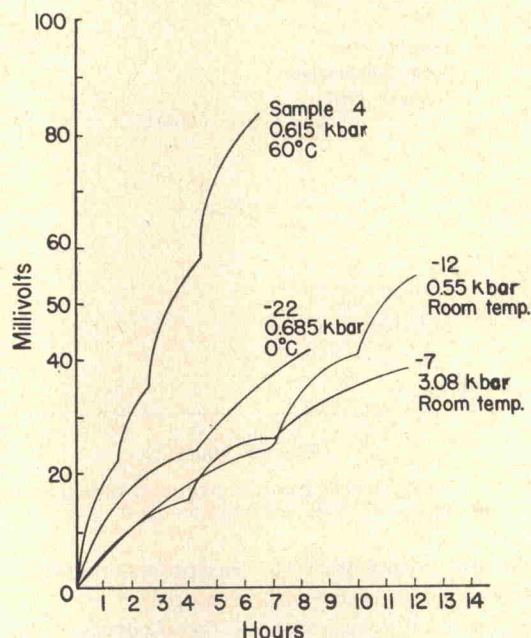


FIG. 5. Typical creep curves at various pressures and temperatures. (Sensitivity 1 V/cm this figure only.)

reading. The voltage output for the same displacement was $\sim 3\%$ higher at 6 kbars than at atmospheric pressure. The stability of the transducer readings is indicated by the amount of drift occurring overnight and in 3 h, respectively.

RESULTS AND DISCUSSION

Figure 5 shows a number of creep curves taken at various temperatures and pressures. Creep deflection is given in mV output. Figure 6 shows a typical creep curve illustrating the effect of sudden pressure changes.

The curves in Fig. 5 are not smooth, but rather have regions of acceleration that give them a wavy appearance, suggestive of recrystallization.²⁸ The notion of

²⁸ D. Hardwich, C. M. Sellars, and W. J. McTegart, *J. Inst. Metals*, **90**, 21 (1961).

recrystallization was strengthened by the behavior of sample 20. After creep at room temperature and 5 kbar, similarly to the other samples, visual inspection of the surface showed the average grain size had been reduced to approximately 0.5 mm in the formerly monocrystalline region. Since recrystallization had occurred with such a large grain it is likely that recrystallization also took place in other samples, since finer-grained material, in general, recrystallizes more readily.⁶ The waves in the creep curve might be explained as follows: At various stages of creep, different points in the sample beam may reach strains sufficient to initiate recrystallization at the temperature and pressure of the experiment. The recrystallization might remove work hardening present in that region of the sample, resulting in an increase of the deformation rate. As

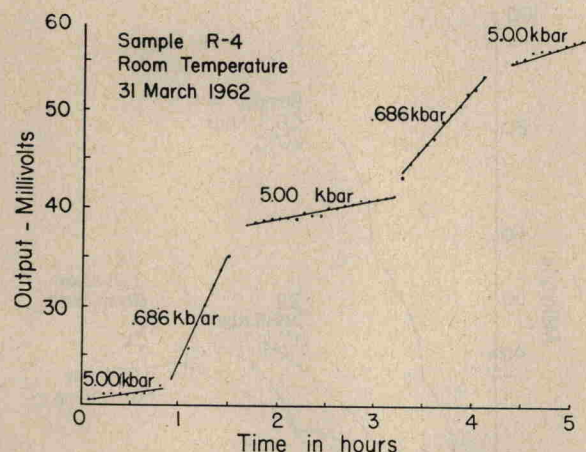


Fig. 6. Typical room temperature creep curve at various pressures (dotted curve). Solid line indicates "best" slope.

macroscopic strain proceeds, this process might be repeated at various places on the sample.

The wavy appearance of the creep curves made interpretation of data similar to that of Fig. 6 difficult and gave rise to quite a bit of scatter. A "best" slope from each of the intervals of Fig. 6 was determined, and these slopes plotted logarithmically against pressure for each sample. Studies were carried out at pressures up to 10 kbars. Equation (2) was used in the determination of the activation volume. In the use of this equation the creep rate in one pressure interval was compared with the average of the pressure intervals before and after it. This may tend to compensate for the change in stress with sample deflection. Figure 7 shows the activation volumes deduced for creep as a

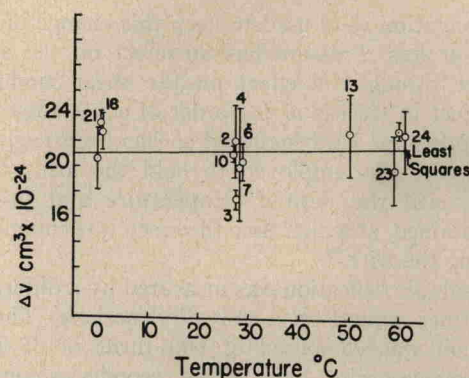


Fig. 7. Temperature dependence of activation volume. Figures indicated samples. Circles indicate average values for a given sample, error bars denote extreme values. Horizontal line represents least squares fit of all measurements.

function of temperature. The center point in each case was taken as the geometric means of the points for any given sample. The uncertainty brackets indicate maximum deviation from these means. The points of maximum deviation from the mean always occurred either early in the run where rather rapid work hardening was taking place, or very late on the creep curve where the curvature of the beam was large. The least-squares average of all the points is approximately $21 \times 10^{-24} \text{ cm}^3$ or about $\frac{2}{3}$ of the room temperature, room pressure atomic volume of $\sim 30.3 \times 10^{-24}$. If only the "well behaved" portions of each creep segment were used in the activation volume calculations, all points could be satisfied by $\Delta V^\ddagger = 21 \pm 4 \times 10^{-24} \text{ cm}^3$. Within the accuracy of these studies no change in activation volume with temperature was indicated.

Within experimental error the activation volume for creep determined in these experiments agrees with that for self-diffusion as determined by Nachtrieb, Resing, and Rice²³ at 253°C, and with those for creep at 70°C by Butcher and Ruoff¹⁷ who claim a greater accuracy. These results are then compatible with diffusion-controlled theories, such as vacancy climb and dragging along of jogs. The Nabarro-Herring^{9,10} mechanism can probably be eliminated because of rate considerations at these temperatures.

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