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STRAIN-AGING AND THE BAUSCHINGER EFFECT IN STEEL*

by

S. P. GUPTA, A. A. JOHNSON and S. P. KODALI**

ABSTRACT

The interaction of strain-aging and the Bauscinger effect has been studied in cylindrical mild steel specimens. Each specimen was prestrained 2% in compression at room temperature, subjected to an annealing treatment, and then strained in tension at room temperature. Isochronal annealing treatments, using an annealing time of one hour, revealed that, as the annealing temperature increased from room temperature to 150° C, the Bauschinger effect was almost completely eliminated. Isothermal studies showed that part of this effect occurred rapidly and part occurred over a period of hours. The proportion occurring rapidly increased with increasing annealing temperature.

Thus, these results show that the substantial reduction in some load bearing characteristics of a cold-formed mild steel structure caused by the Bauschinger effect can largely be removed by an annealing treatment at a moderate temperature. It has not yet been established whether this is also true for other types of steel.

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1. INTRODUCTION

Consider a steel tensile specimen which is tested at room temperature to a strain, ε , and flow stress, σ_F. If it is unloaded and then retested immediately it will begin to flow again at a stress very close to σ_F. If, however, it is tested the second time in compression rather than tension it will begin to flow at a stress, σ_B, which is considerably less than σ_F. A similar reduction in flow stress is observed if the first deformation is in compression and the second in tension. This effect, usually known as the "Bauschinger effect", has been known since 1881 (Bauschinger, 1881, 1886; 1886-7).

The Bauschinger effect is quite general in that it occurs in both polycrystalline metals and in single crystals. As far as the authors are aware it has been observed in all of the metals studied from this point of view. The literature on it has been reviewed by Thompson and Wadsworth (1958), Van Beuren (1961) and others. References pertaining specifically to steels are given in a recent paper on the Bauschinger effect in a high strength steel by Jamieson and Hood (1971). A review of the literature on the Bauschinger effect reveals that very little is known about the effects of an annealing treatment interjected between the tensile and compressive deformation treatments For this reason we are in the process of studying the effects of such annealing treatments in a variety of materials. For this conference on cold-formed steel we choose to report some of our work on a mild steel. We shall report our work in terms of engineering results without discussing the underlying physical mechanisms. These mechanisms will be dealt with in a later publication in the physical metallurgy literature.

2. SPECIMEN PREPARATION AND TESTING

The starting material for the investigation was mild steel in the form of 0.75 inch diameter rod supplied by Joseph T. Ryerson and Son Inc. According to the manufacturers, this steel contained 0.18 to 0.20 wt. % carbon, 0.6 to 0.9 wt. % manganese, 0.04 wt. % phosphorus, and 0.05 wt. % sulphur. Chemical analyses carried out for the authors at the Bridgeport Testing Laboratory gave values for the carbon, oxygen and nitrogen contents of the material of 0.22 wt. %, 0.005 to 0.028 wt. %, and 0.001 to 0.004 wt. % respectively.

Tensile specimens with threaded shoulders having gauge lengths of 2.00 inches and gauge diameters of 0.50 inch were machined from the starting material. The specimens were annealed for one hour at 1000^0 C in a nitrogen atmosphere, furnace cooled to 600^0 C, and then air cooled to room temperature. The nitrided surface layer was then removed with a fine grade of emergy paper. Metallographic examination revealed that the grain size was 25 to 30 μ and did not vary significantly from one specimen to another. The microstructure consisted of ferrite with colonies of coarse pearlite at the grain boundaries.

The testing was carried out on an Instron machine using a compression cell and specially designed grips appropriate for both compression and tension. All of the testing was performed at room temperature using a strain-rate of 3.33×10^{-4} $\sec^{-1}$. In a typical experiment a specimen was compressed to a plastic strain of 2% and then immediately removed from the machine and placed in an oil bath preheated to the desired annealing temperature. After an appropriate time at this temperature it was then quenched into a mixture of ice and water, cleaned with acetone, dried, and finally tested in tension to a strain of a few percent.

3. RESULTS

One of the load-compression curves obtained in the course of precompressing all of the specimens is shown in Figure (1). It shows a sharp yield point and an irregular Luders strain preceding the work-hardening part of the curve. This type of behaviour is of course characteristic of mild steel and other body-centered cubic metals. The average lower yield stress obtained from these precompression curves was 20.55 kg. mm^{-2} with an r.m.s. deviation of ± 0.1 kg mm^{-2}. The average value of the flow stress at the end of the 2% precompression was 25.60 kg mm^{-2} with a r.m.s. deviation of ± 1.5 kg mm^{-2}.

In our first series of experiments the annealing time was held constant at one hour and the annealing temperature was varied from room temperature to 270° C. The load-elongation curves obtained by subsequent testing of these specimens at room temperature are shown in Figures (2a) and (2b). It will be seen that the yield point began to return at an annealing temperature of 100° C. If the proporational limit for those specimens that do not show a yield point and the proporational limit for those that did are plotted against annealing temperature (Figure 3) it is at once apparent that the proportional limit or yield stress increases rapidly with increasing annealing temperature. The yield stress reaches a maximum at about 150° C at a value which is higher than the yield stress of a virgin specimen but slightly lower than the flow stress reached at the end of the precompression treatment. Thus annealing for one hour at 150° C almost completely removes the Bauschinger effect in this material.

In a second series of experiments the isothermal recovery of the Bauschir effect was studied at 102°, 112°, 127° and 147° C (Figure 4). From these results it is clear that the recovery occurs in two stages. The first stage is either instantaneous or very rapid and the amount of recovery increases with increasing annealing temperature. At 147^{o} C nearly all of the recovery is first stage recovery and occurs within ten minutes at most. The results are not sufficiently detailed to tell us whether the recovery occurs gradually over this ten minute period or suddenly as soon as the temperature is raised. During the second stage the yield stress continues to rise slowly with time and, at least for the lower annealing temperatures, continues for several hours. All of the results shown in Figure (4) pertain to the lower yield stress since all of the specimens exhibited yield points.

4. DISCUSSION

The importance and immediate applicability of these results in the field of cold-formed steel structures is self evident. Whenever a piece of steel is cold-formed the load bearing capacity of the cold formed structure when subjected to stresses tending to reverse the plastic deformation carried out during cold forming is limited by the Bauschinger effect. It now seems that, at least in the case of mild steel, this load bearing capacity can be substantially improved by a moderate heat treatment that can be applied even to quite large structures.

As an extremely simple example we may consider a cylindrical rod which is cold formed into a "U" shape. If stresses are applied to the rod in such a way that they tend to open up the "U" the stresses which can be sustained before plastic deformation starts are determined by the Bauschinger effect. If the "U" is made from mild steel these stresses can be substantially increased by eliminating the Bauschinger by means of a heat treatment. Another example occurs in the manufacture of steel by rolling sheet into a cylinder and welding the edges together. The final operation is frequently the "sizing" of the pipe by applying an extrenal pressure until it conforms to the shape of an internal mandril. This operation has the effect of reducing considerably the internal hydrostatic pressure at which the pipe begins to bulge. This has been recognized for some time and to some extent our work has been anticipated by Snow and Pegues (1967) who holds a patent on an annealing process for improving the strength of steel pipe sized in this manner. The reader can no doubt think of many other manufacturing and construction procedures which potentially can be improved by the use of an annealing treatment to remove the Bauschinger effect.

The temperature range in which we have observed the elimination of the Bauschinger effect is of course the same temperature range as that for strain aging in mild steel. It therefore seems possible, and indeed likely, that the two effects are associated. In view of this it is clearly necessary to continue our work and find out whether the elimination of the Bauschinger effect occurs concurrently with strain aging in other body-centered cubic metals, including other steels. If it does one might expect that the effect would be absent in other materials, such as pure face-centered cubic metals, which do not exhibit strain-aging. We are currently extending our studies to include both of these classes of materials.

5. ACKNOWLEDGEMENTS

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SUMMARY

Cylindrical specimens of mild steel were prestrained 2% in compression, subjected to various heat treatments, and then strained in tension at room temperature. It was found that an appropriate heat treatment, e.g. one hour at 150° C, almost eliminated the Bauschinger effect.

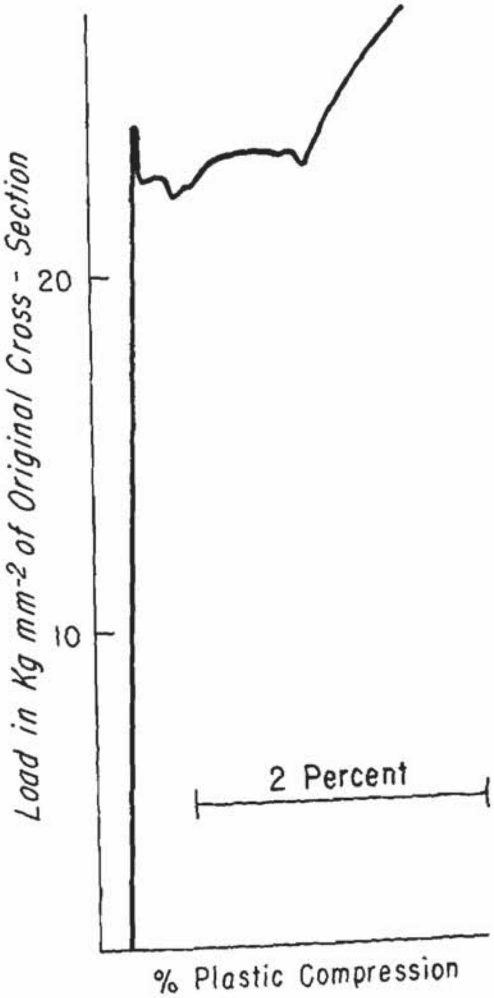

Figure (1) A typical load-compression curve obtained during the precompression of a mild steel specimen at room temperature.

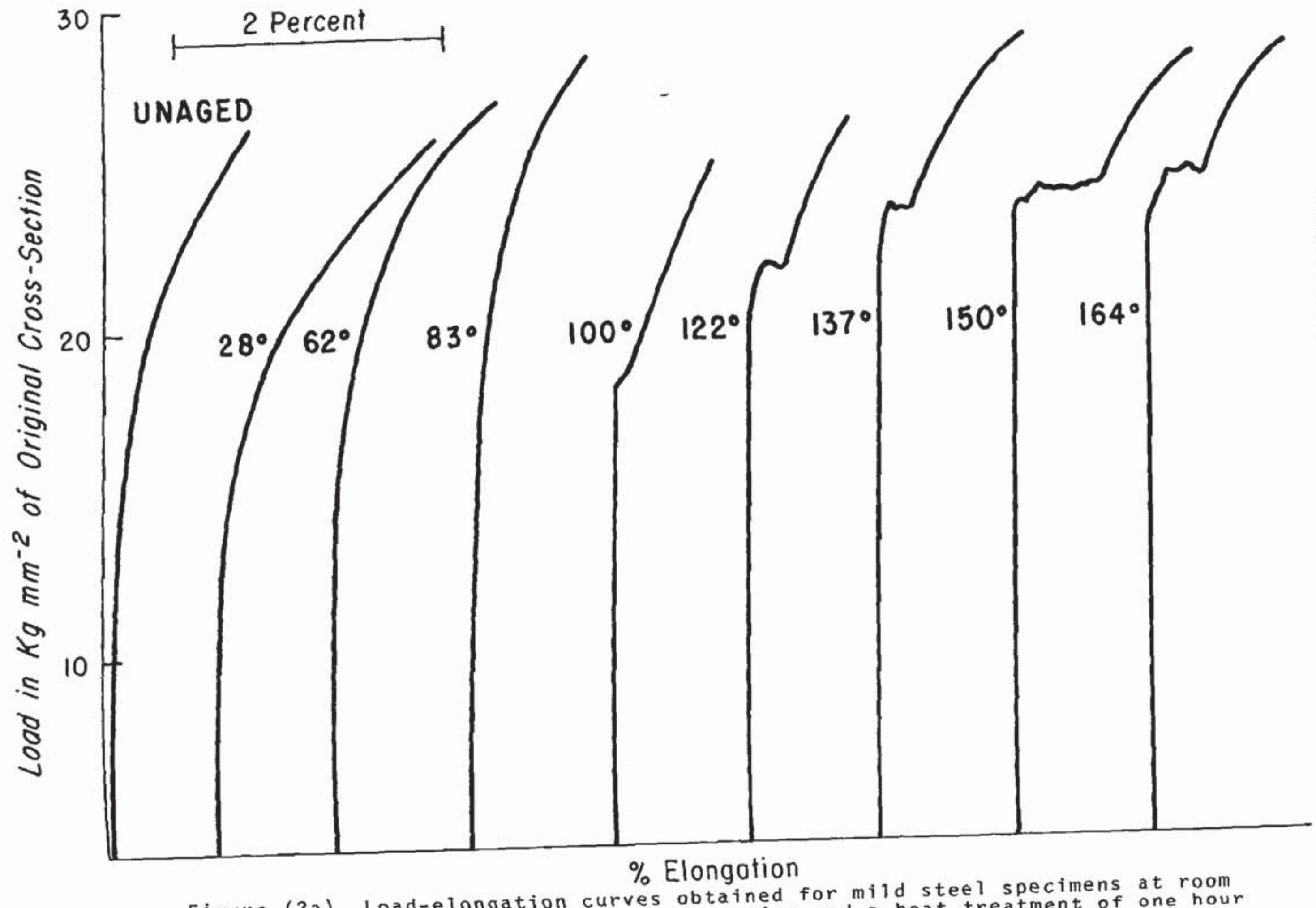

Figure (2a) Load-elongation curves obtained for mild steel specimens at room temperature after precompression and a heat treatment of one hour

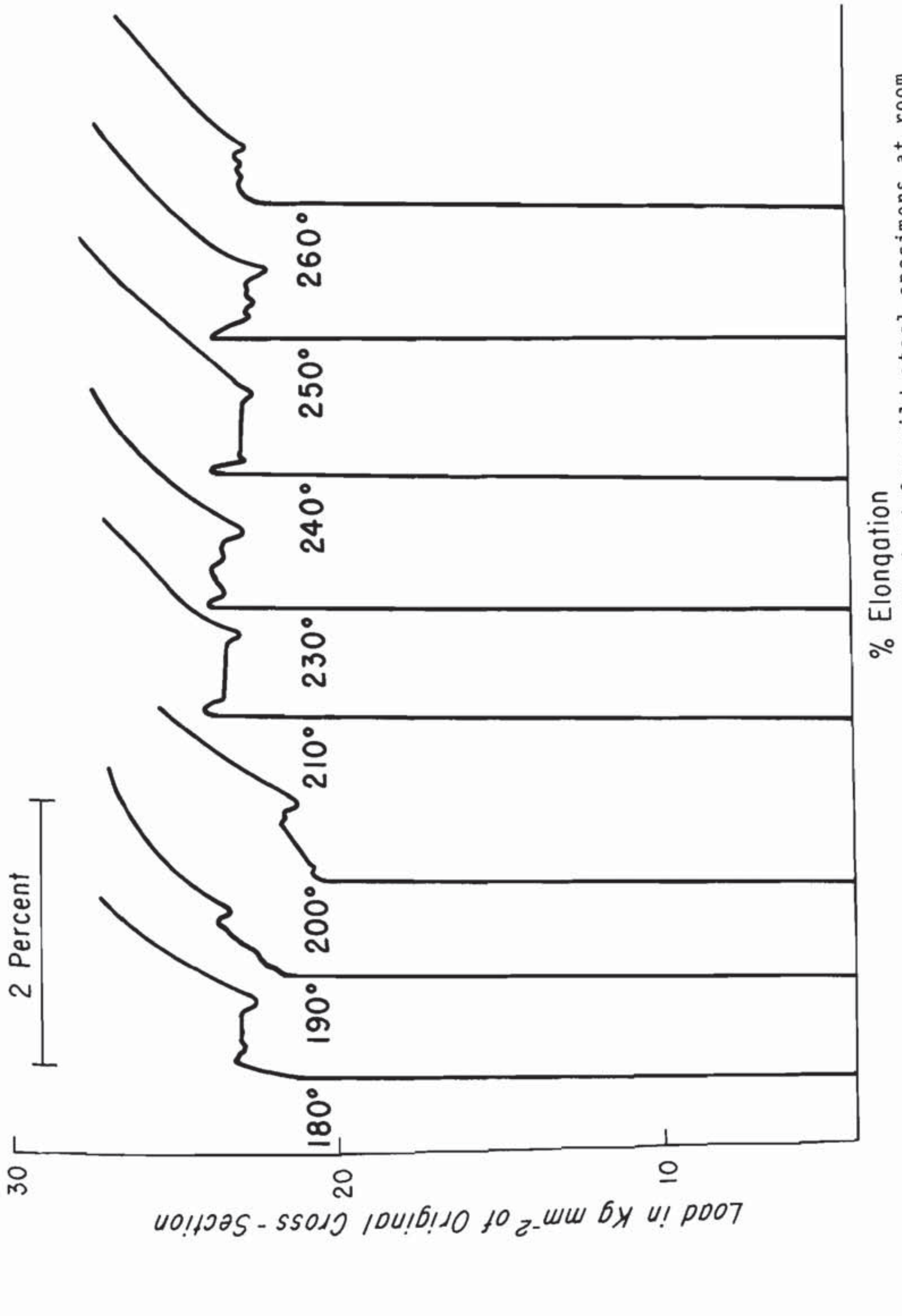

Figure (2b) Load-elongation curves obtained for mild steel specimens at room temperature after precompression and a heat treatment of one hour at the temperatures indicated (All temperatures are in °C).

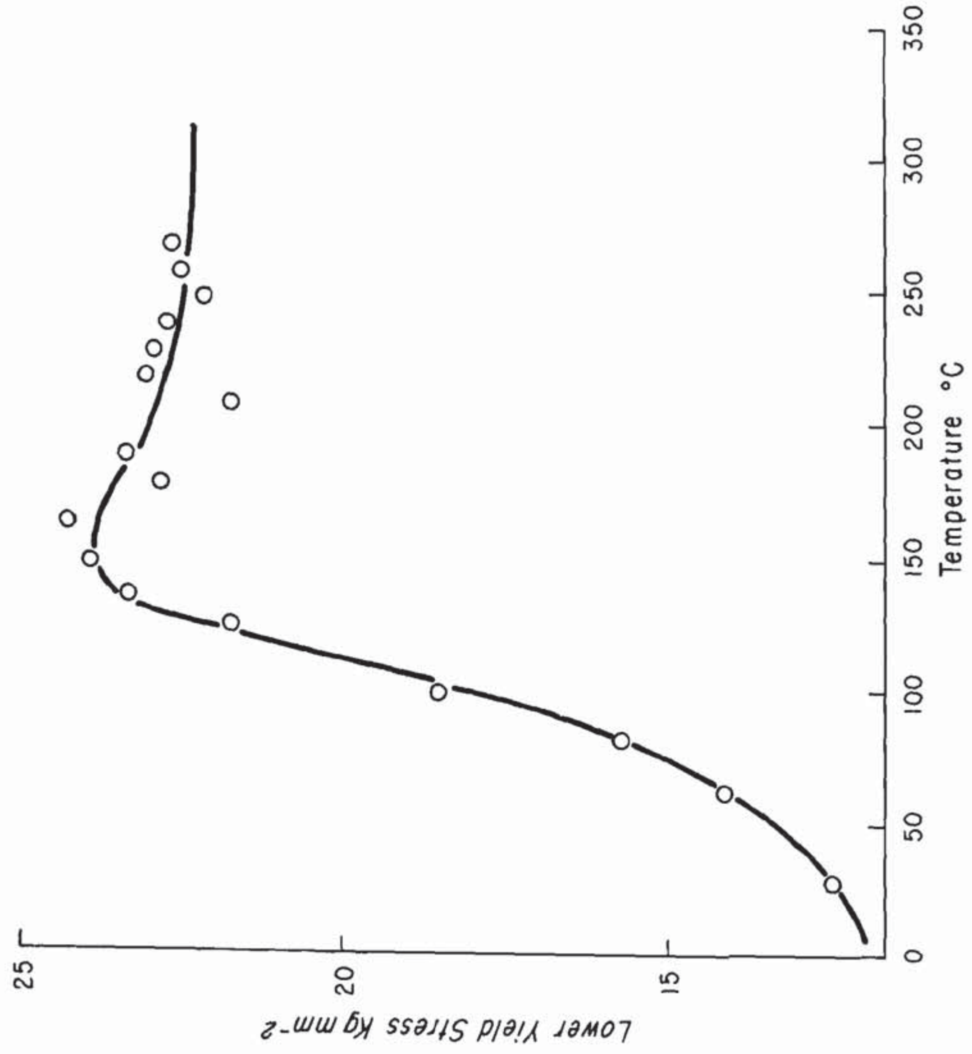

Figure (3) An isochronal aging curve obtained by plotting room temperature yield stress against aging temperature. The aging time was one hour in each case.

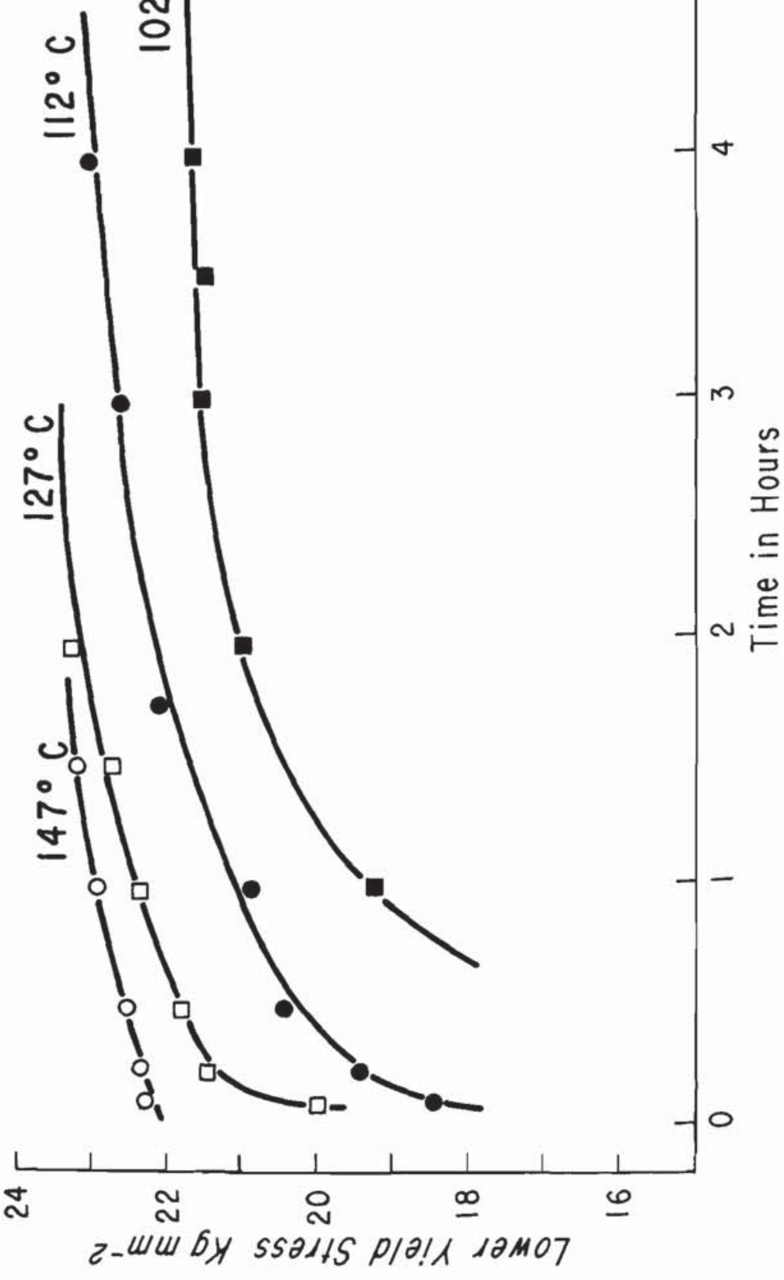

Figure (4) Isothermal aging curves for specimens precompressed at room temperature and then aged at the temperature indicated.