COO-1367-56

EFFECT OF POINT DEFECTS ON MECHANICAL PROPERTIES OF METALS

Technical Progress Report

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ABSTRACT

During the past twelve months, the major effort was on iron. The recovery of the electron irradiation effect was studied in pure iron and iron-carbon alloys. This investigation resulted in several new findings in addition to the confirmation of two assumptions used in the interpretation of the mechanical effects of electron irradiation in our high purity iron single crystals. The irradiation softening effect was studied in single crystals oriented for the (011) slip and polycrystalline specimens. Then, a striking orientation effect was discovered and a large irradiation softening was found in single crystal specimens oriented for the hard (121) slip; in this orientation, more than 60% of the yield stress is reduced by electron irradiation, thereby, the hardest orientation becomes the softest orientation following electron irradiation. Finally, the solution softening and hardening effects of carbon atoms were investigated using high purity iron single crystals similar to those used in the irradiation softening study. The general behavior of the softening and hardening was in good agreement with the theory we proposed, based on the irradiation softening experiment.

1. Irradiation Softening in High Purity Iron

It is generally accepted that the critical resolved shear stress depends on the crystallographic orientation in B.C.C. metals.[1] In the case of iron, the lowest critical resolved shear stress is obtained in a specimen in which the maximum shear plane and the maximum shear direction coincide with the (011) plane and the $[1\bar{1}1]$ direction.[2] For this orientation the tensile axis of the specimen is situated near the center of the standard (001)-(111)-(101) triangle of a stereographic projection. We have been investigating the effects of electron irradiation on the strength of the high purity iron in a single crystal of this orientation for a few years. The most important conclusion is that the irradiation reduces the flow stress if the specimens are kept below the temperature where the long range migration of self-interstitial atoms can occur. This observation has an important implication on the mechanism of plastic deformation and strength of iron and possibly other B.C.C. metals, since the irradiation induced self-interstitials are known to interact strongly with dislocations. Some of the theoretical implications of this observation were explored in this research project.[3] The important experimental observations have been summarized in COO-1367-51.

Recently, a similar irradiation softening has been reported in a high purity polycrystalline iron.[4] The softening effect was observed following neutron irradiation as well as electron irradiation. The general nature of the irradiation softening was extremely similar to that observed in our iron single crystals, except for the fact that the magnitude of the softening was about an order of magnitude greater in the polycrystalline specimens than in the single crystal specimens. A possibility that the iron single crystals are not as pure as the polycrystalline iron has been suggested; we therefore examined the electron irradiation softening effect in polycrystalline specimens prepared from the Battelle-AISI ultrapure iron (from which our single crystals were grown). At low temperatures, the annealed polycrystalline specimens deformed with large serrations indicating twinning, as reported by Groh et al.[4] The electron irradiation removed the serrations, and at the same time, the yield stress decreased significantly. The magnitude of the softening was similar to that reported by Groh.[4] Therefore it is concluded that the large softening is a polycrystalline effect and is not due to a difference in purity.

A number of possibilities can be suggested to answer the question why the polycrystalline specimens behave differently than the single crystal specimens. (1) It may be due to the intrinsic nature of dislocation motion. (See Section 3.) (2) The pronounced irradiation softening effect may exist in the grain boundary regions. (3) It may be related to the twinning mode of deformation which is unavoidable in polycrystalline iron at low temperatures. The first possibility will be discussed further in conjunction with the orientation dependence of irradiation softening in Section 3. The second possibility may be related to the grain boundary brittleness found in the iron in which the carbon content in solution was reduced.[5] The third possibility is suggested phenomenologically. It is our opinion that for the first and third possibilities, the critical observations will be made in single crystal experiments. The second possibility may be closely related to the role of grain boundaries in improving the ductility of polycrystalline iron and its alloys at low temperatures.

2. Recovery of the Radiation Effect in High Purity Iron and Effect of Carbon Atoms on Recovery

The motivation to examine the recovery of the electron irradiation effect was two-fold in the present investigation. We have always assumed that there is no significant recovery stage in the temperature range (up to 60° K) where the irradiation and the mechanical tests are performed. This assumption is based on previous investigations.(6,7) The purity and impurity species of our specimens are different from the ones used in those investigations and the susceptibility of radiation recovery to these factors has always been suspected. A question of the possible scavenging of interstitial impurities by irradiation induced self-interstitial atoms has often been raised against the intrinsic softening effect of the self-interstitial atoms. Carbon atoms can be regarded as representative interstitial impurities in iron. There is only a single literature which reports the effect of carbon doping on the recovery of the electron irradiation effect in iron.(8) Unfortunately, sufficient care was not taken to insure carbon atoms in solution.

The details of the recovery results were reported in COO-1367-52 and COO-1367-54. This investigation confirmed our earlier assumptions; namely, there is no long range migration of interstitials (or any other point defects) in the temperature range used in our mechanical studies and the first significant recovery state (I_B) occurs at $\sim 70^\circ$ K. There is no apparent interaction between self-interstitials and carbon atoms until Stage I_E is reached (at $\sim 130^\circ$ K). The important results can be summarized as follows:

1) A new significant recovery stage was found at 21° K in both pure and carburized iron and was named I_{A0} recovery stage.
2) None of the low temperature peaks (I_{A0}, I_{A1}, I_{A2}, I_B, I_C, and I_D) were

affected by the introduction of carbon. This may be taken as evidence that the irradiation softening found in iron is caused by the direct interaction between dislocations and irradiation induced defects.

3) By the use of a relatively low electron dose, recovery stage I_E (130° K) was separated from the I_D peak at 101° K.

4) The I_E peak was suppressed by the introduction of carbon.

5) A significant recovery, termed II_A', appeared in the carbon-iron alloy, slightly below the temperature for the II_A peak of pure iron.

6) Irradiated iron-carbon alloys showed a negative recovery between 250° $\sim$ 300° K and this was interpreted as due to the release of self-interstitials (or vacancies) from carbon traps.

7) The recovery stage above 300° K is always present in the as-quenched iron-carbon alloys with or without irradiation and is caused by the migration of carbon atoms.

3. Effect of Tensile Orientation on Irradiation Softening

The orientation dependence of yield stress, work-hardening behavior, mode of deformation and slip morphology in iron has been suspected but has never been investigated systematically. The only systematic work was carried out in an iron-silicon alloy by Taoka and his coworkers.(2) We have determined the yield stress as a function of the tensile orientation from the soft ($\bar{1}12$) slip orientation to the hard (121) slip orientation via the ideal (011) slip orientation. A significant orientation effect was observed (~ 30% change). However, the most striking result was the orientation dependence of the irradiation softening effect. These results are summarized in Fig. 1. In this figure, the yield stress resolved to the (011)-[$1\bar{1}1$] slip system is plotted against the orientation parameter χ. χ is the angle between the maximum shear stress plane and the (011) plane. Therefore, $\chi = -30^\circ$, 0°, and 30°, corresponds respectively to the cases where the maximum shear stress plane coincides with the ($\bar{1}12$), (011) and (121) planes. For the specimens of the hard (121) slip orientation, the irradiation softening is an order of magnitude larger than that for the (011) slip orientation. In fact, the post-irradiation yield stress is lowest at the hard (121) orientation, as can be seen in Fig. 1.

In all, eight specimen orientations were examined, ranging from $\chi = \sim -30^\circ$ to $\chi = \sim 30^\circ$. Typical stress-strain curves for three representative orientations are shown in Fig. 2 where the initial tensile directions are indicated in the standard stereographic triangle.

Further investigations are being made to determine the dosage dependence, test temperature dependence and work-hardening behaviors; at the same time, the theoretical implication of the present findings is being examined. We believe that the present observation is one of the key features in the plastic deformation of B.C.C. metals. Some of the initial findings are reported in COO-1367-53 .

It was reported in section 1 that the irradiation softening observed in polycrystalline specimens was considerably larger than that observed in single crystal specimens. These single crystal results were obtained from the (011) slip specimens. On the other hand, the irradiation softening observed in the hard (121) slip specimens is larger than that of the polycrystalline specimens. Therefore the simplest explanation may be that some of the grains oriented for the hard (121) slip become softest after the irradiation and consequently the yield stress is determined by these grains.

4. Solution Softening and Hardening Effects of Carbon Atoms in Iron

The effect of interstitial solute atoms on the strength of iron was examined, using carbon. High purity iron single crystals were prepared in a manner similar to those used in the irradiation study. Carbon atoms were added by carburizing the single crystals in a H_2-n-pentane atmosphere at various temperatures. Following the carburization, specimens in a U-shaped vycor tube were quenched into iced water. Various carbon concentrations up to 400 atomic ppm were thus obtained.

The temperature dependence and the concentration dependence of the yield stress are shown in Figs. 3 and 4 respectively. As our theory predicted, the maximum solution softening effect appeared in the intermediate temperature range ($\sim 200^\circ$ K). At this temperature, the yield stress decreases with carbon concentration and reaches the minimum around 150 ppm. Beyond this concentration, the yield stress increases with concentration. Specimens with 400 ppm carbon showed only the solution hardening effect.

A brief account of this investigation is given in COO-1367-55 and the detailed results are being written into a paper.

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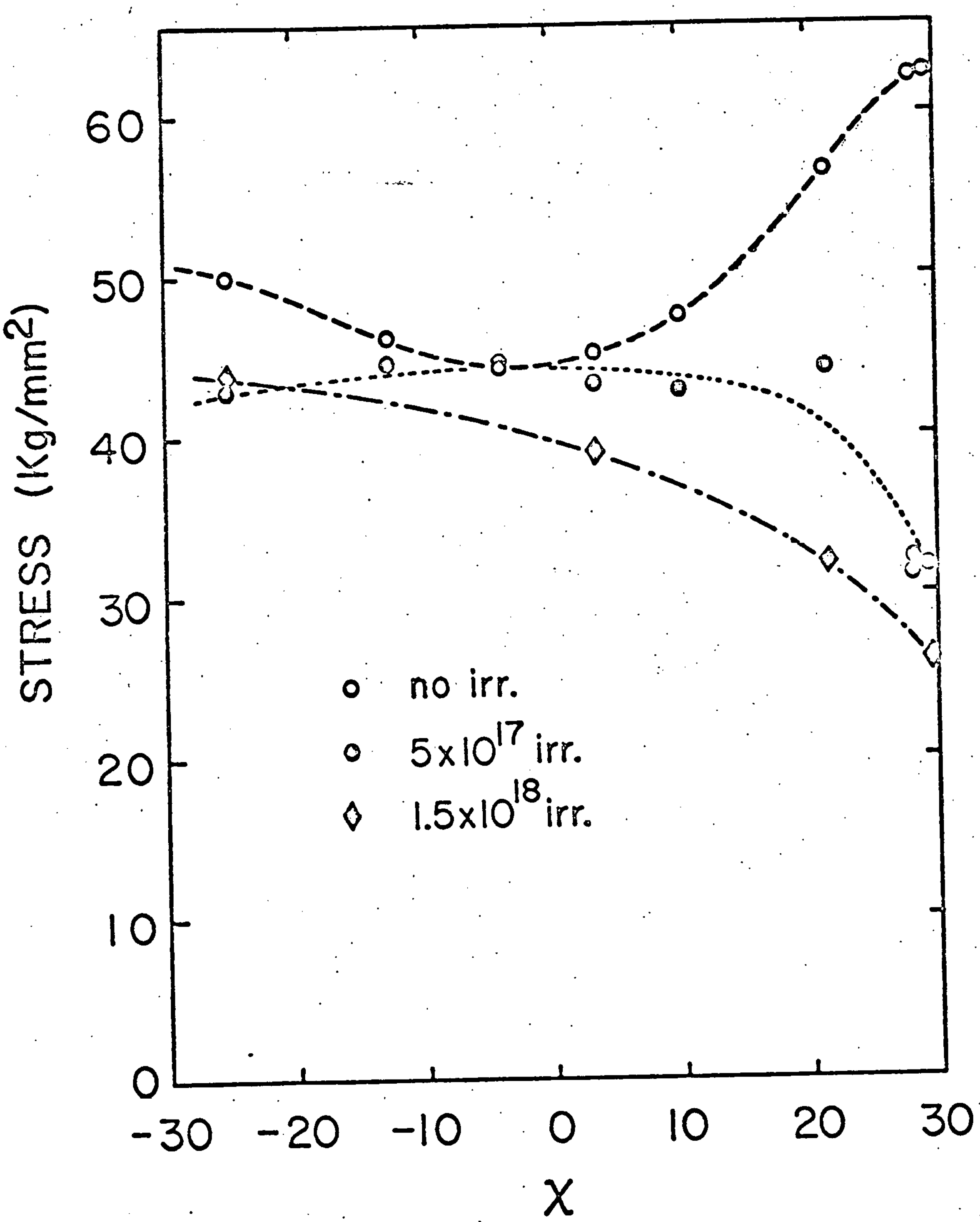
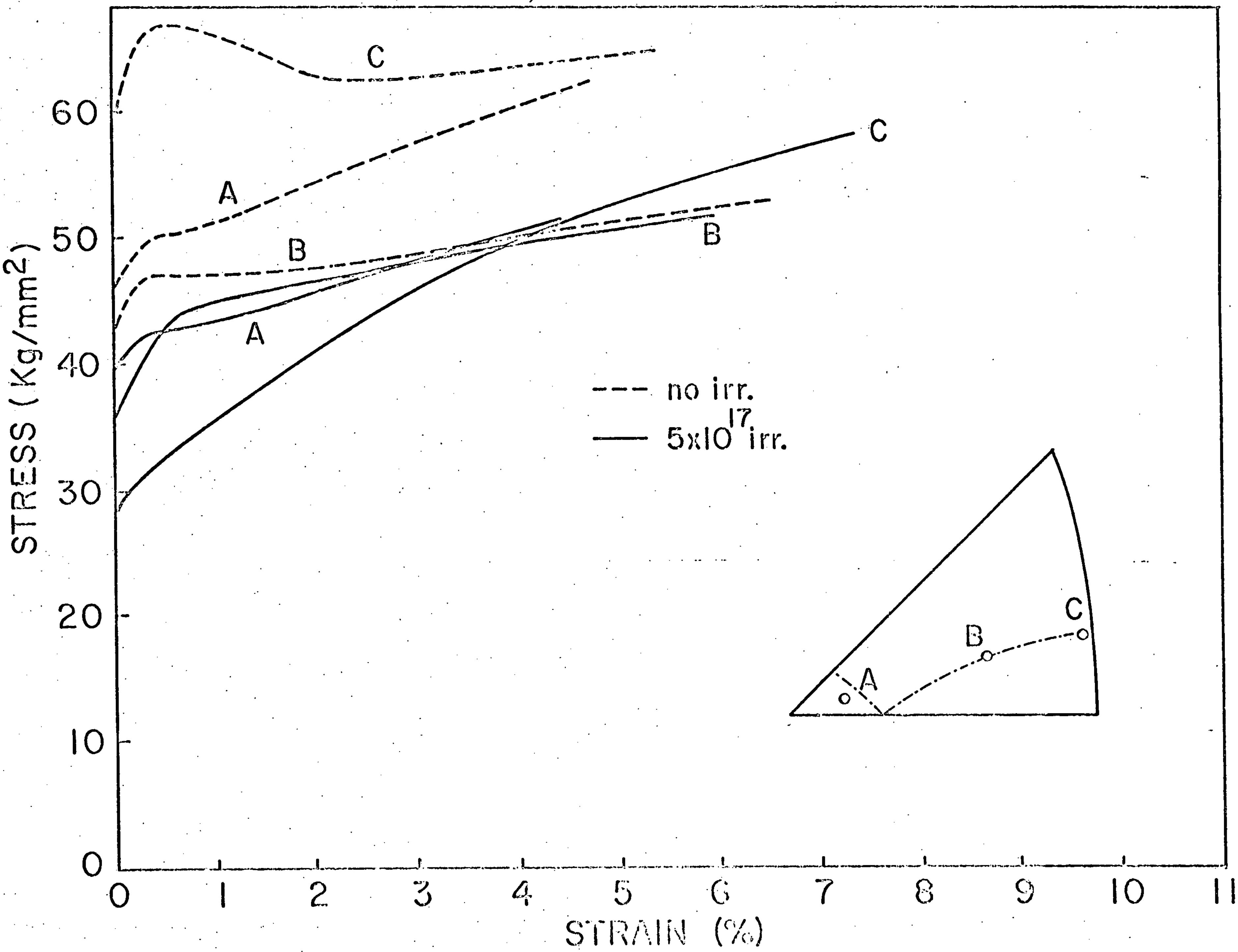


STRESS (Kg/mm^2)
0
10
20
30
40
50
60
-30
-20
-10
0
10
20
30
X
no irr.
5x10^{17} irr.
1.5x10^{18} irr.

Fig. 1

Fig. 1

Fig. 2



STRESS (Kg/mm²)
STRAIN (%)
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
8
9
10
11
C
A
B
A
C
B
no irr.
5x10^{17} irr.
A
B
C

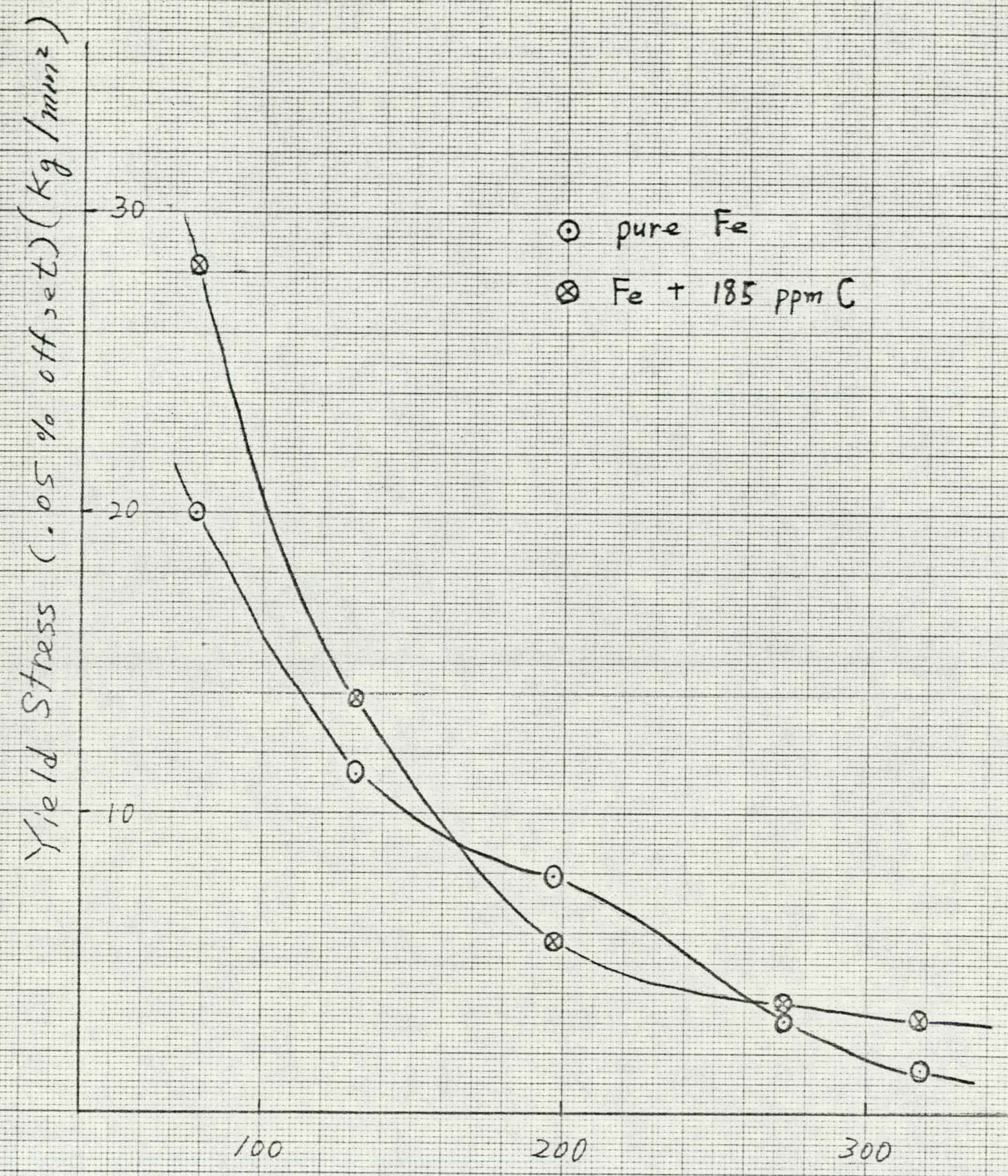

Yield Stress (.05 % offset) (Kg/mm²)
30
20
10
pure Fe
Fe + 185 ppm C
100
200
300
Temperature (oK)

Fig. 3

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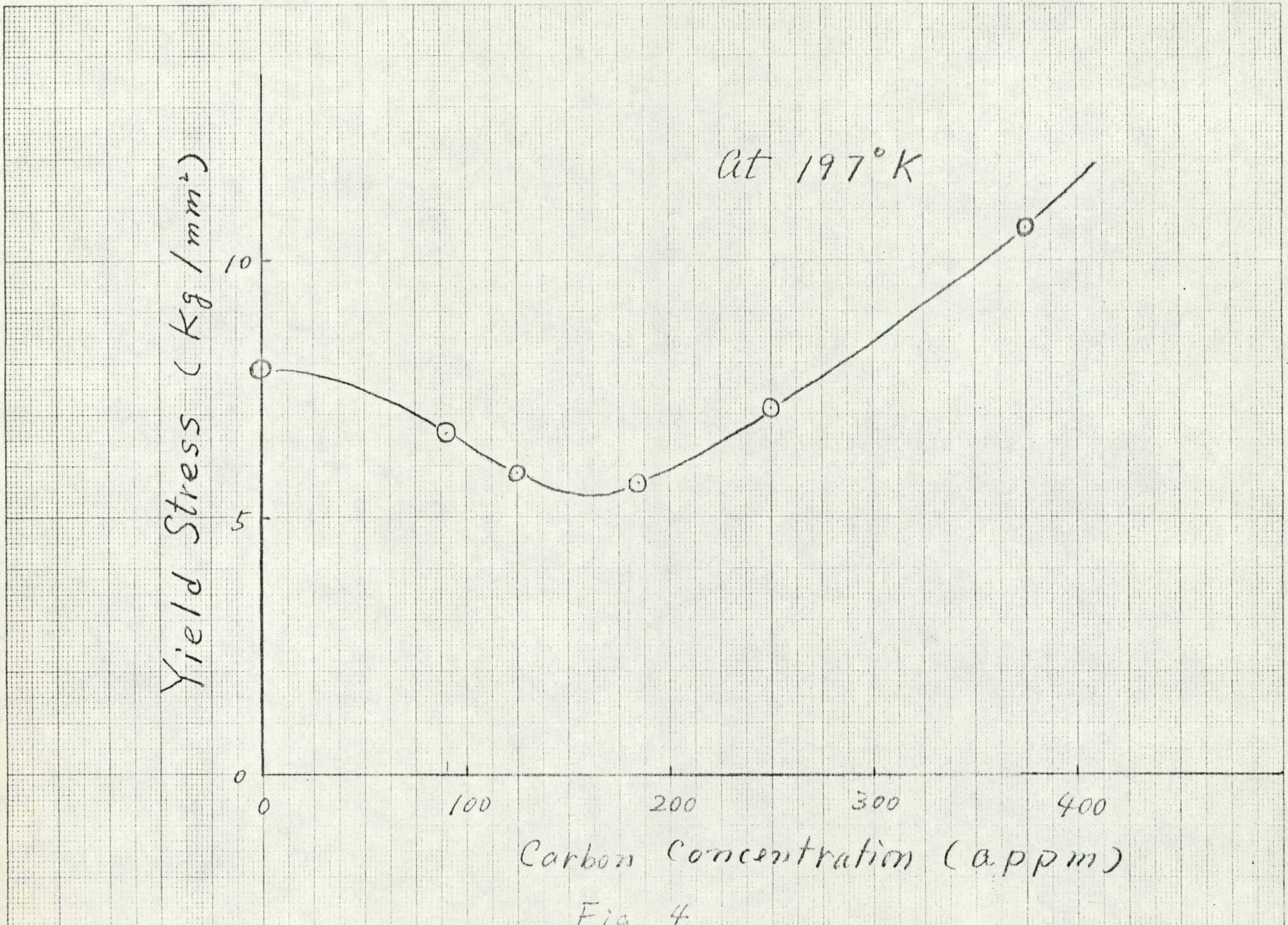

Fig. 4

Reports Resulting from the Present Project

(1) - (50) COO-1367-1 through COO-1367-50. For these reports, see our technical progress reports submitted previously (COO-1367-45 and COO-1367-50).

(51) "Irradiation Softening in Pure Iron Single Crystals," physica status solidi (a), 18 (1973) 699, COO-1367-51.

(52) "Effect of Interstitial Carbon on the Recovery of Electron Irradiation Induced Defects in α-Iron," Abstract of Talk presented at the Fall Meeting of ASM/AIME, October 1973, Chicago, COO-1367-52.

(53) "Asymmetry in the Yield Stress and Irradiation Softening of High Purity Iron Single Crystals," Abstract of Talk to be presented at the Spring Meeting of The Metallurgical Society of AIME, May 1974, Pittsburgh, COO-1367-53.

(54) "Recovery of Irradiation Induced Defects in High Purity Iron and Iron-Carbon Solid Solutions," submitted to physica status solidi for publication, COO-1367-54.

(55) "Solution Softening and Hardening Effects of Carbon Atoms in High Purity Iron Single Crystals," Abstract of Talk to be presented at the Spring Meeting of The Metallurgical Society of AIME, May 1974, Pittsburgh, COO-1367-55.

(56) "Technical Progress Report for the Period from January 1, 1973 to December 31, 1973," submitted to the U. S. Atomic Energy Commission for renewal of Contract AT(11-1)1367-56.