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ABSTRACT

Precracked, single-edge-notched specimens of 4340 steel (194-ksi yield strength) and 18% Ni maraging 300 steel were prestressed in laboratory air to various percentages (0% to 90%) of K_{Ic} and then unloaded. The times to failure were subsequently determined in 3.5% aqueous NaCl solution as a function of initial stress intensity. Prestressing increased the threshold stress intensity K_{Iscc} of the 4340 steel, but had only a slight effect on the K_{Iscc} of the maraging steel. The times to failure of both steels at initial stress-intensity levels above K_{Iscc} were unaffected by prestress. These effects are attributed to the presence of compressive stresses at the crack tip.

INTRODUCTION

Prior to service, pressure vessels and other structural items are frequently prestressed to a level greater than the operating stress. Prestressing can reduce the possibility of subsequent brittle fracture in three ways (1):

1. By reducing residual welding stresses in structures not thermally stress relieved.
2. By demonstrating that a structure does not contain defects which would initiate failure at the operating stress, provided that subcritical crack growth does not occur.
3. By reducing the damaging effect of any flaw that is present.

Steels with yield strengths exceeding approximately 180 ksi are susceptible to stress-corrosion cracking in relatively mild environments

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(2). If the stress intensity at the tip of a crack is greater than the threshold stress factor K_{Iscc} for the operating environment, then stress-corrosion crack growth will occur (3). The purpose of the present investigation is to determine whether prestressing improves the stress-corrosion cracking resistance of high-strength steels in the presence of cracks.

MATERIALS

Two high-strength steels, low-alloy 4340 and 18% Ni maraging 300, were tested. The form in which the materials were procured and the chemical compositions are shown in Table 1. The heat treatments, Table 2, were selected to produce yield strengths of approximately 200 and 280 ksi in the 4340 and 18% Ni maraging steels, respectively. The tensile strengths obtained may be seen in Table 3.

EXPERIMENTAL WORK

Single-edge-notched specimens of the configuration shown in Fig. 1a were machined to final dimensions in the WT orientation from the 4340 plate and heat treated in an argon atmosphere. The specimens were then fatigue precracked in cantilever bending to introduce a 0.1-in.-long crack in such a manner that stress intensity at the crack tip did not exceed 27 ksi $\sqrt{in.}$ This specimen configuration was used for both fracture-toughness and stress-corrosion tests.

Single-edge-notched specimens of the configuration shown in Fig. 1b and standard 10-mm-square Charpy specimens were machined to final dimensions in the transverse direction from the maraging steel billet and heat treated in air. The larger single-edge-notched specimens were fatigue precracked in the same way as the 4340 steels. The Charpy specimens were fatigue precracked in three-point bending to introduce a crack 0.030 to 0.050 in. long. The final stress intensity on the fatigue crack tip could not be definitely established, but was believed to be less than 25 ksi $\sqrt{in.}$ The larger specimens were used for fracture-toughness measurements, and the Charpy specimens were used for stress-corrosion studies.

Tension specimens 0.25 in. in diameter were machined from both materials and heat treated with the single-edge-notched specimens. Tensile properties were determined at room temperature at a strain rate of 0.005 in./in./min through yield and 0.02 in./in./min to fracture.

Plane-strain fracture toughness K_{Ic} tests were conducted in three-point bending at room temperature, and the data analyzed according to the recommended ASTM procedure (4).

Specimens for stress-corrosion testing were first loaded in the following manner to prestress the crack tip to selected percentages (0% to 90%) of K_{Ic}. The crack length was measured at the specimen surface, and the load determined from the equation given by Brown and Srawley (5). Specimens were loaded by three-point bending in laboratory air. The required load was maintained for 30 sec and then removed. A clip gage was attached to the notch of each 4340 specimen loaded to 90% K_{Ic} to determine whether crack growth had occurred. All specimens were aged at room temperature for at least 24 hr prior to stress-corrosion testing.

To evaluate stress-corrosion resistance, the prestressed single-edge-notched specimens were sustain loaded to selected initial stress-intensity K_{Ii} levels. The 4340 specimens were loaded in four-point bending, and the 18% Ni maraging 300 steel specimens were loaded in cantilever bending. Stress intensities were calculated for both from the Brown and Srawley equation for pure bending (5). The notches of the maraging steel specimens were exposed to a continuous flow of 3.5% aqueous NaCl solution, whereas the 4340 specimens were continuously immersed in that environment. In all tests the environment was introduced prior to load application. The specimens were exposed until failure occurred or until a selected time period (> 100 hr) had elapsed. Those which did not fail were rapidly broken open by bending in air. The region below the fatigue crack was macroscopically examined for evidence of environmental crack growth. The fatigue crack depth was also measured to provide a more accurate measurement of the prestress stress intensity and K_{Ii}.

RESULTS AND DISCUSSION

Plane-strain fracture-toughness data for the two steels are shown in Table 3. Curves of load versus crack opening displacement obtained during prestressing indicated that no crack growth occurred in the 4340 specimens. Curves of load versus crack opening displacement obtained during the fracture-toughness testing showed that no crack growth had occurred in the maraging 300 specimens before maximum load was reached. Since the fracture-toughness and stress-corrosion specimens of the maraging 300 steel were of simular thickness, it is considered that no crack growth occured during the prestressing of the maraging 300 specimens. The K_{Ii} values for both steels indicate that the stress-corrosion specimens were sufficiently thick to maintain plane-strain conditions at all stress-intensity levels (Table 3).

Stress-corrosion curves of initial stress intensity K_{Ii} versus time to failure are shown in Figs. 2 and 3 for both materials in the non-prestressed condition. The threshold stress-intensity K_{Iscc} values of 8.5 ± 1.5 and 7.5 ± 2.5 ksi$\sqrt{\text{in.}}$ obtained for the 4340 and maraging steels, respectively, are considered rather low for the material/strength level combinations in this study. Values for 4340 are usually in the range 20 to 30 ksi$\sqrt{\text{in.}}$ and those for maraging 300 are usually in the range 10 to 15 ksi$\sqrt{\text{in.}}$ at the strength levels studied (2,6).

Stress-corrosion data obtained from 4340 specimens prestressed to stress-intensity levels K_{Ip} corresponding to 25%, 50%, 80%, and 90% K_{Ic} are shown in Fig. 4. The stress-corrosion curve obtained from specimens that were not stressed (Fig. 2) is included for comparison. Because the actual precrack length was occasionally misjudged from surface measurements, there was some variation in K_{Ip} at each nominal level. The variations were relatively small, as indicated in Fig. 4. Stress-corrosion data from the maraging steel specimens are compared in a similar manner in Fig. 5; the maximum K_{Ip} used for this steel was 80% K_{Ic}.

Two significant features emerge from the data obtained:

1. In the 4340 steel, the threshold stress intensity K_{Iscc} increased linearly with K_{Ip} (Fig. 6). In the maraging steel, an increase in K_{Iscc} was observed only at the highest K_{Ip} level (80% K_{Ic}) examined (Fig. 7).
2. At K_{Ii} levels exceeding K_{Iscc}, preloading had no significant effect on the time to failure of either steel.

The prestressing conditions were such that general yielding did not occur and any permanent effects were necessarily restricted to the crack-tip region. Four theories to explain the significant features observed are considered below.

1. OXIDE FILM

Prestressing causes displacement of the crack-tip surfaces and exposes them to laboratory air. It can be envisioned that an oxide film, impervious to aqueous NaCl solution, forms at the crack tip. The film would have to be ruptured to allow ingress of the corrodent. However, the observed effects of prestressing on K_{Iscc} in the 4340 steel would require the fracture resistance of the oxide film to increase with K_{Ip}. As a result, this theory is considered to be untenable.

2. CRACK-TIP SHARPNESS

If the prestressing level is sufficiently high, the crack-tip sharpness may be reduced and K_{Iscc} thereby increased. It can be shown that crack-tip displacement which results from prestressing is proportional to K_{Ip}^2 divided by the yield stress σ_{ys} (7). A number of investigations have shown that below a certain root radius p_o, notches and sharp cracks are indistinguishable with respect to fracture strength (8,9). Irwin (10) and Malkin and Tetleman (8) have suggested that for brittle fracture, p_o is a function of $(K_{Ic}/\sigma_{ys})^2$. By analogy, p_o should be a function of $(K_{Iscc}/\sigma_{ys})^2$ for stress-corrosion cracking. Therefore, if the crack opening displacement that results from prestressing exceeds p_o, crack blunting should be observed. This can be expressed as

$$\frac{K_{Ip}^{\ 2}}{\sigma_{ys}} > A \left(\frac{K_{Iscc}}{\sigma_{ys}}\right)^2$$

where A is a numerical factor which includes the elastic modulus. This can be rewritten as

$$\frac{K_{Ip}}{K_{Iscc}} > \frac{A}{\sigma_{ys}^{1/2}}$$

Thus, at similar K_{Iscc} levels, blunting should be more readily obtained in high-yield-strength materials. This was not observed in the present study, the yield strength of the maraging steel being almost 50% greater than that of the 4340 steel. Hence, a reduction in crack-tip sharpness does not appear to explain the effects of prestressing.

3. PLASTIC DEFORMATION

As K_{Ip} is increased, the degree and extent of plastic deformation at the crack tip also increase. It is therefore necessary to consider the possible effect of plastic deformation on environmental crack growth resistance. However, investigations have shown that cold work can decrease the stress-corrosion resistance of low-alloy steels (11,12). It is also becoming increasingly evident that stress-corrosion cracking in high-strength steels can be attributed to a hydrogen embrittlement mechanism. Cold work could provide trap sites for hydrogen and lead to a distribution of hydrogen different from that in the same material in the non-prestressed state. Nevertheless, this would be a transient condition because hydrogen, in the absence of polarization, is continuously generated as a result of corrosion processes. These considerations indicate that an increase in failure time could be expected, but that K_{Iscc} would not increase. Therefore, cold working does not explain either the increase in K_{Iscc} with K_{Ip} in the 4340 steel or the absence of a prestressing effect on failure time in both steels.

4. COMPRESSIVE STRESSES

During removal of the prestress load, the crack-tip plastic zone is compressed by the surrounding elastically strained material and compressive stresses are introduced around the crack tip. Upon reloading, the size of the plastic zone and magnitude of the crack-tip stresses or displacements that may develop will be reduced by the zone of compressive stresses. The size of this zone is proportional to $(K_{Ip}/\sigma_{ys})^2$ (13), and, as shown in Fig. 8, the effect of prestressing on both steels appears to be similar when K_{Iscc} is related to this ratio.

When K_{Ii} exceeds K_{Iscc} in a prestressed specimen, the initial crack growth will be resisted in the compressive stress zone. The time required for zone penetration will depend upon the zone size and the crack velocity corresponding to the effective stress intensity in this region; that is, the applied stress intensity minus the compressive stress zone influence. Once the zone is penetrated, the crack will extend at the same rate, with respect to crack length, as in an identical, non-prestressed specimen loaded to the same K_{Ii} level. For K_{Ii} levels close to K_{Iscc}, the size of the compressive stress zone (13) is two or three orders of magnitude less than the extent of the stress-corrosion crack growth required to break the specimen. Hence, the time for zone penetration will, in general, be small compared with the failure time of the non-prestressed specimen. Also, it can be inferred from the shapes of the curves in Figs. 2 and 3 that above a stress-intensity level of approximately 20 ksi $\sqrt{\text{in.}}$, the stress-corrosion crack velocity in both steels is essentially constant and independent of stress intensity (14). It follows that if the effective stress intensity in the compressive stress zone exceeds this value, the crack velocity and hence the failure time will be the same as in a non-prestressed specimen. Therefore, compressive stresses satisfactorily explain the effect of prestressing on K_{Iscc} in both steels and the absence of a significant effect on time to failure.

It should be noted that in some materials the stress corrosion crack velocity increases rapidly with stress intensity (14). Under these circumstances the initial crack velocity, corresponding to the effective stress intensity at the crack tip following prestressing, can be very much lower than in a nonprestressed specimen loaded to the same K_{Ii} level. This would lead to an increase in the time required for a detectable amount of crack growth (apparent incubation period) compared to the nonprestressed specimen. Factors controlling the magnitude of this effect are the relationship between velocity and stress intensity and the prestress level.

PRACTICAL IMPLICATIONS

The effects observed indicate that fatigue cracking of stress-corrosion specimens at high stress-intensity levels could lead to an overestimate of K_{Iscc}. The results also emphasize that prestressing of a structure does not necessarily provide immunity to stress-corrosion growth at operating stress levels—immunity is demonstrated by prestressing only when the crack size to cause rapid brittle fracture at the applied prestress is smaller than the critical crack size required to initiate stress-corrosion cracking at the operating stress. Although an increase in K_{Iscc} with prestressing would raise this critical crack size, it must be remembered that the compressive stress zone could be penetrated by fatigue crack growth or corrosion processes.

CONCLUSIONS

Prestressing in air prior to stress-corrosion testing increased the threshold stress intensity K_{Iscc} in 4340 steel heat treated to 194-ksi yield strength. However, there was only a slight effect on the K_{Iscc} of 18% Ni maraging 300 steel. The times to failure at initial stress-intensity levels exceeding K_{Iscc} were unaffected by prestressing. These observations can be interpreted in terms of compressive stresses at the crack-tip.

ACKNOWLEDGMENT

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REFERENCES

1. R. W. Nichols, "The Use of Overstressing Techniques to Reduce the Risk of Subsequent Brittle Fracture," *British Welding Journal*, Vol. 15, 1968, pp. 21 and 75.

2. B. F. Brown, "Application of Fracture Mechanics and Fracture Technology to Stress Corrosion Cracking," presented at ASM Conference on Fracture Control, Philadelphia, Pa., January 1970.

3. B. F. Brown, "A New Stress Corrosion Cracking Test for High Strength Alloys," *Materials Research and Standards*, Vol. 6, 1966, p. 129.

4. "Proposed Method of Test for Plane Strain Fracture Toughness of Metallic Materials," *ASTM Standards*, Part 31, May 1969, p. 1099.

5. W. F. Brown, Jr., and J. E. Srawley, *Plane Strain Crack Toughness Testing of High Strength Metallic Materials*, ASTM STP 410, Am. Soc. Testing Mater., Philadelphia, Pa., 1966.

6. C. S. Carter, unpublished data.

7. A. A. Wells, "Application of Fracture Mechanics At and Beyond General Yielding," *British Welding Journal*, Vol. 10, 1963, p. 855.

8. J. Malkin and A. S. Tetelman, "Relationship Between K_{Ic} and Microscopic Strength for Low Alloy Steels," presented at National Symposium on Fracture Mechanics, Lehigh University, August 1969 (to be published in *Journal of Engineering Fracture Mechanics*).

9. J. H. Mulherin, D. F. Armiento, and H. Markus, "The Relationship Between Fracture Toughness and Stress Concentration Factors for Several High Strength Aluminum Alloys," *Transactions ASME, Journal of Basic Engineering*, 1964, p. 709.

10. G. R. Irwin, "Structural Aspects of Brittle Fracture," *Applied Materials Research*, Vol. 3, 1964, p. 65.

11. G. A. Dreyer and W. G. Gallaugher, *Investigation of the Effects of Stress Corrosion on High Strength Steel Alloys*, ML-TDR-64-3, Air Force Materials Laboratory, 1964.

12. H. P. Leckie and A. W. Loginow, "Stress Corrosion Behavior of High Strength Steels," *Corrosion*, Vol. 24, 1968, p. 291.

13. P. C. Paris, "The Fracture Mechanics Approach to Fatigue," Fatigue, Interdisciplinary Approach, Syracuse University Press, Syracuse, N.Y., 1964, p. 107.

14. C. S. Carter, "Stress Corrosion Crack Branching in High Strength Steels," presented at the National Symposium on Fracture Mechanics, Lehigh University, August 1969 (to be published in Journal of Engineering Fracture Mechanics).

Table 1. Form and chemical composition (weight percent) of steels tested

Steel	Form	C	Si	Mn	S	P	Cr	Mo	Co	Ni	Al	Ti	B	Zr
4340	1-in.-thick plate	0.44	0.37	0.7	0.012	0.011	0.84	0.27	---	1.90	---	---	---	---
18% Ni maraging 300	9- by 9-in. billet	0.007	0.03	0.07	0.009	0.005	---	4.79	9.45	18.81	0.19	0.74	0.033	0.01

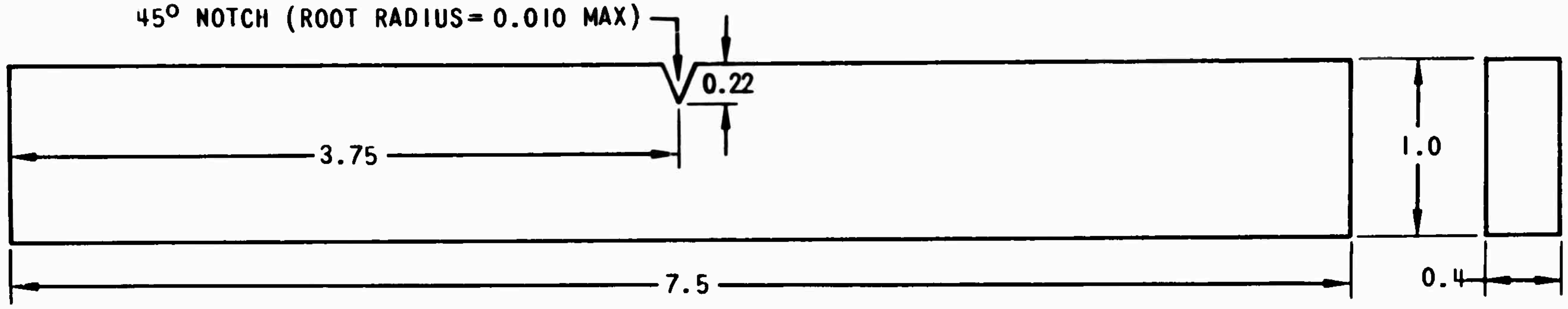
Table 2. Heat treatment of steels tested.

Steel	
4340	Austenitized at 1350°F, oil quenched, and tempered at 750°F for 1¼ hr
18% Ni maraging 300	Billet was received in the double-solution-treated condition (1700°F + 1500°F); specimens were aged at 900°F for 6 hr

Table 3. Mechanical properties of steels tested.

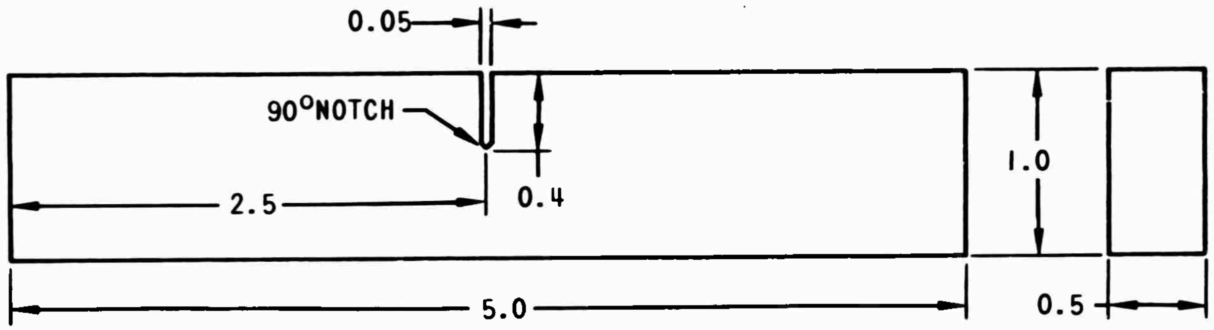
Steel	Tensile yield strength (ksi)	Tensile ultimate strength (ksi)	Plane-strain fracture toughness, K_{Ic} (ksi $\sqrt{\text{in.}}$)	Minimum thickness to maintain plane-strain conditions* (in.)
4340	194.2	213.8	72.2	0.35
18% Ni maraging 300	284.3	292.9	72.4	0.17

*Based on $t = 2.5\left(\frac{K_{Ic}}{\text{Yield Strength}}\right)^2$ (from Ref. 5)



(a) FROM 1-IN.-THICK PLATE OF 4340 STEEL

ALL DIMENSIONS IN INCHES



(b) FROM 9-BY 9-IN. BILLET OF 18% Ni MARAGING STEEL

Figure 1 Single-edge-notched specimens.

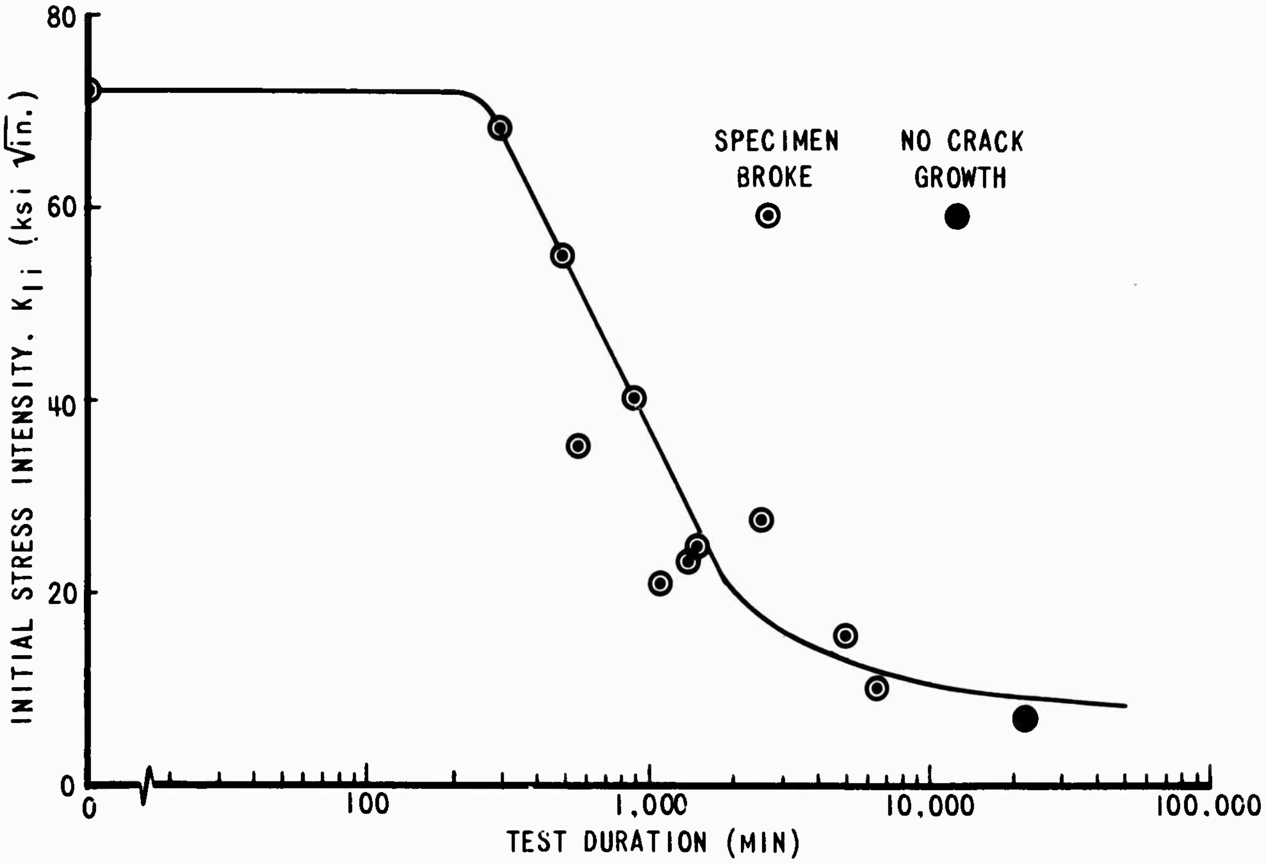


Figure 2 Stress-corrosion curve for 4340 steel (no prestress).

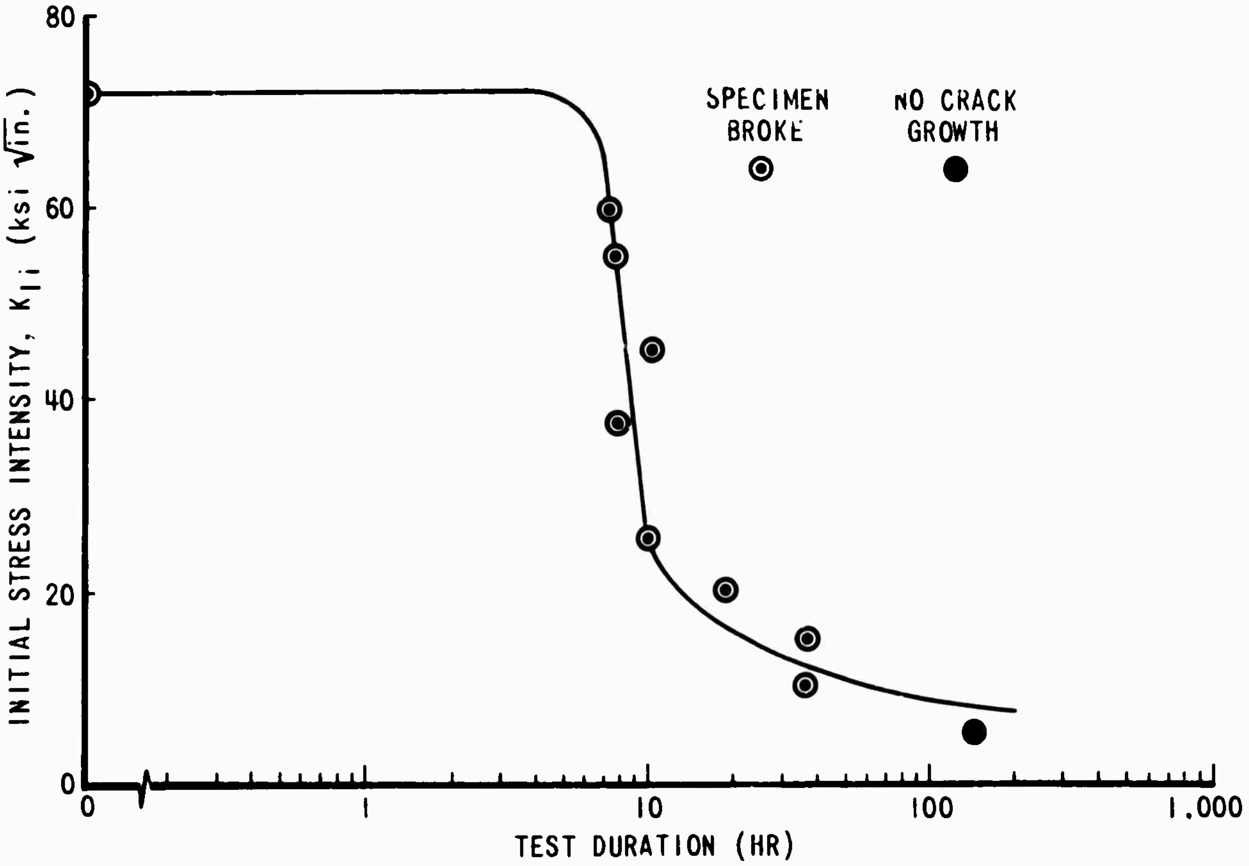


Figure 3 Stress-corrosion curve for 18% Ni maraging 300 steel (no prestress).

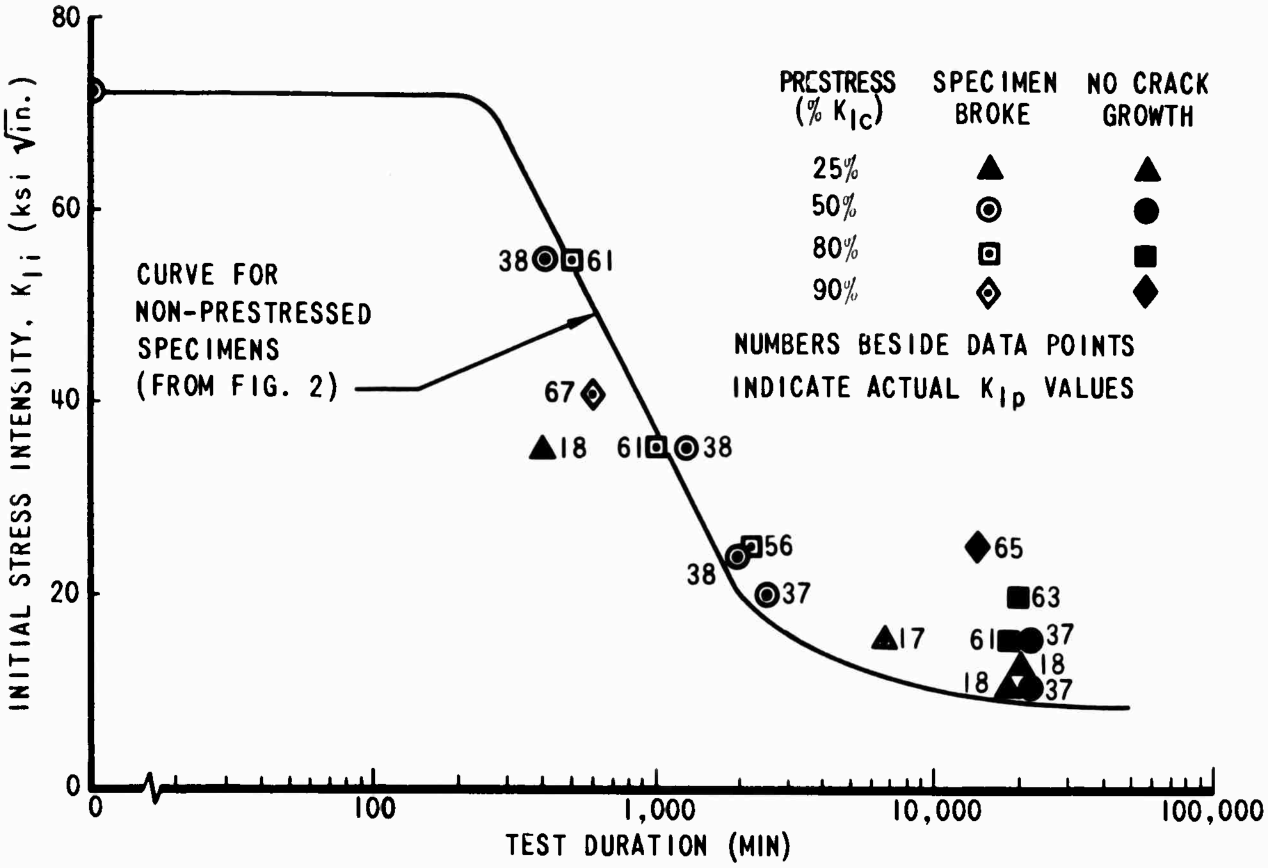


Figure 4 Effect of prestressing on stress-corrosion resistance of 4340 steel.

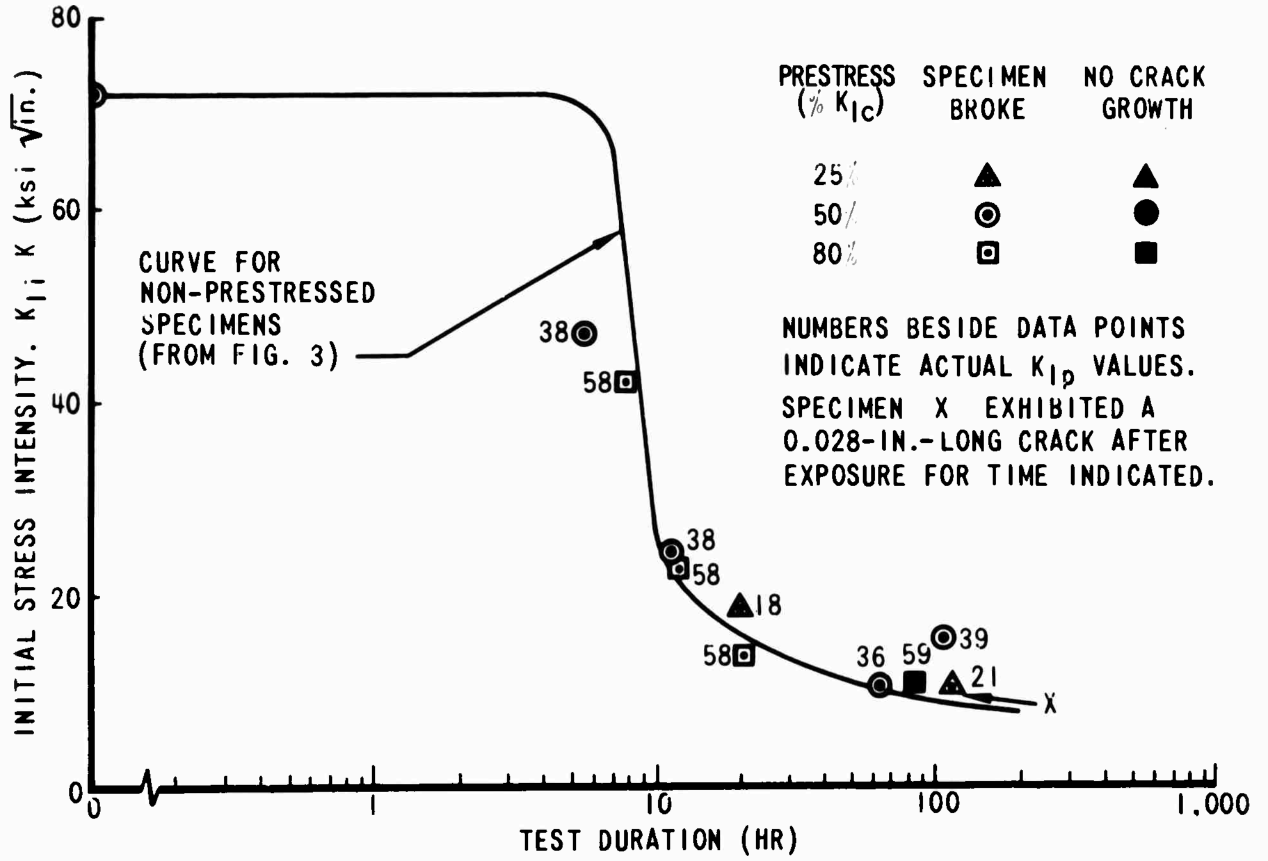


Figure 5 Effect of prestressing on stress-corrosion resistance of 18% Ni maraging 300 steel.

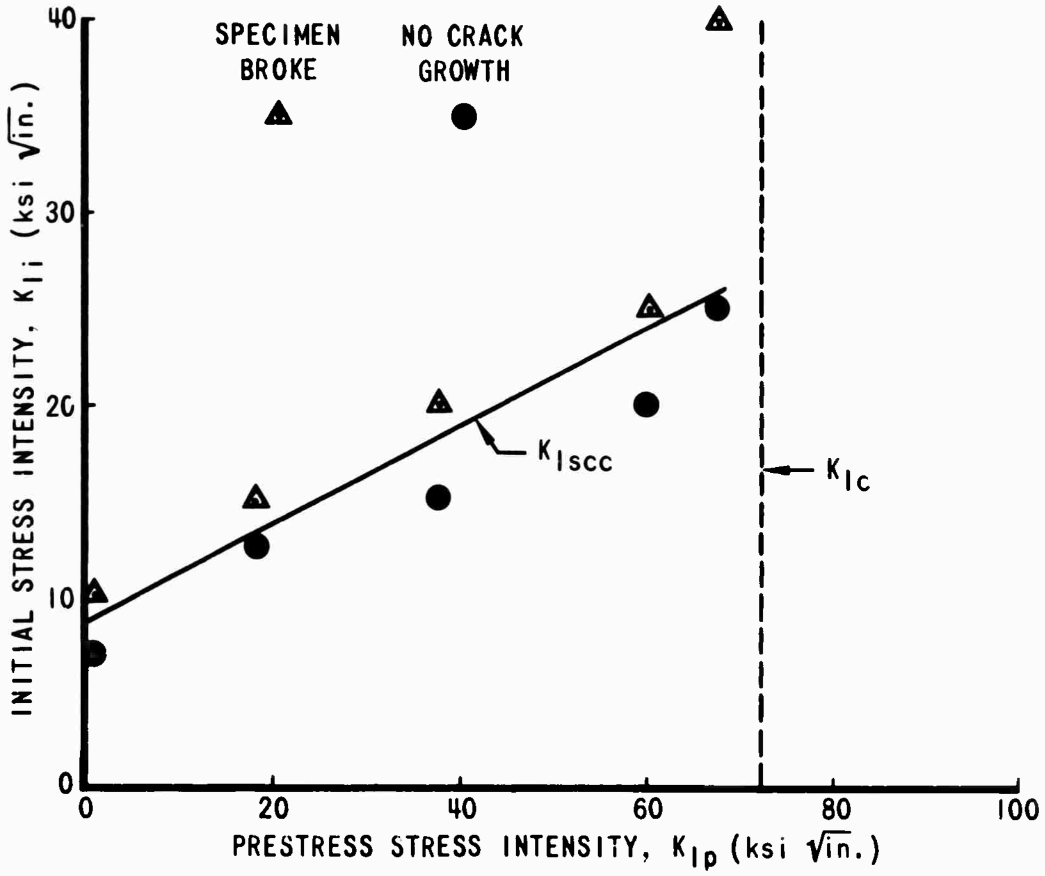


Figure 6 Effect of prestress stress intensity K_{Ip} on threshold stress intensity K_{Iscc} of 4340 steel.

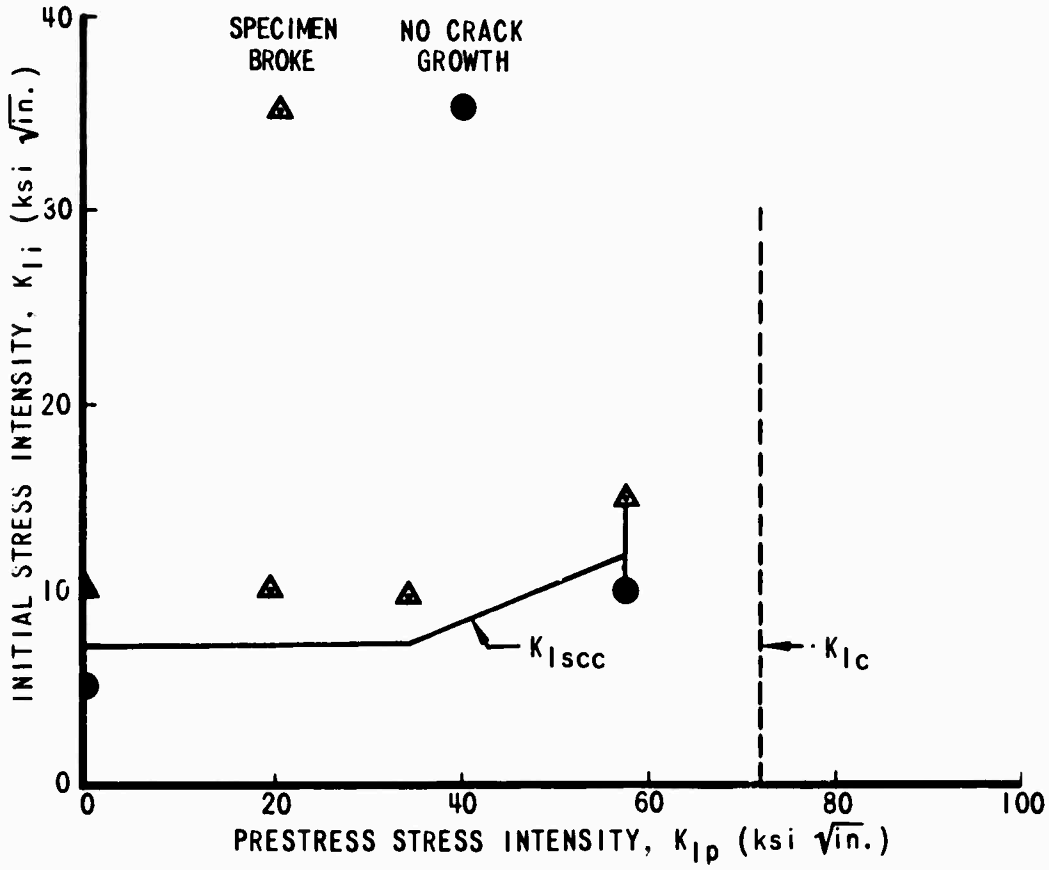


Figure 7 Effect of prestress stress intensity K_{Ip} on threshold stress intensity K_{Iscc} of 18% Ni maraging 300 steel.

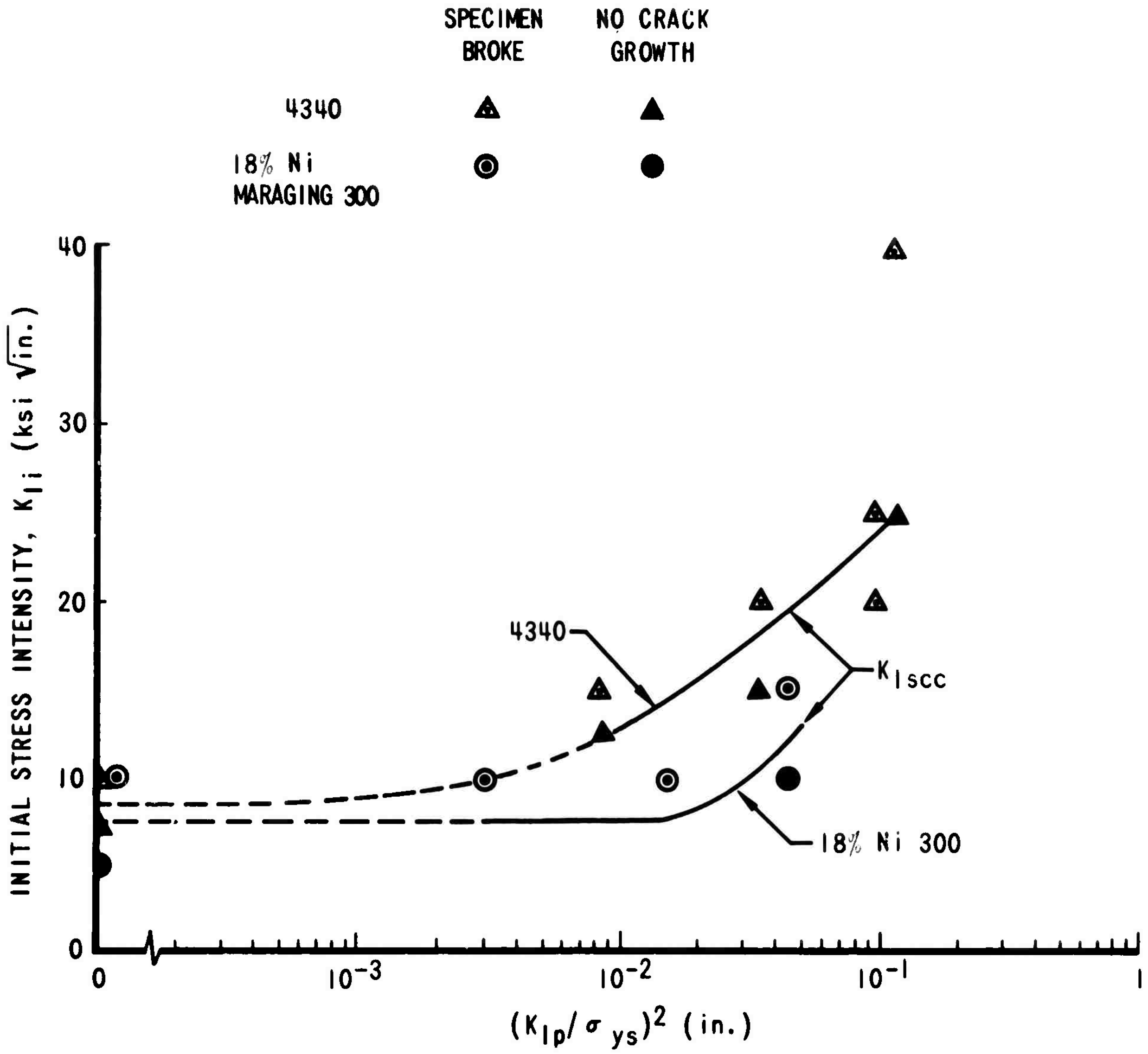


Figure 8 Relationship between K_{Iscc} and $(K_{Ip}/\sigma_{ys})^2$ for 4340 and 18% Ni maraging 300 steels.

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13. ABSTRACT

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