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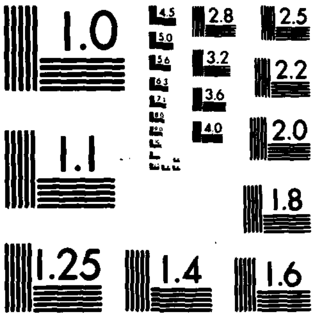

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CHANGES IN RESIDUAL STRESSES DURING TENSION FATIGUE OF NORMALIZED AND PEENED SAE 1040 STEEL.

by

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(10) M. McClinton ~~and~~ J. B. Cohen

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Changes in Residual Stresses During Tension Fatigue of Normalized and Peened SAE 1040 Steel

by

M. McClinton[+] and J. B. Cohen[o]

ABSTRACT

Appreciable compressive stresses develop during tensile fatigue (R=0) of normalized SAE 1040 steel, but only in or near regions of stress localization. These stresses develop in stages. After shot peening, the resultant compressive stresses are rapidly eliminated by tension-tension fatigue above the endurance limit, and replaced by tensile stresses. At lower stress levels the induced stresses fade quickly.

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INTRODUCTION

It is now well known (but often ignored!) that residual stresses develop during fatigue of well annealed specimens of most metals and alloys. Compressive or tensile stresses are formed, apparently depending on the mode of testing. For example, tensile stresses occur in impact fatigue,(1) but compressive stresses arise in reverse bending.(2,3) In fact, in low-cycle fatigue, the sign of the stress is opposite to the sign of the load before this load is released, and reverses every half cycle(4,6) (in fully reversed axial loading). For stresses below the endurance limit, stress concentrators, such as second-phase particles or grain junctions can cause such changes; the residual stress forms early in the test and subsequentally is constant. At higher applied stresses, the residual stresses increase and then decrease well before failure.(1,2) These induced stresses can develop without any appreciable slip band formation.(1)

Surface treatment is often employed to produce compressive residual stresses, as such stresses are thought to improve fatigue life. But the results are not completely clear. For soft steels, plastic deformation in the near-surface regions appears to be the primary cause of this increase (not the residual stresses), whereas for hardened steels, the residual stress is the main factor.(7) In axial loading of Al alloys, this improvement is primarily in the low cycle regime, with no effect (or decreased life) in the high cycle regime.(8,9) These induced stresses are altered during fatigue.(10-15) It is generally accepted that the stress "fades", the more rapidly the higher the applied stress, and the less steep is the stress gradient.(16,17) All detailed studies of fading have so far been carried out in a bending mode. (Tests in uniaxial loading under strain control were used to simulate residual stresses, in ref. 18, by altering the strain limits. Under such conditions the "residual stress" will obviously vanish as the specimen lengthens. Also, in such simulations, the induced stress is uniform across the cross-section, but this is not the case with actual residual stresses.)

The rate of fading sometimes depends on the sign of the residual stress,(15,19) but sometimes does not.(20) Stress relief should depend on the sum of applied and residual shear stresses; if the residual stress is isotropic in the surface, it cannot contribute.(21) Unfortunately, whether or not the stress was isotropic was not checked in most studies. There is also one case (316 stainless steel, tension-tension fatigue) in which initial compressive stresses (the source was not reported) were quickly replaced by tensile stresses.(22)

Surface treatments like peening lead to subsurface cracking in fatigue(8) and the maximum compressive stress (which is below the surface) gradually moves into the specimen during fading.(10)

It is the purpose of this paper to examine the changes in residual stress during fatigue of both a normalized and normalized and peened plain carbon steel, in tension-tension fatigue. This is the first stage of a study of fading in steels.

EXPERIMENTAL PROCEDURES

Specimens

Hot rolled SAE 1040 steel plate was normalized by heating at 1145° K for 30 min. and air cooling. Flat fatigue specimens were cut from this plate, 6.4 mm thick 90 mm long (in the rolling direction) and 25 mm wide. The gage section was 9 mm long, 6 mm wide, with a 6.35 mm radius joining to the grip sections. These specimens were milled to remove oxide and the decarburized zone, then polished through 600 grit paper. The resultant surface residual stress was - 372 MPa (-54 ksi). A subsequent anneal for 1 hr. at 973° K in Argon followed by furnace cooling, resulted in a near zero value of stress. Some of these specimens were shot peened for 45 seconds (on both sides) with 230 grit steel shot; the nozzle was 100 mm from a specimen and the air pressure was 90 Psi. The Almen value was 0.0343. The resultant profile of residual stress is shown in Fig. 1. The mechanical properties of both types of specimen are given in Table I.

The endurance limit for this steel is available only for fully reversed loading. For the tension-tension fatigue employed in this study the limit was estimated from Table I by Goodman's method.(23) Gerber's approach(24) yields values ~ 20 pct higher, while Soderberg's(25) results in values ~ 30 pct lower. Results will be reported in terms of the load as a fraction of the static yield stress, with this estimate of the fraction of the endurance limit in parentheses.

Fatigue Equipment

Cyclic loading was carried out on an MTS servo-hydraulic machine, in load control at 50 Hz. The wave form was sinusoidal, with $R = 0$, and a maximum stress ranging from 263 to 414 MPa. In some cases, hysterisis loops were recorded, to establish the onset of permanent strain.

X-ray Measurements

An automated Picker X-ray diffractometer was employed, with (line focussed) CoK_α radiation and the 310 peak. The divergence was 0.4 - 1°, and a stationary receiving slit was employed, 0.5 mm wide. Stresses were obtained via an on-line minicomputer control system,(26) employing a five point parabolic fit to the top 15 pct of a peak, and six ψ tilts (to 45°). The stress was obtained parallel to the long direction.

There was only slight curvature in the interplanar spacing$^{(d)}$ vs $\sin^2\psi$, which indicates there were no appreciable changes in stress over the penetration depth of the x-ray beam.(27) The correlation coefficient for a least-squares line (d vs $\sin^2\psi$) was typically 0.99 or better. Repeated measurements showed that the stress was measured with a reproducibility of 3 - 10 pct.

RESULTS

As normalized

Plastic strain ($\sim 3 \times 10^{-5}$) was detected after 10^6 cycles at or above a maximum stress of 296 MPa, 0.7 (0.92) of the yield. No significant stresses developed below 0.61 (0.77) yield, even after 5×10^6 cycles. Fig. 2 gives results on the changes in residual stress vs number of cycles at increasing stress levels. In fig. 3, results are given on changes in the shape of the x-ray peaks. For both shape and stresses there are stages in the changes, but these occur at different numbers of cycles. (Such stages for the breadth, but not the stresses, have been reported previously (28).)

Up to and including loads of 0.73 (0.92) of the yield, the specimen's surface is identical to an untested piece under the optical microscope, and only small compressive stresses develop. At 0.92 σ_y (1.16), Fig. 3b, between 0 and 5000 cycles, a specimen is still smooth. But beyond this point, regions of strain localization develop, and there is a sharp increase in the residual stress, but only in or near such regions. The deformation markings are spread over the entire specimen near the plateau in residual stress at this load. A fourth stage occurs at $\sigma = 1.01\ \sigma_y (1.28)$, with no additional unusual changes in the surface appearance, and just prior to failure at 1.8×10^6 cycles.

Etching revealed that these compressive stresses extended (unchanged) to at least 0.8 mm below the surface.

Shot Peened Condition

The results for residual stress are given in Fig. 4. There is some slight fading even well below the endurance limit, Fig. 4a, which is very much more pronounced near the limit, Fig. 4b. At $\sigma = 0.96\ \sigma_y (1.16)$, the compressive stress is eliminated quite early in the life and replaced by a tensile residual stress. Failure occurs at $\approx$ 115,000 cycles. The stress profile in this regime is illustrated in Fig. 5. Comparing this figure to Fig. 1, it is clear that the original profile has been completely changed; tensile stresses now extend to $\approx$ 0.1 mm.

The x-ray peak's width decreases linearly (from $\sim 3.6^\circ$) with cycles, with a slope which increases with load. However, even at the highest loads examined in this study, the breadth near failure is $\sim 2.8^\circ\ 2\theta$, compared to an annealed value of 0.6° and 0.9° after fatigue of annealed specimens (Fig. 3c).

DISCUSSION

The principal results of this study are:

1) In annealed (soft) steel, appreciable compressive stresses develop in tension-tension fatigue, but only in regions of strain localization.

2) This stress (as well as line broadening) develops in stages.

3) In shot peened steel, the surface compressive stress is replaced by tensile stresses very early in fatigue, at stress levels just above the endurance limit.

4) This stress reversion occurs over appreciable depths.

5) Appreciable fading occurs at lower stress levels.

We consider first the unpeened steel. Weissmann and Kramer(29) have demonstrated that the surface of many materials exhibits considerably more x-ray line broadening than the interior, implying that there is considerably more deformation in this region. This greater strain under a fixed load could be due to a lower yield stress (due to the biaxial nature of the strains in this region) or due to greater work hardening. In either case, the stress-strain curve in a local region under stress controlled fatigue can be illustrated schematically as in Fig. 6a. When the load is released, the near-surface regions are more extended than the bulk and are put into compression. After shot peening, the stress strain curves of a local region are reversed, as shown in Fig. 6b, and the surface is placed in tension, as observed here. This simple model appears to provide a suitable rationalization of the results. It should be kept in mind that these stress strain curves are for local regions. The fact that there are regions of strain localization, and x-ray line broadening, implies that strains vary from point to point, so that it is possible for there to be a difference in total displacement from one region to another.

The drastic decrease in fatigue life in tension due to peening reported here may be in part due to the tensile stresses, but there is undoubtedly a contribution due to the roughened surface.

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Mr. W. P. Evans, Caterpillar Tractor Co. graciously performed the shot peening. This research was supported by the Office of Naval Research. The X-ray measurements were carried out in the X-ray Facility at Northwestern University, supported in part by the NSF-MRL program under grant No. DMR-76-80847. Portions of this study were presented (by M. M.) in partial fulfillment of the requirements for the M. S. degree in the Materials Science and Engineering Department, Northwestern University.

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FIGURE CAPTIONS

Fig. 1	Stress profile of shot peened 1040 steel. Layers were removed by chemical etching (100 pts 30% H_2O_2, 10 pts 48% HF).
Fig. 2a	Residual stress vs. cycles at σ_{max} = .73 (0.92) of the static yield stress, normalized 1040 steel.
b	Residual stress vs. cycles at σ_{max} = 92 (1.16) of the static yield stress, normalized 1040 steel. The two symbols represent two different specimens cycled under indentical conditions. Points with a horizontal cross mark indicate repeated residual stress measurements at different locations on the same specimen.
c	Residual stress vs. cycles at σ_{max} = 1.01 (1.28) of the static yield stress, normalized 1040 steel. Points with a vertical cross indicate repeated residual stress measurements.
Fig. 3a	Peak width vs. cycles at .92 (1.16) of the static yield stress, normalized 1040 steel.
b	Peak width vs. cycles at 1.01 (1.28) of the static yield stress, normalized 1040 steel.
Fig. 4a	Residual stress vs. cycles for shot peened specimen, σ_{max} = .62 (.75) of the yield stress.
b	Residual stress vs. cycles for shot peened specimen, σ_{max} = .79 (.95) of the yield stress.
c	Residual stress vs. cycles for shot peened specimen, σ_{max} = .96 (1.16) of the yield stress.
Fig. 5	Stress profile of shot peened specimen after 800 cycles at .96 (1.16) of the yield stress.
Fig. 6a	A hypothetical stress vs. strain curve, comparing the response of the surface and interior of an annealed steel.
b	A hypothetical stress vs. strain curve, comparing the response of the surface and interior of a shot peened steel.

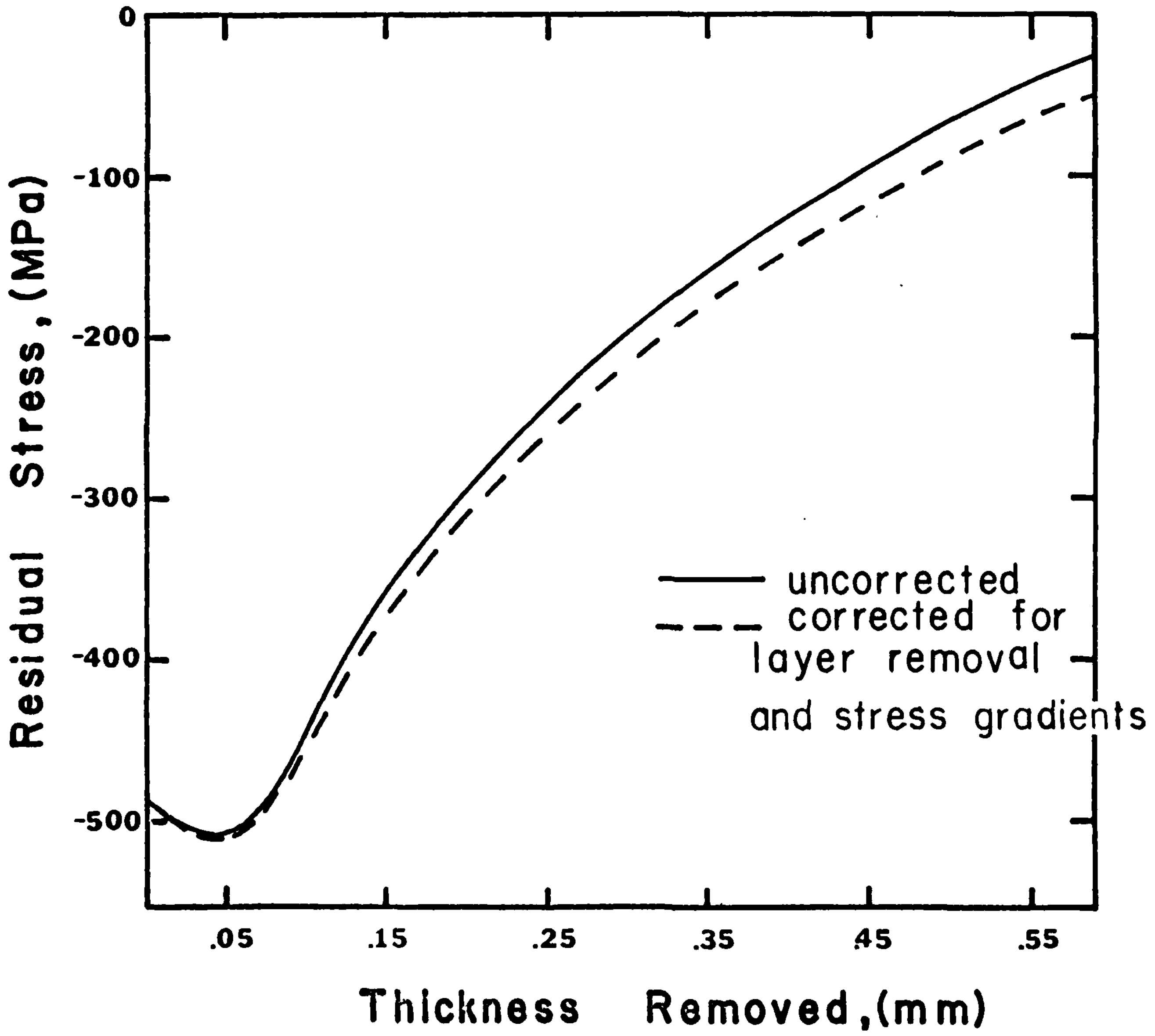

FIG. 1

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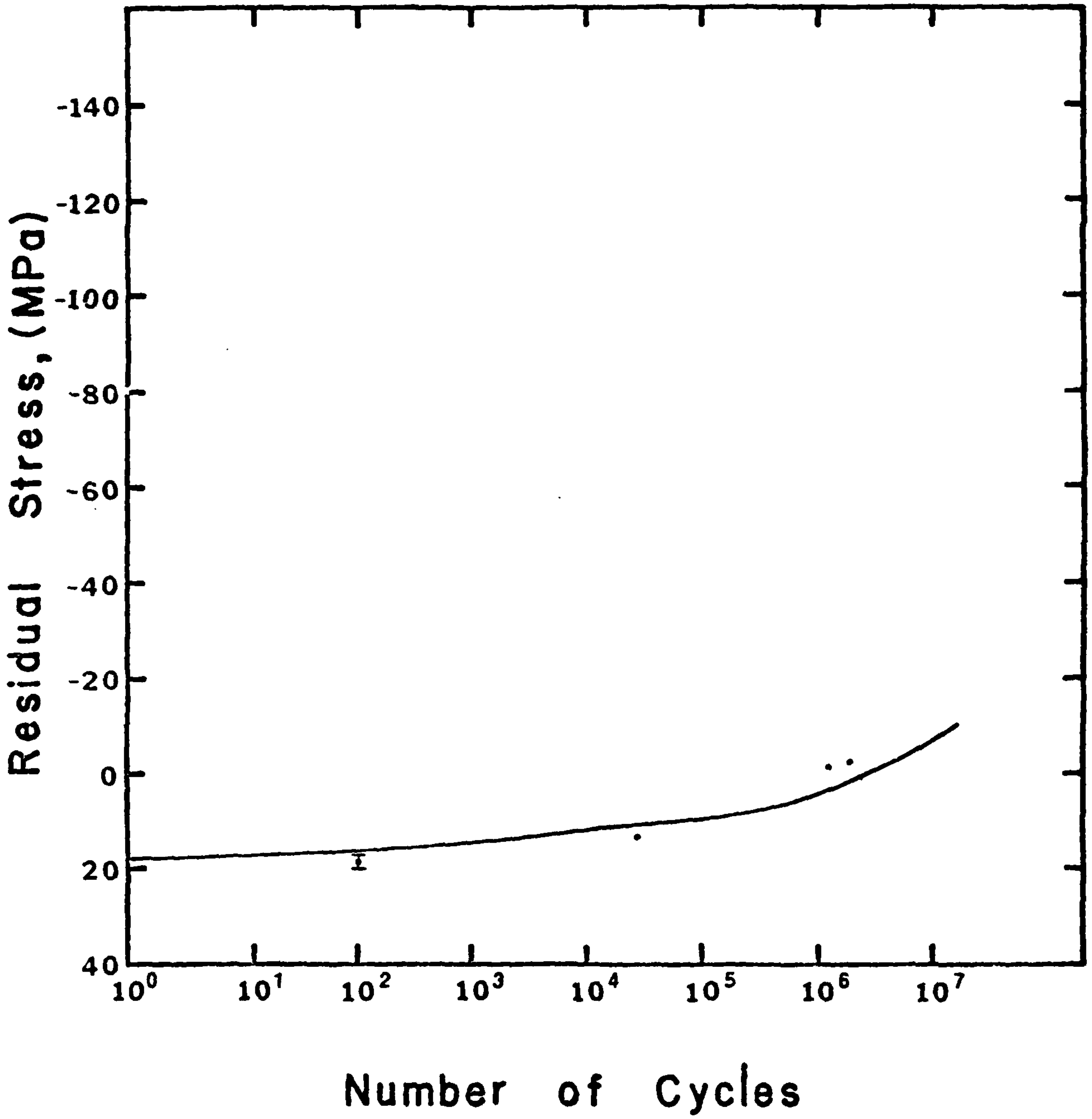

FIG. 2a

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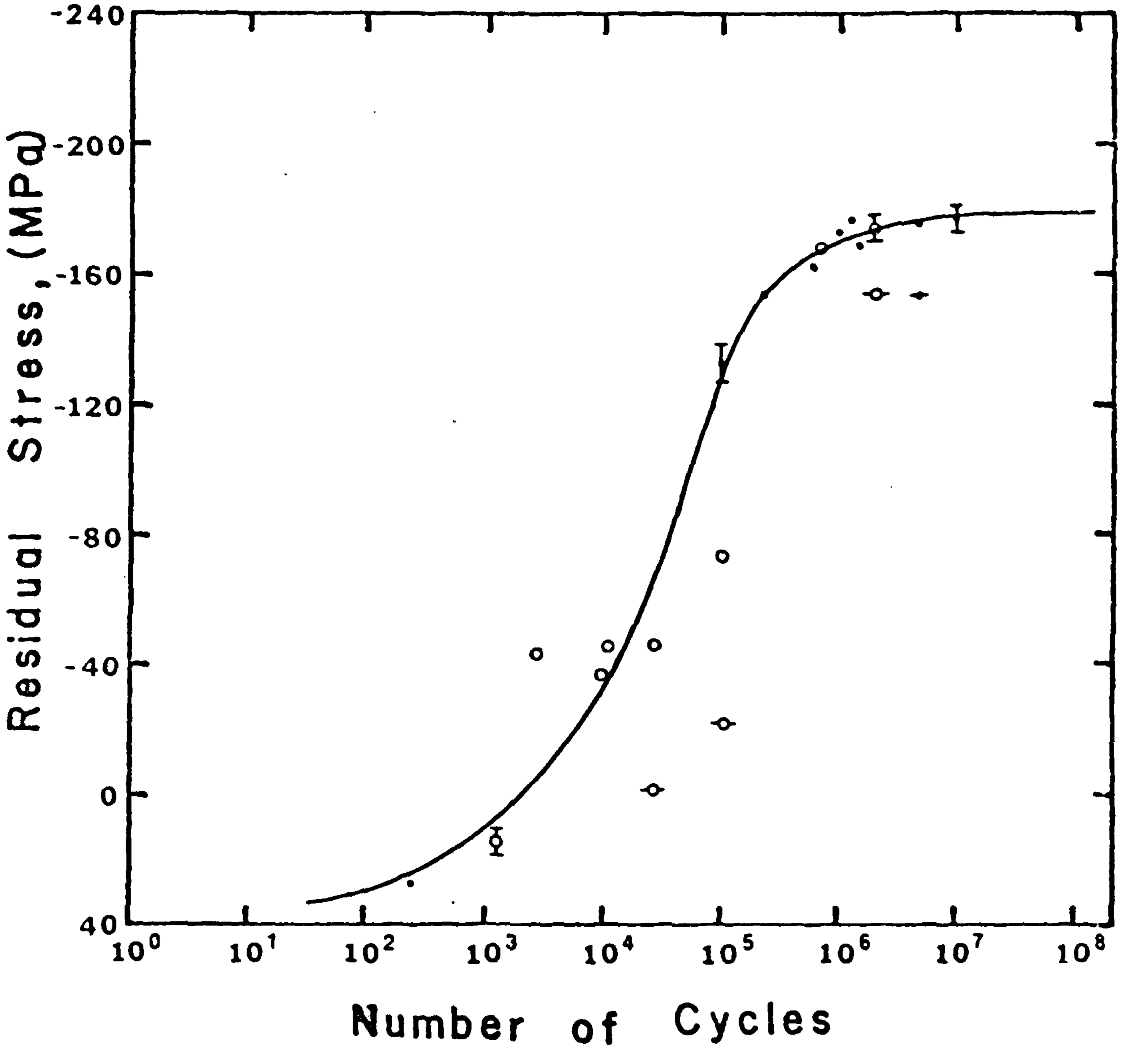

FIG. 2b

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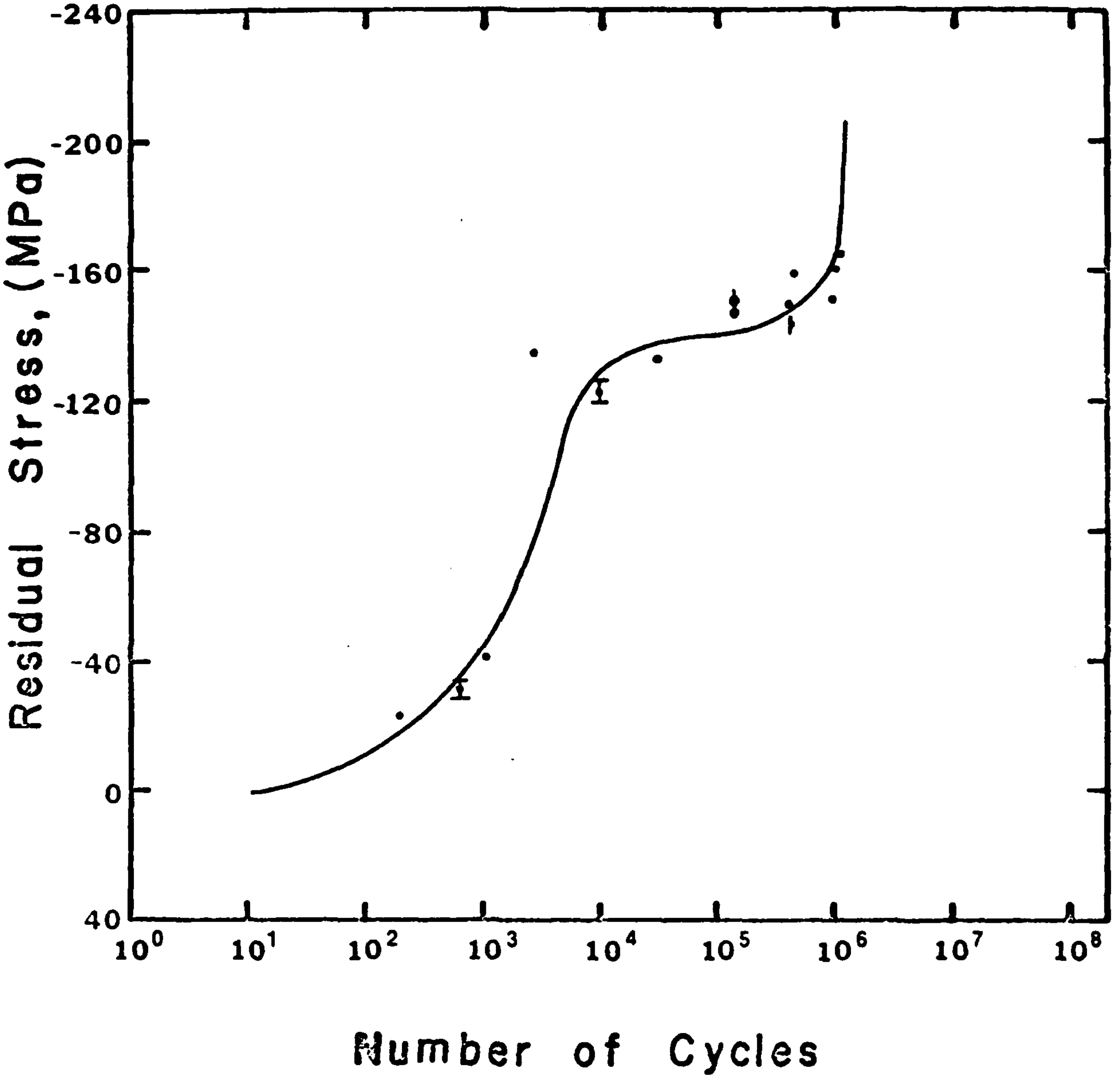

FIG. 2c

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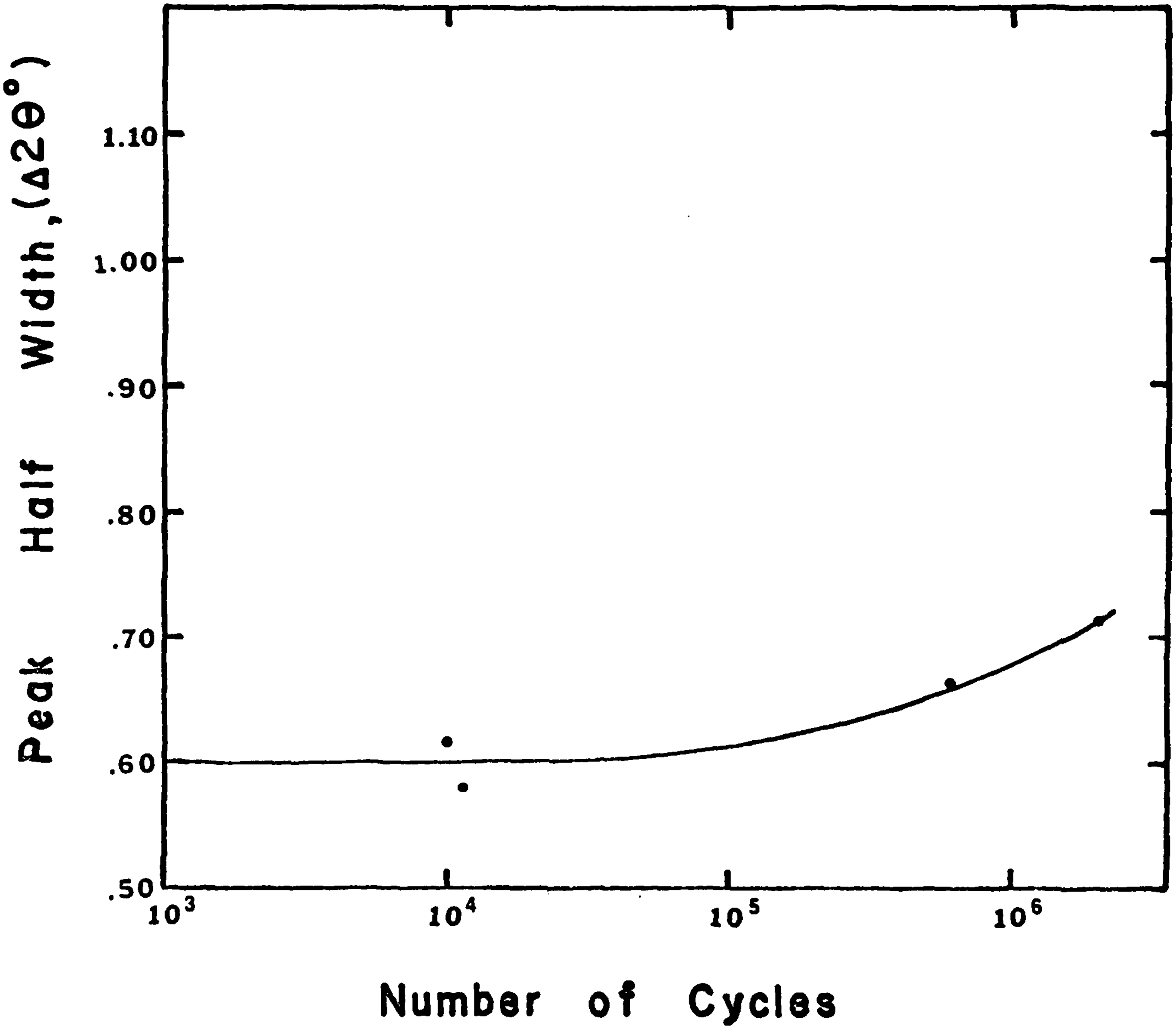

FIG. 3a

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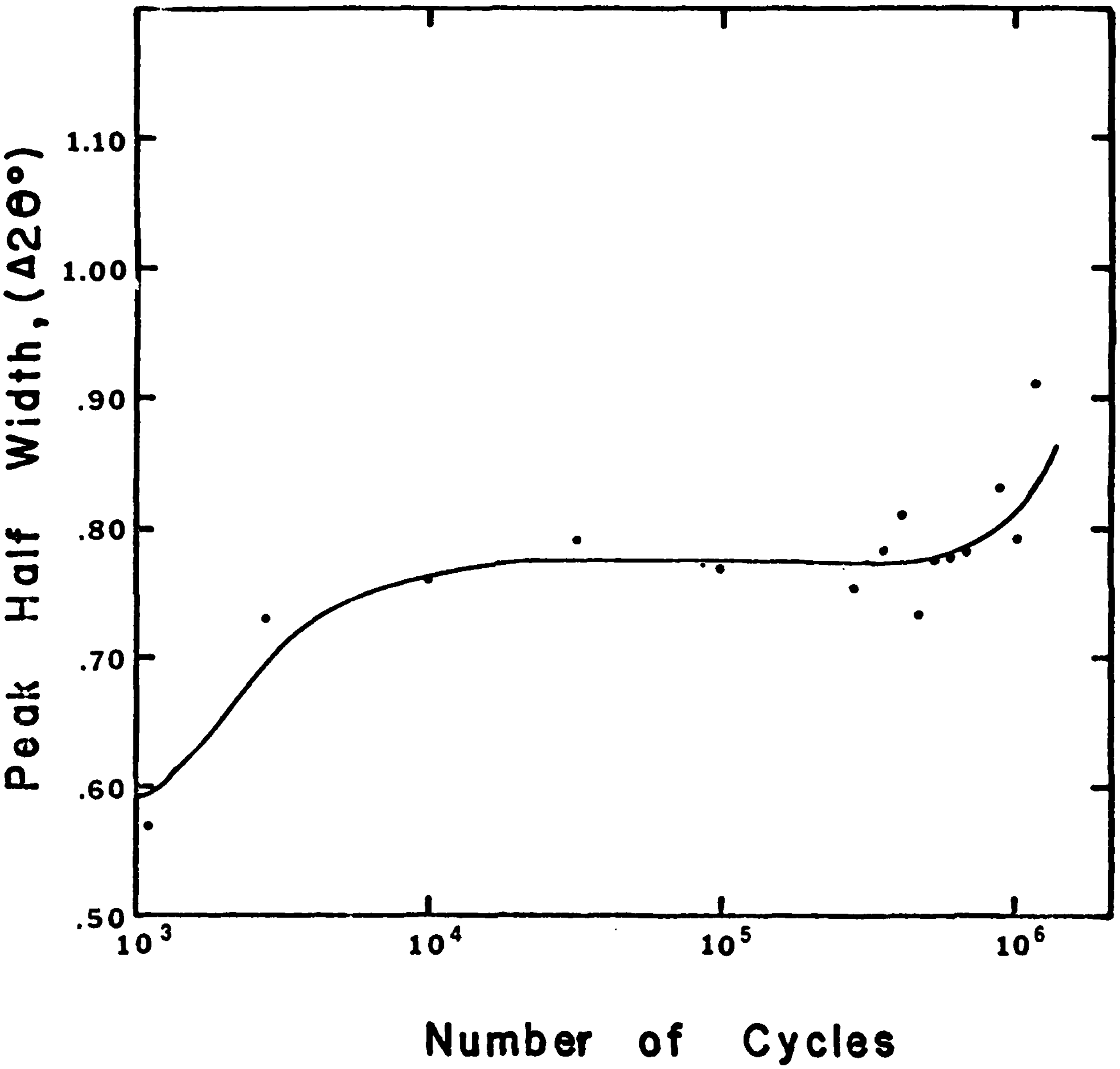

FIG. 3b

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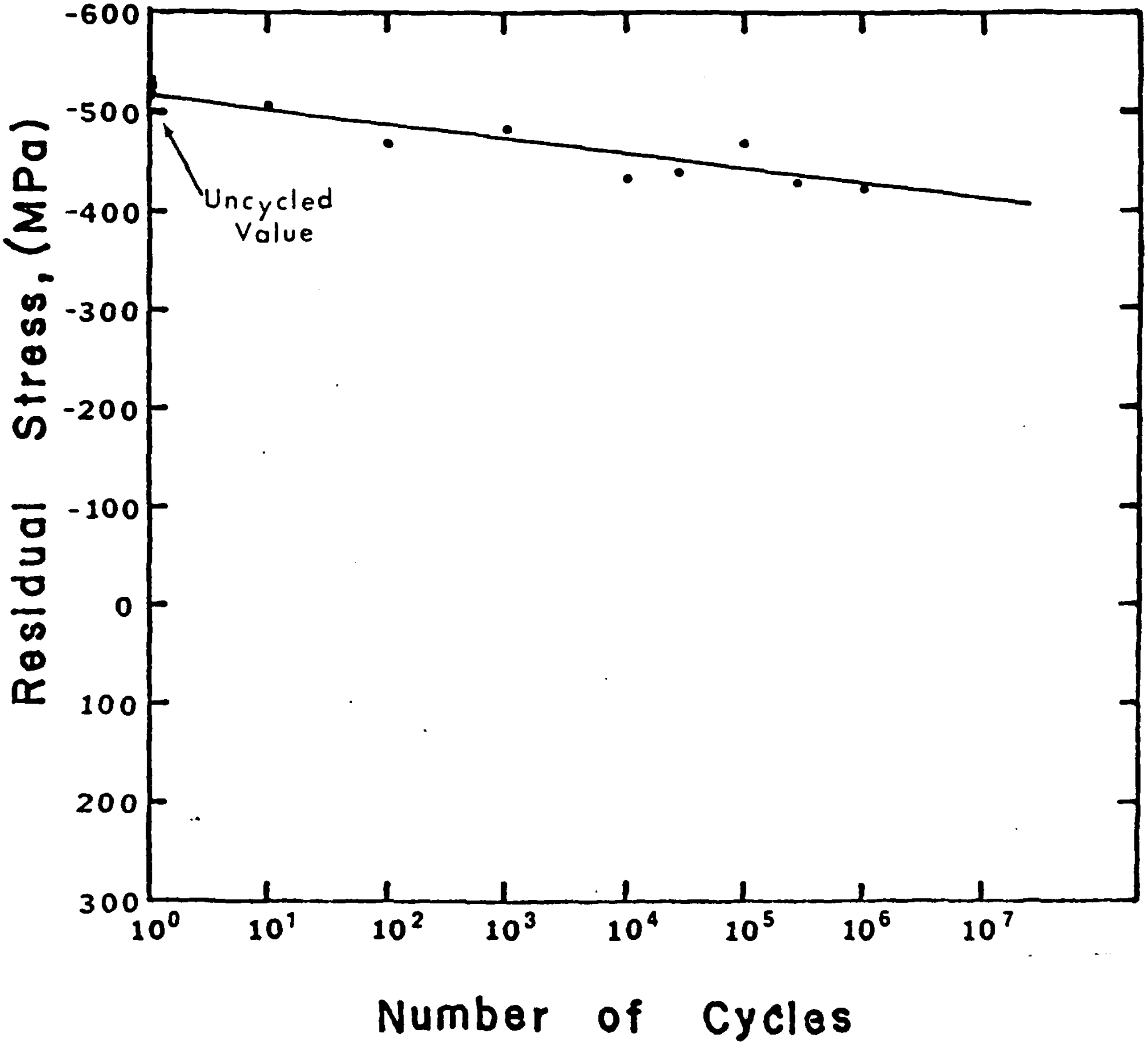

FIG. 4a

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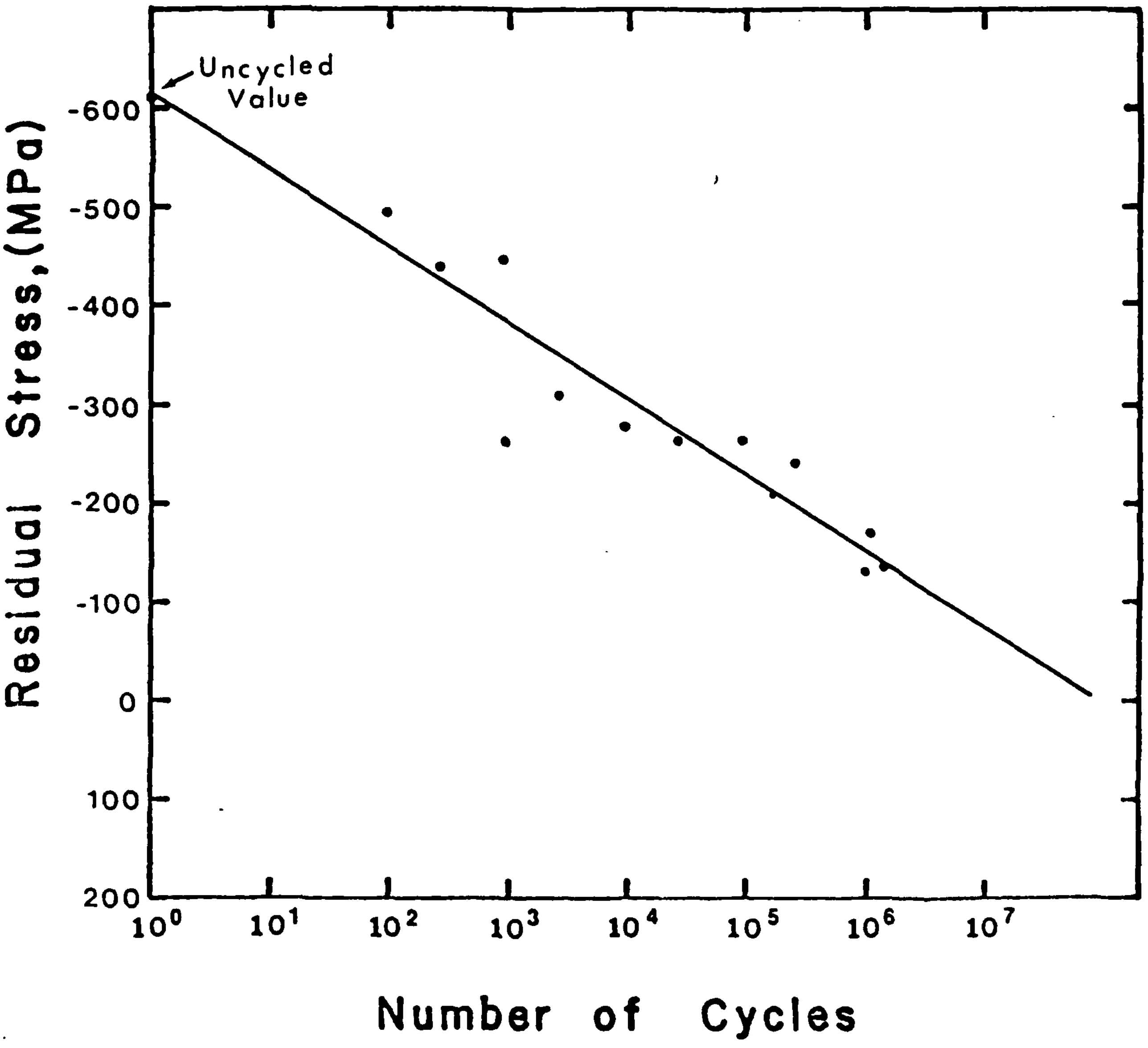

FIG. 4b

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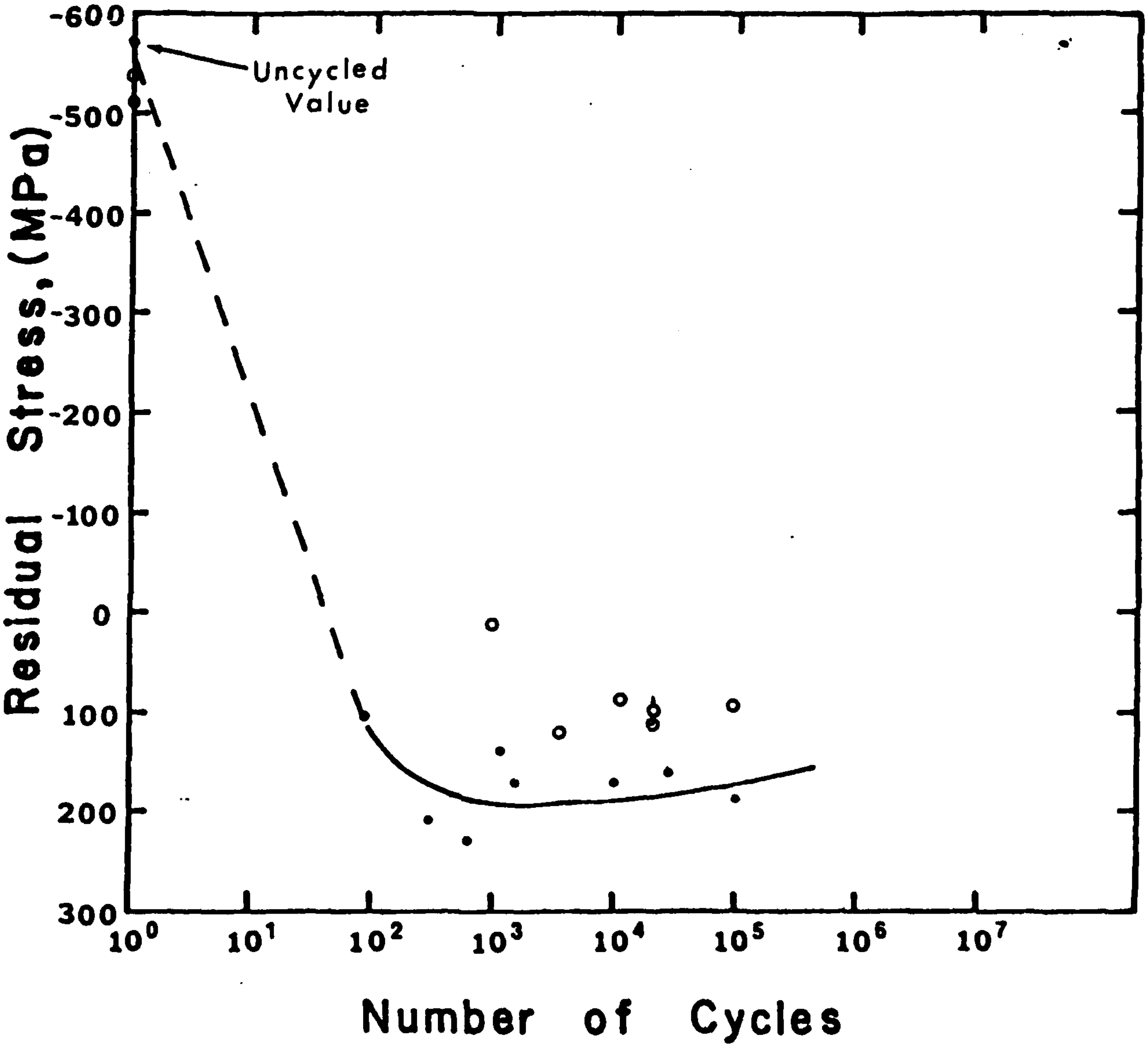

FIG. 4c

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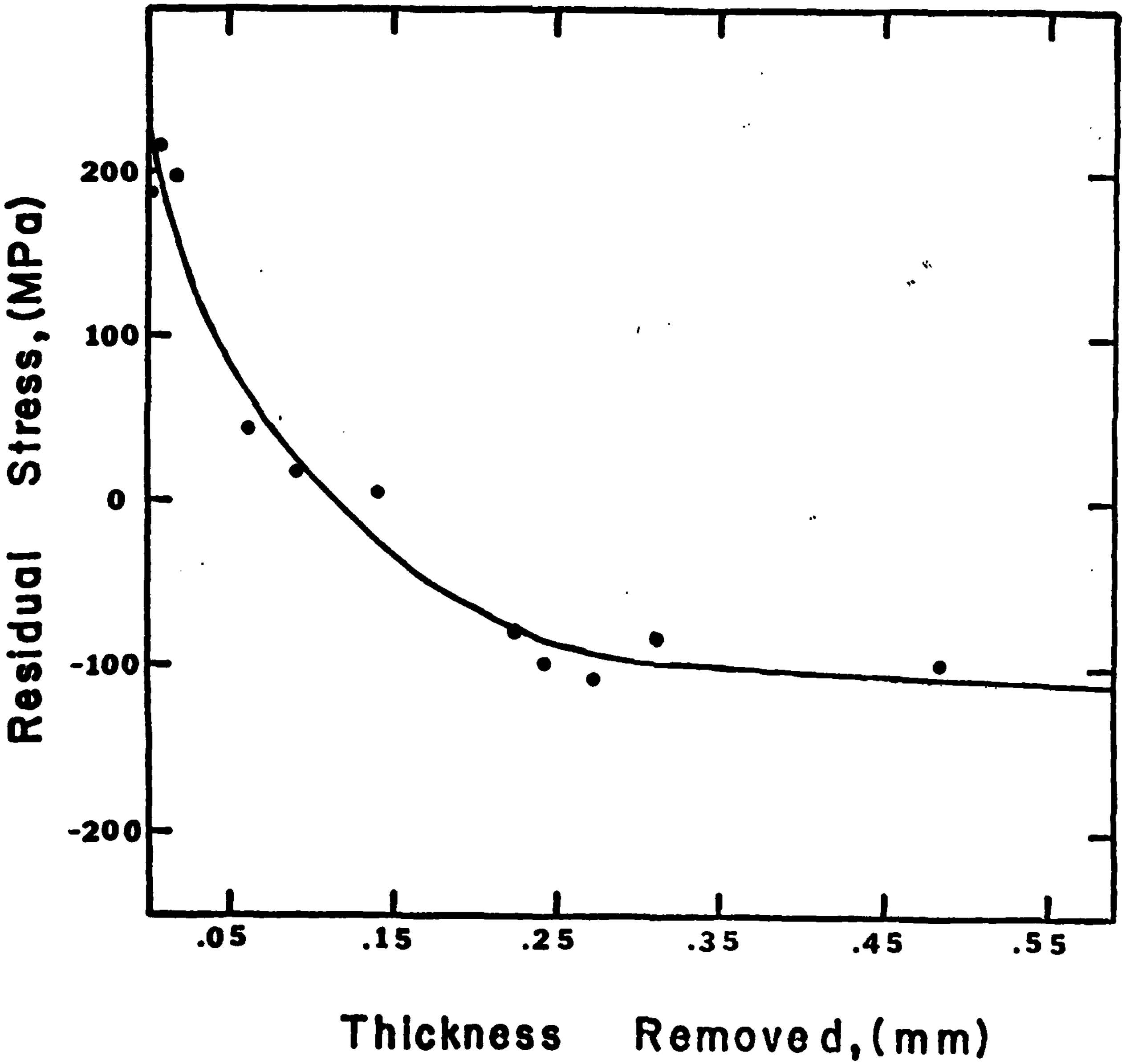

FIG. 5

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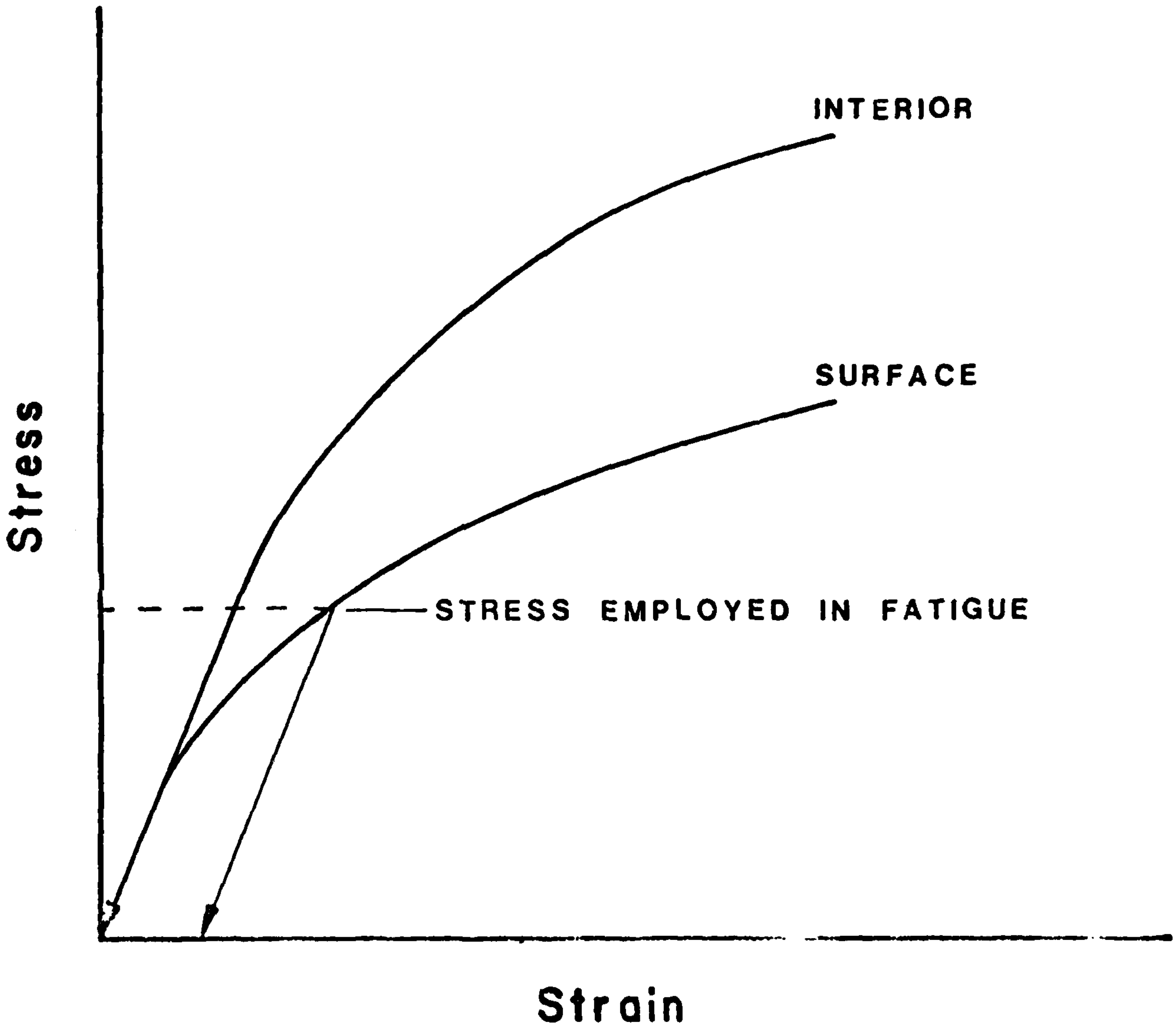

FIG. 6a

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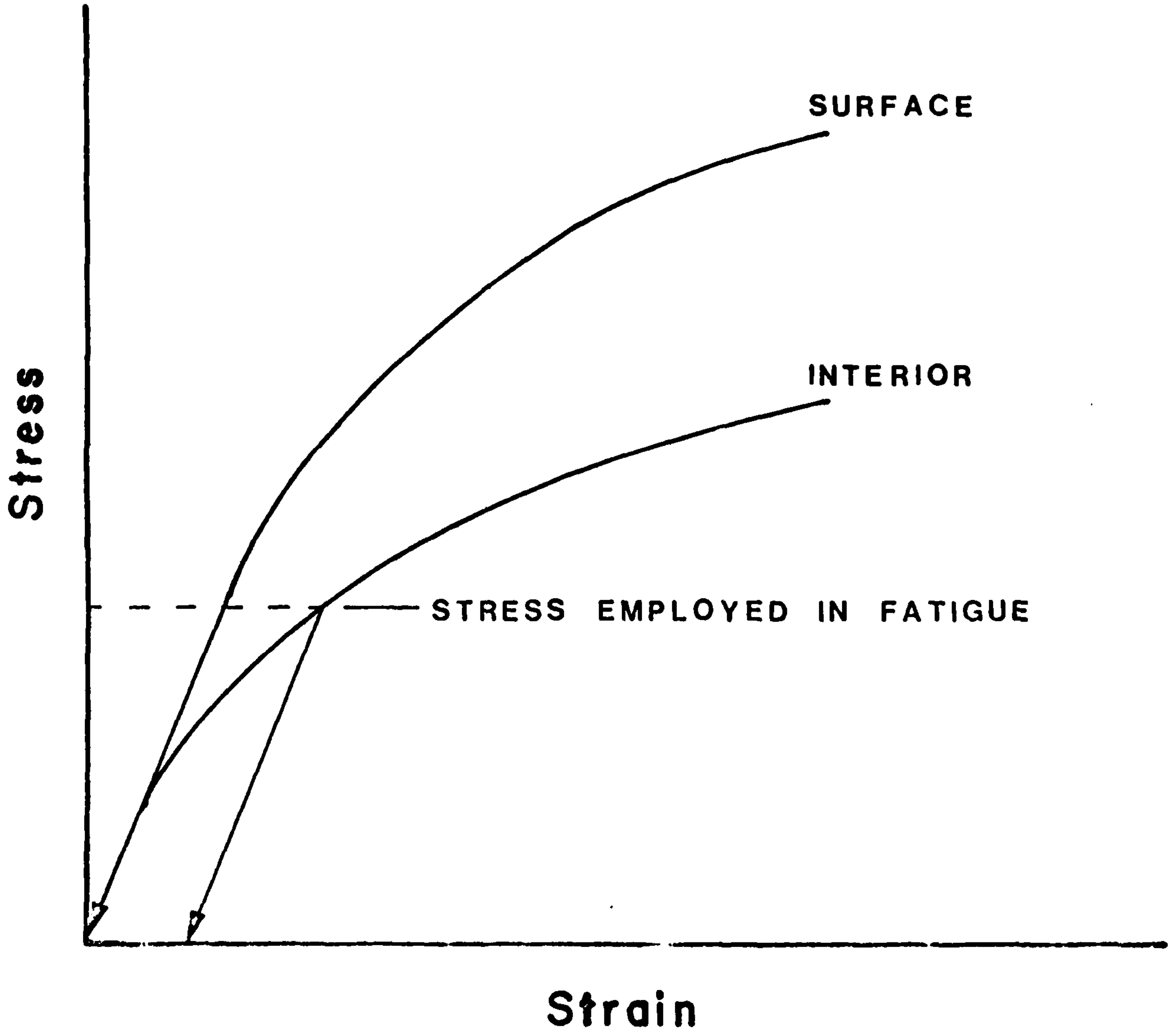

FIG. 6b M. McClinton and J. B. Cohen

Table I

The Experimentally Determined Mechanical Properties of the Normalized and Normalized and Shot Peened 1040 Steel[*]

1040 Steel	σ_y (.2%) (MPa)	UTS (MPa)	% elongation
Normalized	407.72	613.74	.270
shot peened	425.98	596.37	.266

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[*] Experiments were performed using an Instron Tensile testing machine.

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