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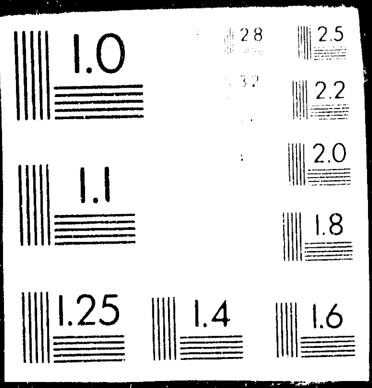

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POSTIRRADIATION DEFORMATION BEHAVIOR IN FERRITIC Fe-Cr ALLOYS

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REFERENCE: Hamilton, M. L., Gelles, D. S., and Gardner, P. L., "**Postirradiation Deformation Behavior in Ferritic Fe-Cr Alloys,**" Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175, Arvind S. Kumar, David S. Gelles, and Randy K. Nanstad, Editors, American Society for Testing and Materials, Philadelphia, 1993.

ABSTRACT: It has been demonstrated that fast-neutron irradiation produces significant hardening in simple Fe-(3-18)Cr binary alloys irradiated to about 35 dpa in the temperature range 365 to 420°C, whereas irradiation at 574°C produces hardening only for 15% or more chromium. The irradiation-induced changes in tensile properties are discussed in terms of changes in the power law work-hardening exponent. The work-hardening exponent of the lower chromium alloys decreased significantly after low-temperature irradiation ($\leq$ 420°C), but increased after irradiation at 574°C. The higher chromium alloys failed either in cleavage or in a mixed ductile/brittle fashion. Deformation microstructures are presented to support the tensile behavior.

KEYWORDS: Key words: ferritic alloys, postirradiation deformation, work-hardening coefficient, yield strength, mechanical properties, tensile strength, deformation, microstructure

INTRODUCTION

Ferritic/martensitic steels continue to be considered for application as structural materials in proposed fusion irradiation devices. Since it is not possible to duplicate for testing purposes the irradiation conditions anticipated in a fusion device, significant effort is devoted to understanding the fundamental irradiation response of ferritic materials to facilitate extrapolation to a fusion environment from the response in the available fission environment. Experiments on simple alloys have therefore been included in the fusion materials program to allow comparison with the behavior of more complex alloys.

Miniature tensile specimens of six binary Fe-(3-18)Cr alloys were previously irradiated in the Fast Flux Test Facility (FFTF) and tested

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at room temperature.[1] Neutron exposures ranged from ~7 dpa at 365°C to ~35 dpa at 403 and 574°C. Significant hardening was observed in alloys irradiated at 365 and 403°C, whereas irradiation at 574°C produced hardening only for chromium levels of 15% or more. Several unusual types of yield behavior were also observed that raised questions about the deformation response of the alloys. The work hardening behavior of the alloys was therefore determined to provide an improved understanding of post-irradiation deformation response in simple ferritic alloys. Deformed microstructures were also examined using transmission electron microscopy.

EXPERIMENTAL PROCEDURE

The load and displacement data obtained in reference 1 were digitized manually between the 0.2% offset yield point and the maximum load, and converted to true stress and true strain according to $\sigma = s(e+1)$ and $\epsilon = \ln(e+1)$, where σ and ϵ are true stress and strain, respectively, and s and e are engineering stress and strain, respectively. The data were fit by linear regression to the power law definition of strain hardening, $\sigma = K\epsilon^n$, where K is a constant. The strain hardening coefficient n was determined as the slope of log σ versus log ϵ for as many tests as possible. The value of r^2 for the regressions was generally on the order of 0.9 or higher, except where brittle failure precluded the reasonable application of the work hardening concept.

Transmission electron microscopy disks were prepared from the gauge sections of two tested tensile specimens. The thinned area being examined was therefore located about 1.5 mm from the actual fracture surface, theoretically well within the uniformly deformed region of the gauge. Microscopy was performed on a 1200EX electron microscope operating at 120 keV.

RESULTS

Previous Tensile Data

The original tensile data are summarized in Figure 1. Only yield strength and total elongation are shown since the ultimate tensile strength and uniform elongation behaved similarly. Significant hardening and loss of ductility were observed at all chromium levels after irradiation at 365 and 403°C (to ~7 and ~35 dpa, respectively). Similar irradiation-induced changes in behavior after irradiation at 574°C were only observed for chromium levels of 15% or more.

Schematic examples of the unusual yield responses that were observed are shown in Figure 2. The hatch marks on each type of curve delineate the data used for the determination of the work-hardening coefficient. The "bump" occurs as a short, gradual decrease in load from the maximum load, very shortly after the 0.2% offset yield point. A yield plateau was sometimes observed, although it was not preceded by the upper yield point that is typical of ferritic alloys, nor did it exhibit the irregularities typically associated with the propagation of Lüder's bands. The third type of unusual response could be characterized as a slight "wow" in the elastic portion of the data, where the data immediately preceding and succeeding the "wow" are collinear.

The possibility that equipment-related problems could be the source of any of these unusual behaviors was eliminated by repeated checks on the machine operation. All three of these types of behavior were reproducible when duplicate specimens were available and allowed multiple tests of the same alloy condition. Both the "bump" and the yield plateau phenomena have also been observed in tensile data obtained at room temperature on simple austenitic ternary alloys. In addition, B. A. Loomis, of Argonne National Laboratory, has also seen the "wow" behavior, in tests performed at elevated temperatures on various vanadium alloys.

Strain Hardening Behavior

The strain hardening coefficients determined for the 3-15Cr alloys are shown in Figures 3 through 7, which include an annotation as to where the unusual yield phenomena were observed. The ductility of the 18 Cr alloy was so low that no valid work hardening coefficient could be extracted from the data. The values of n ranged from about 0.14 to about 0.25 in the unirradiated condition. The 3, 6, and 9Cr alloys exhibited values of n that increased with irradiation temperature, ranging from below the starting value at 365 and 403°C to above the starting value at 574°C. Yield plateaus were associated with the 3 and 9Cr alloys in the unirradiated condition, while "bumps" were associated with the 6 and 9Cr alloys following irradiation at both 365 and 403°C.

The 12Cr specimens exhibited virtually identical values of n in the unirradiated condition and following irradiation at 574°C, but exhibited highly variable values at the lower irradiation temperatures, where the "wow" appeared in the load-displacement curves. The 12Cr specimens also exhibited a yield plateau in the unirradiated condition similar to that shown by the 3 and 9Cr alloys.

The 15Cr specimens exhibited a large amount of variability in the values of n obtained for the unirradiated condition, consistent with the variability in the tensile data itself.[1] Most of the specimens irradiated at the lower temperatures failed by cleavage. Those 15Cr specimens for which valid n values were determined exhibited almost classic elastic-perfectly plastic load-displacement traces, hence the very low values of n.

The work-hardening coefficient data are summarized in Figure 8. It is evident that the lower Cr alloys are reduced to very low n values at low irradiation temperatures, which then increase with increased irradiation temperature. The low values of n appear to be associated with load-displacement traces exhibiting "bumps". Yield plateaus appear to be associated with unirradiated material only, and the variability evident in the values of n for the 12Cr alloy at the lower irradiation temperatures appears to be associated with load-displacement traces exhibiting a "wow".

Electron Microscopy

Two specimens were prepared for transmission electron microscopy, one each of the 6 and 12Cr alloys, from the gauge sections of miniature tensile specimens that had been irradiated at 403°C and then tensile tested at room temperature. Uniform elongations were on the order of 0.6% for both tensile tests. The purpose of the microscopy examinations was to determine the consequences of postirradiation deformation on the dislocation structure.

The dislocation structures contained a<100> loops and $\frac{a}{2}$<111> dislocation line segments similar to those found in Fe-6Cr and Fe-12Cr specimens irradiated at 403°C to 15 dpa.[2] Examples are given in Figures 9 and 10 for Fe-6Cr and Fe-12Cr, respectively. The dislocation structure was imaged in each case using both g=011 and 200 for a grain tilted near <011> and then with either g=110 or 101 after further tilting. The 200 contrast image shows one set of a[100] loops in strong contrast elongated vertically and all of the $\frac{a}{2}$<111> dislocation segments in weaker contrast. In comparison, the 011 contrast shows the other sets of a<100> loops and only half of the $\frac{a}{2}$<111> dislocation line segments.

No interactions are apparent between the $\frac{a}{2}$<111> line segments and the a<100> loops in Figures 8 and 9. Nor are there indications of distorted a<100> loop shapes. Stereoscopic examination of stereo pair micrographs confirmed that there was no interaction between the $\frac{a}{2}$<111> dislocation line segments and a<100> loops, as well as the absence of any irregularities in the size or shape of a<100> loops. Deformation does not appear to have occurred in either of the regions examined despite their proximity to the fracture, and the local strain in these regions is therefore effectively zero rather than the 0.6% indicated by the uniform elongation data.

DISCUSSION

This work was initiated to provide further understanding of the consequences of the complex dislocation structures encountered in irradiated ferritic alloys. Such dislocation structures generally included both $\frac{a}{2}$<111> and a<100> Burgers vectors, the former common in unirradiated ferritic alloys, but the latter generally occurring only as a result of radiation damage. Furthermore, it has been suggested that channel deformation may occur in ferritic alloys following irradiation,[2] although it was not observed in this study. Further investigation of deformation in ferritics was therefore warranted.

This work has demonstrated that the ability of a material to work harden is decreased when radiation significantly increases dislocation densities, but after irradiation at higher temperatures, the work hardening capability can increase. It remains to be seen whether a high pre-irradiation dislocation density, such as that conferred by cold work, could exhibit similar decreases in work-hardening capability with the creation of $\frac{a}{2}$<111> and a<100> dislocations during irradiation. Such a study could be considered in the future, but similar reductions in work-hardening coefficient are unlikely due to inherent limitations in the hardenability of a material.

The observation that no interaction could be found between mobile $\frac{a}{2}$<111> dislocations and a<100> loops in a region approximately 1.5 mm from the fracture surface and in the gauge section characterized by 0.6% uniform elongation appears to verify the potential for channel deformation in irradiated ferritic alloys. Further efforts appear to be warranted to determine the possible existence of channel deformation and its mechanism.

CONCLUSIONS

The work-hardening capability determined for Fe-(3-9)Cr following irradiation was significantly reduced for low irradiation temperatures

(365-403°C) but was effectively unchanged at 574°C. The response in Fe-12Cr was different, with unusual yield behavior in the elastic regime and wide scatter in the work-hardening coefficients for low-temperature irradiation.

Microstructural examination of irradiated and deformed Fe-6Cr and Fe-12Cr specimens with nominally 0.6% uniform deformation showed no interaction between $\frac{a}{2}$<111> network dislocations and a<100> loops. Localized rather than uniform yielding is indicated.

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FIGURE CAPTIONS

Figure 1. Room temperature tensile data on Fe-(3-18)Cr binary ferritic alloys irradiated in FFTF to ~7 dpa (365°C) and ~35 dpa (403 and 574°C).

Figure 2. Schematic representations of unusual yield phenomena observed in room temperature tensile tests on binary ferritic alloys.

Figure 3. Values of work hardening coefficient determined for 3Cr specimens.

Figure 4. Values of work hardening coefficient determined for 6Cr specimens.

Figure 5. Values of work hardening coefficient determined for 9Cr specimens.

Figure 6. Values of work hardening coefficient determined for 12Cr specimens.

Figure 7. Values of work hardening coefficient determined for 15Cr specimens.

Figure 8. Summary of work hardening coefficients for 3-15Cr alloys.

Figure 9. Dislocation structures in an area of the gauge section of a specimen of Fe-6Cr irradiated at 403°C to 37.3 dpa using (a) 011, (b) 200 and (c) 110 contrast.

Figure 10. Dislocation structures in an area of the gauge section of a specimen of Fe-12Cr irradiated at 403°C to 37.3 dpa using (a) 011, (b) 200 and (c) 101 contrast.

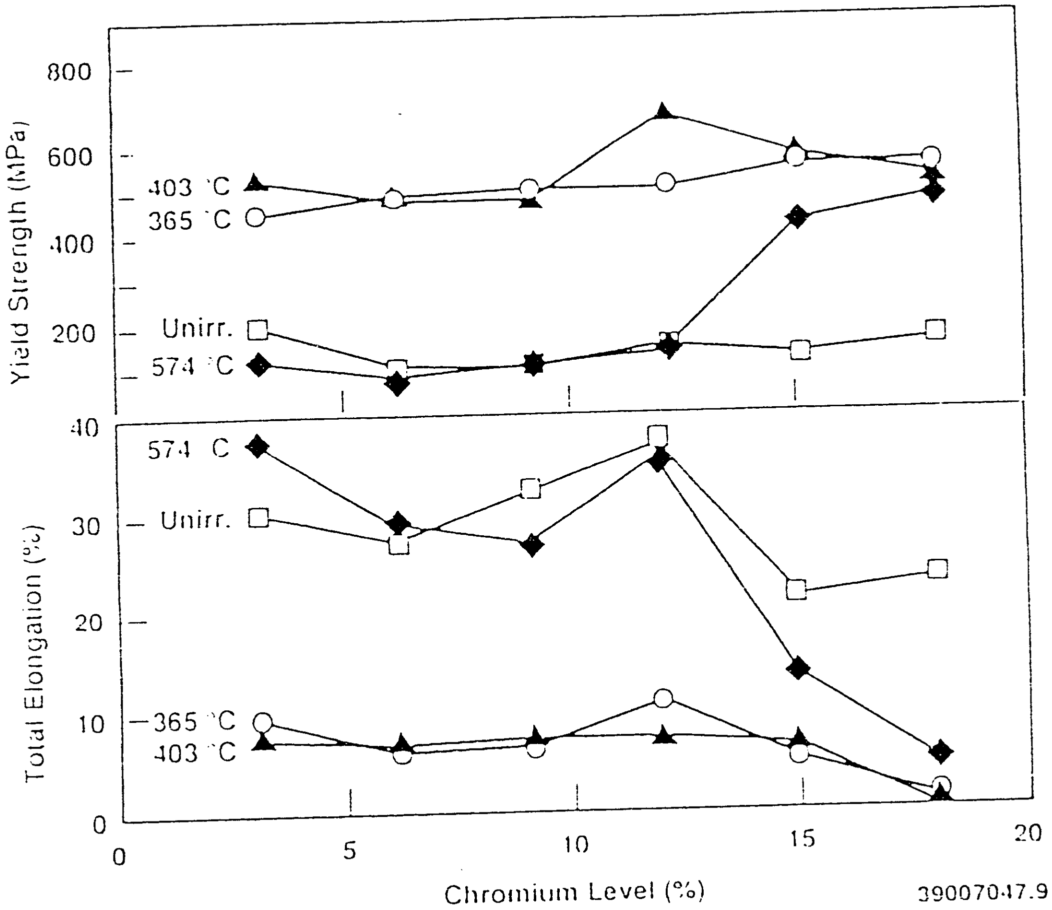

Yield Strength (MPa)
800
600
400
200
403 °C
365 °C
Unirr.
574 °C
Total Elongation (%)
40
30
20
10
0
574 °C
Unirr.
365 °C
403 °C
0
5
10
15
20
Chromium Level (%)
39007047.9

Figure 1.

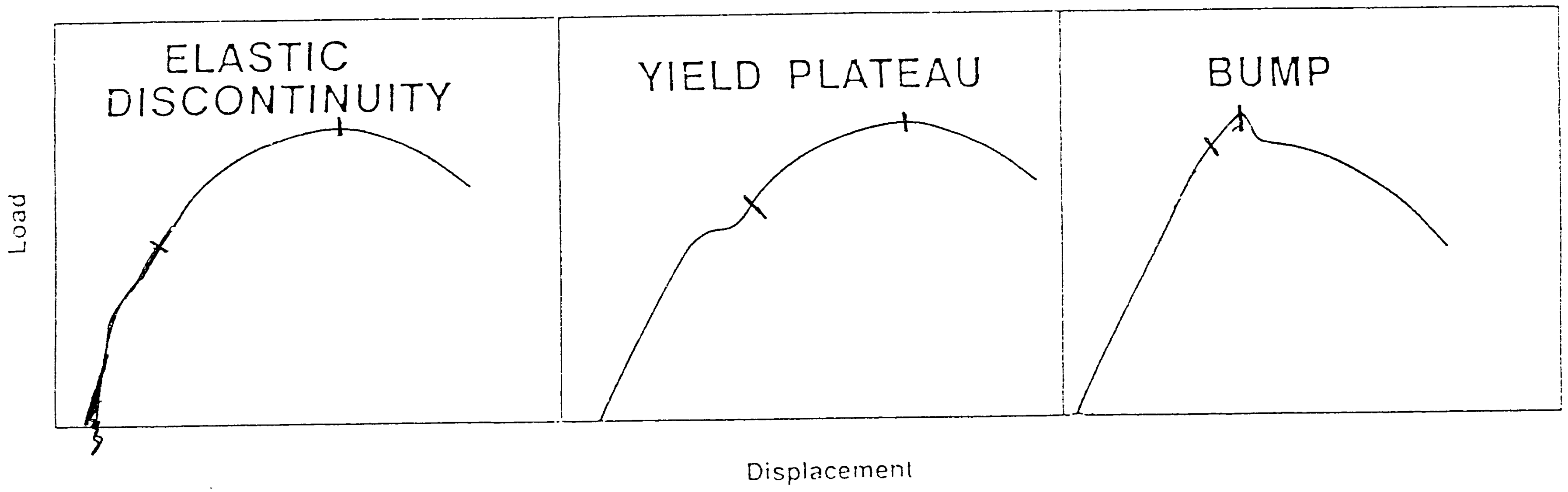
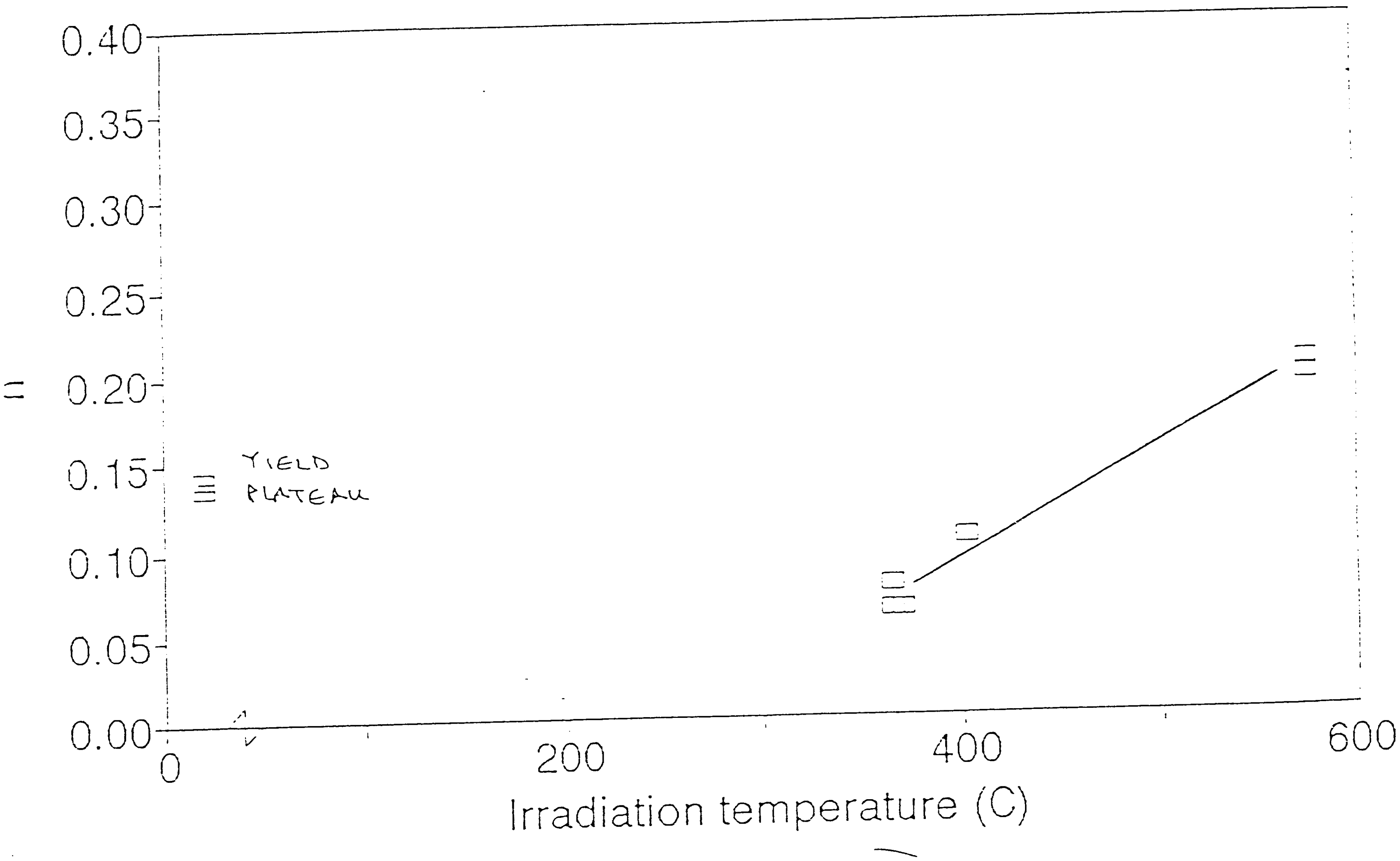

ELASTIC DISCONTINUITY
YIELD PLATEAU
BUMP
Load
Displacement

Figure 2.


0.40
0.35
0.30
0.25
0.20
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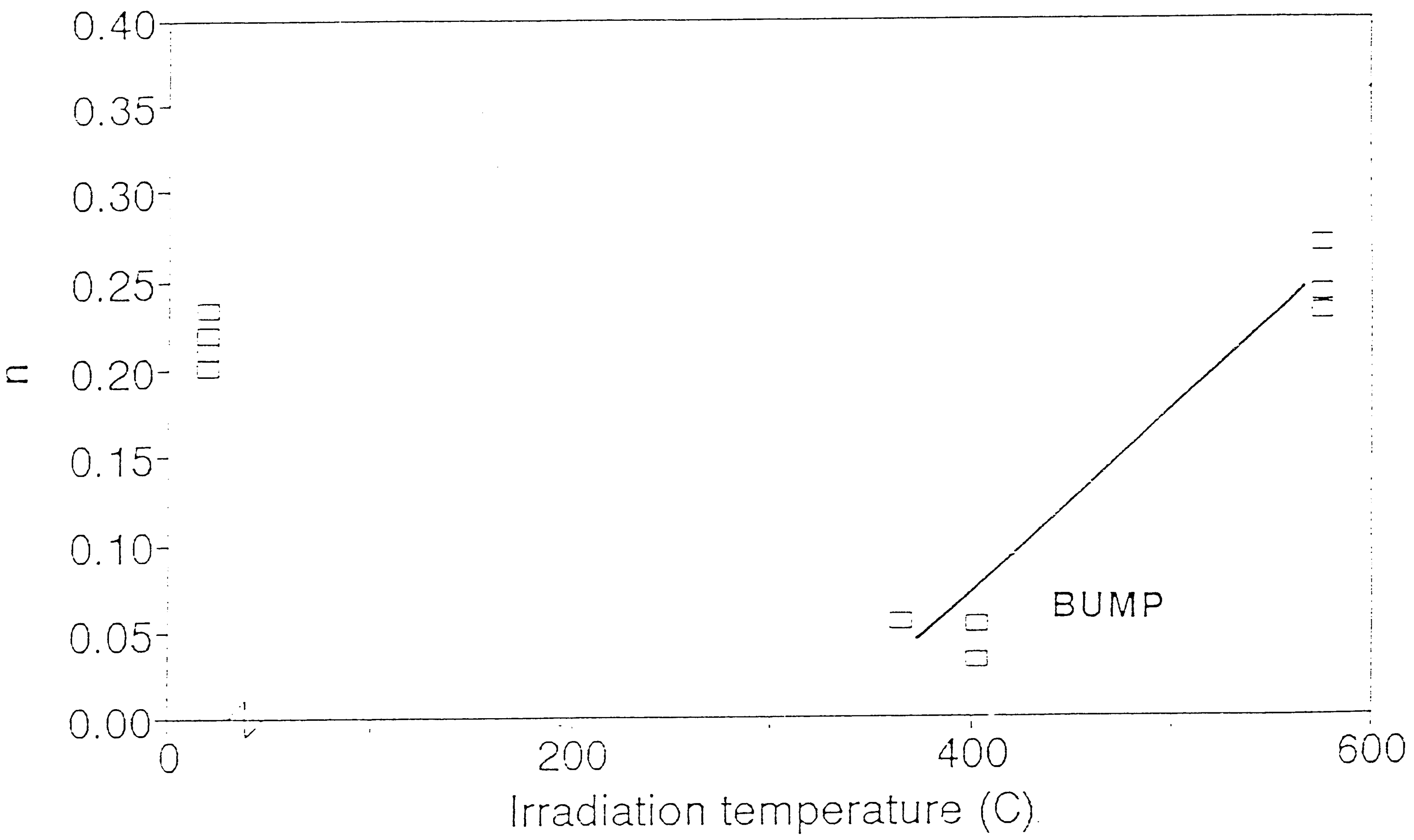
0.10
0.05
0.00
0
200
400
600
Irradiation temperature (C)
YIELD PLATEAU

Figure 3.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200
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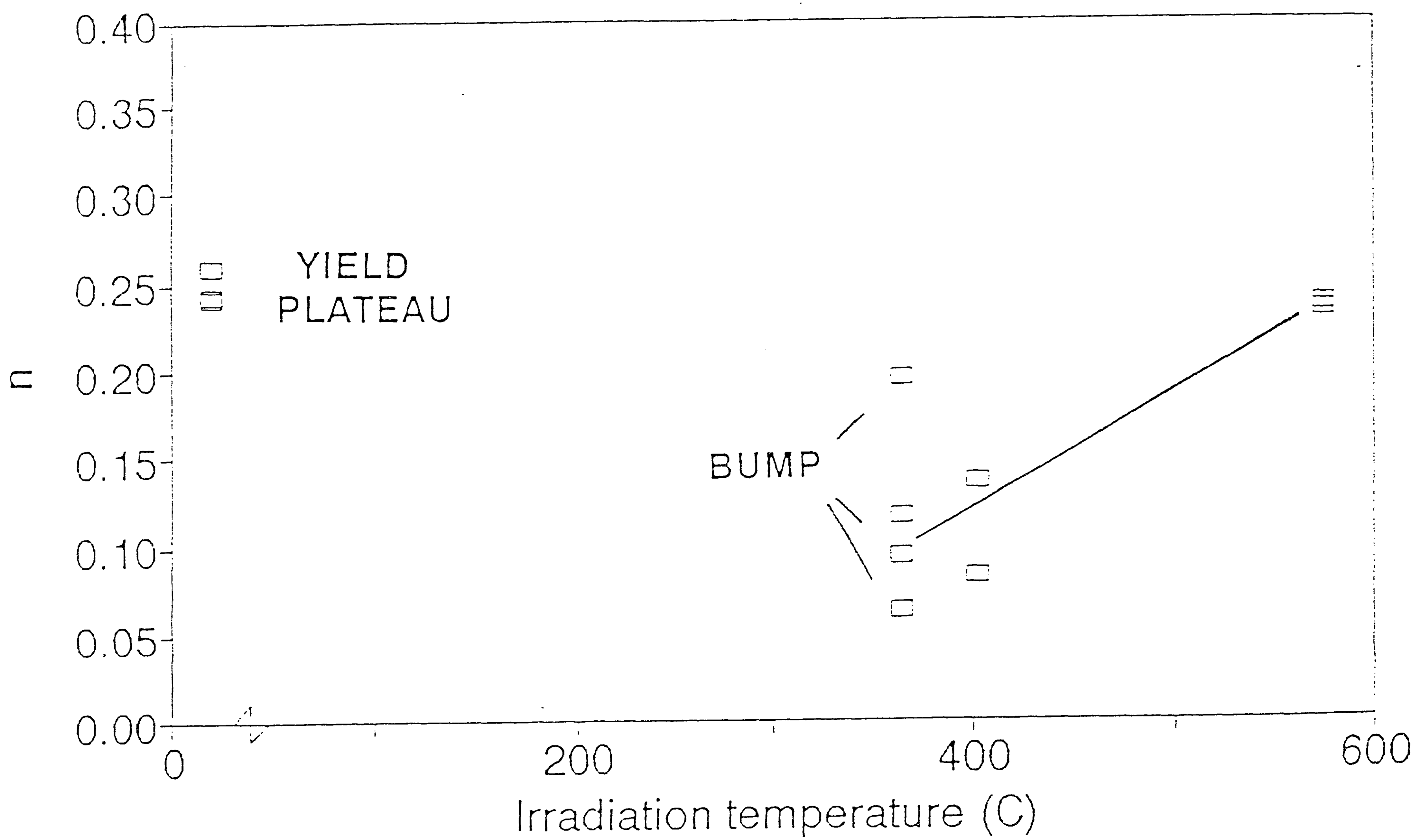
600
Irradiation temperature (C)
BUMP

Figure 4.


0.40
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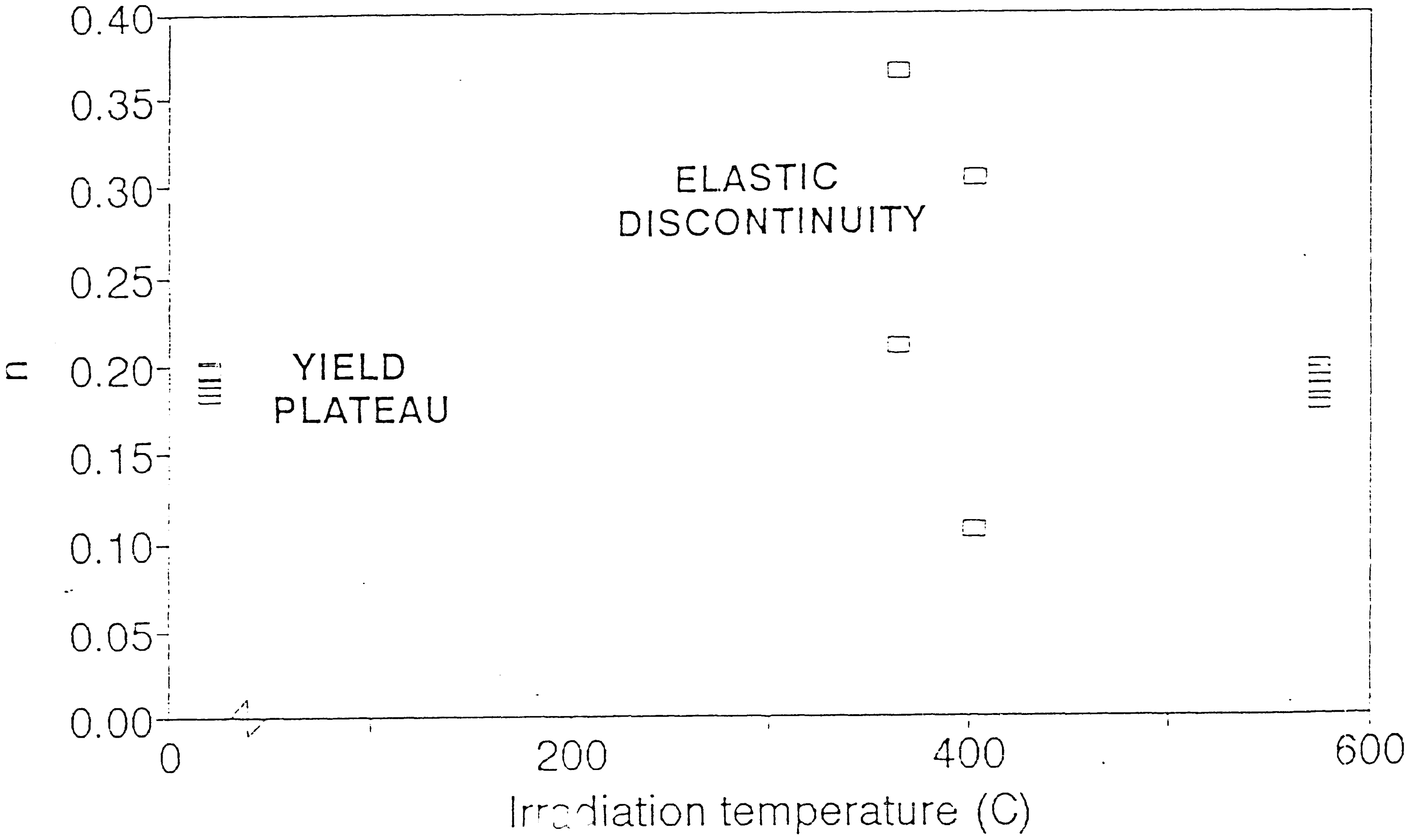
200
400
600
Irradiation temperature (C)
YIELD
PLATEAU
BUMP

Figure 5.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n
0
200
400
600
Irradiation temperature (C)
ELASTIC
DISCONTINUITY
YIELD
PLATEAU

Figure 6.

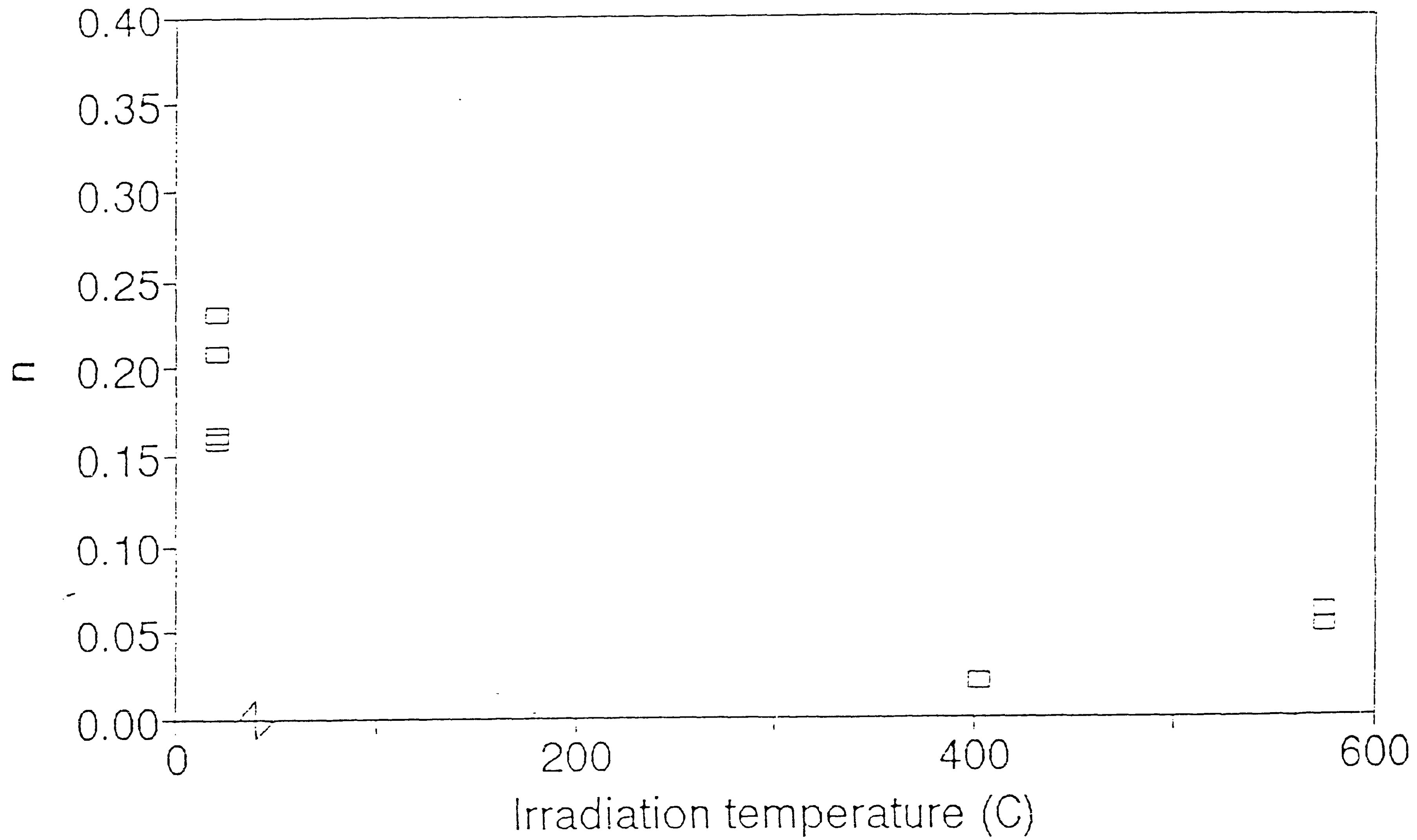
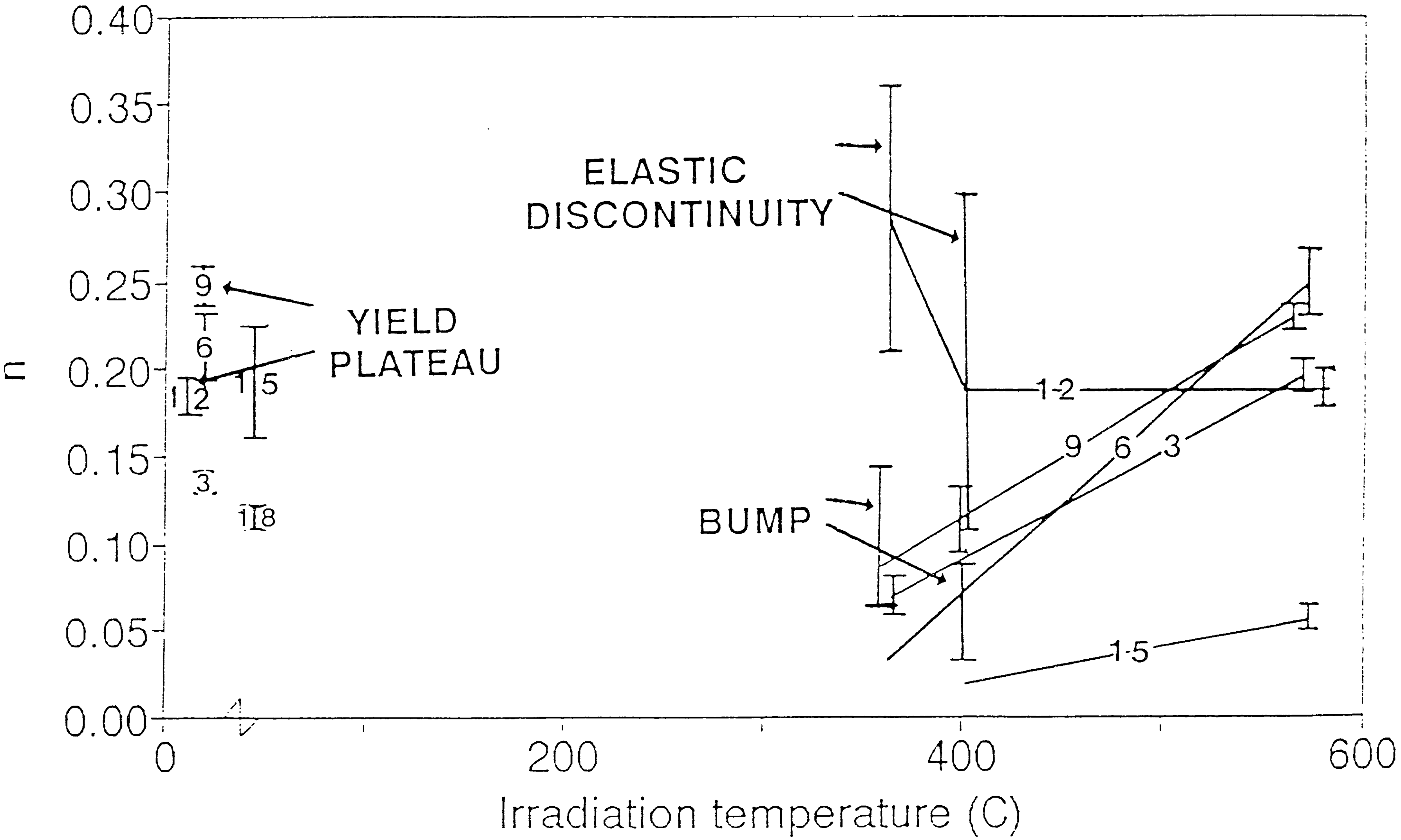

n
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
200
400
600
Irradiation temperature (C)

Figure 7.



0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
n
0
200
400
600
Irradiation temperature (C)
ELASTIC DISCONTINUITY
YIELD PLATEAU
BUMP
9
6
1 2
1 5
3
1 8
1-2
9
6
3
1-5

Figure 8.

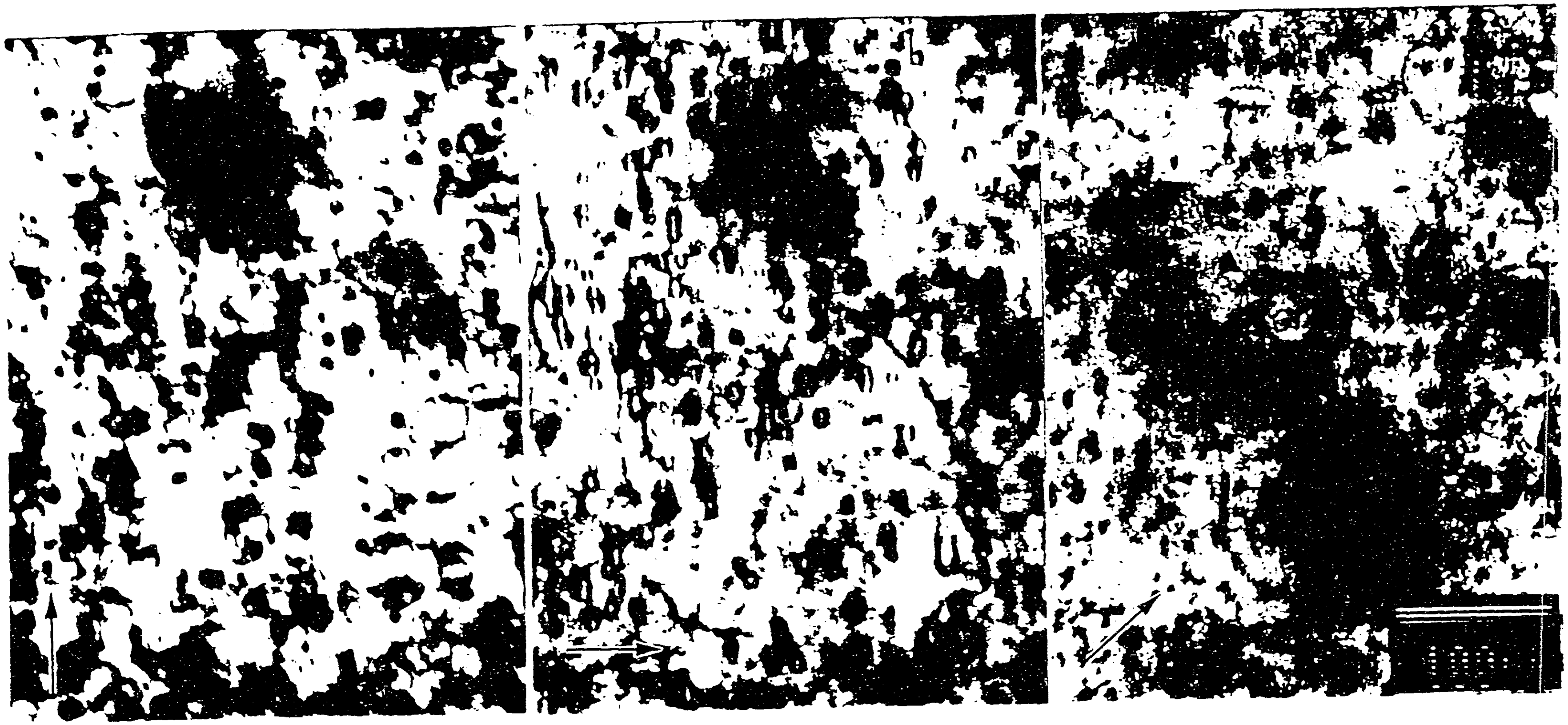


Figure 9.

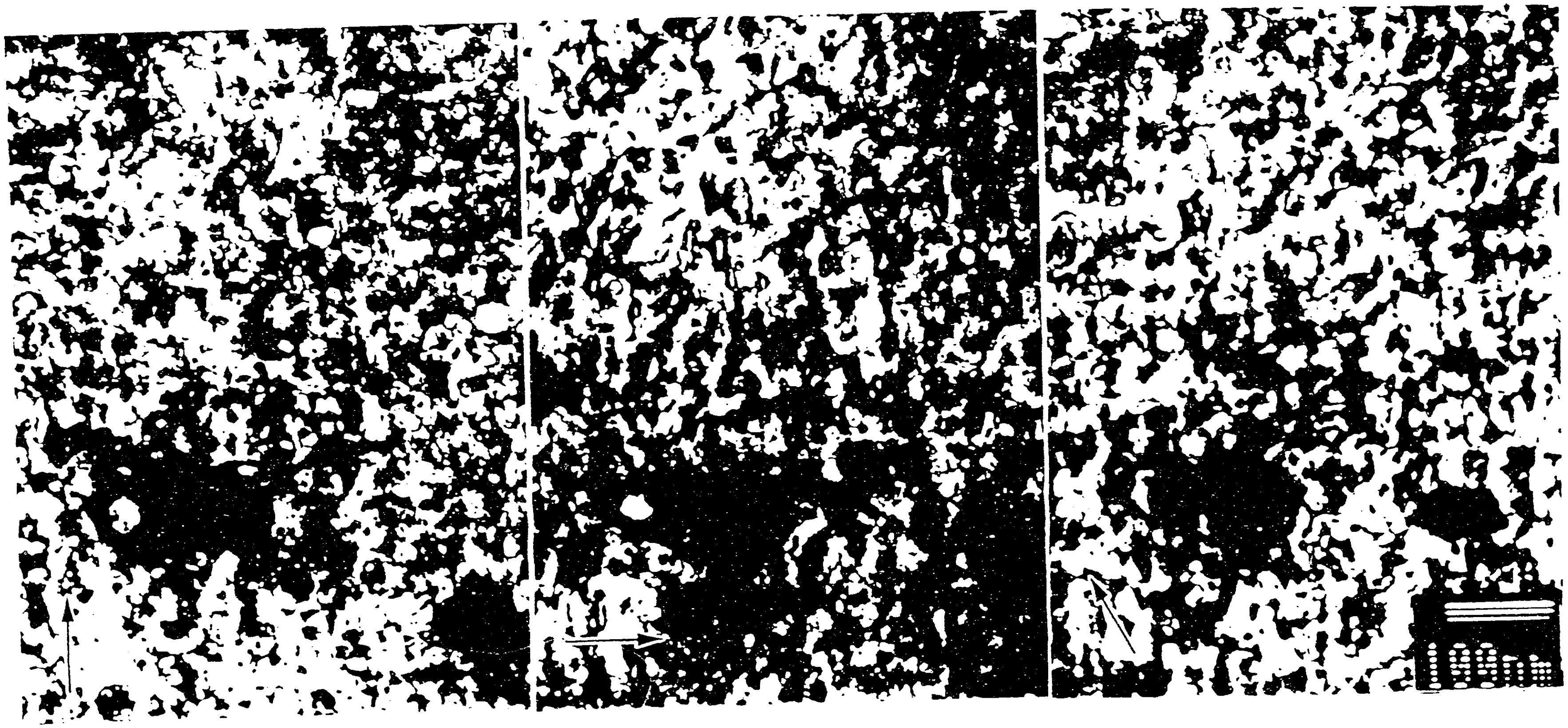


Figure 10.

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