



H^+ and He^+ Accelerator Facility for Fusion Reactor Materials Simulation Studies

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H⁺ AND He⁺ ACCLERATOR FACILITY FOR
FUSION REACTOR MATERIALS SIMULATION STUDIES

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ABSTRACT

The materials used in the construction of D-T fusion power plants will be subjected to a severe radiation environment from 14 MeV neutrons with the subsequent in-situ production of helium and hydrogen. These gas atoms can enhance cavity nucleation, resulting in unacceptable structural swelling and changes in material mechanical properties. To study these effects, we simulate the fusion neutron environment by pre-implanting 200-700 keV He^+ and/or H^+ ions into various candidate alloys with a model AN-700 electrostatic accelerator. The displacement damage caused by the 14 MeV neutrons is then emulated by an irradiation of the material with 14 MeV Ni^{3+} ions using an EN Tandem Van de Graff accelerator.

The light ion accelerator facility using the AN-700 has recently been completed. Other components in the system include beam focusing and analyzing equipment, vacuum system equipment, and a specimen holder/heater. Part of the beam handling equipment includes a 90° analyzing magnet to separate the H^+ or He^+ beams from any contaminant beams and to distinguish between the hydrogen ion, H^+ , beam and the molecular hydrogen, H_2^+ , beam. We have obtained beam currents of 1.0 to 2.0 μA on a 3 mm disc target for both H^+ and He^+ beams. These currents are equivalent to particle fluxes of $0.8-1.6 \times 10^{14}$ ions/cm²/sec.

Gas effects on cavity nucleation have been observed in previous studies and it is expected this facility will allow a more quantitative analysis of this problem.

INTRODUCTION

An accelerator facility capable of putting up to 7.0 particle $\mu\text{A}/\text{cm}^2$ (6.18×10^{14} He^+ or H^+ ions/ $\text{cm}^2 \cdot \text{sec}$) on target at energies from 200 keV to 700 keV has recently been constructed at the University of Wisconsin.

The facility will be used to simulate environments and conditions expected for D-T fusion reactors. Specifically, we are investigating near surface damage, i.e. blistering as well as the effect that interstitial gas has on cavity formation, an expected fusion materials problem.

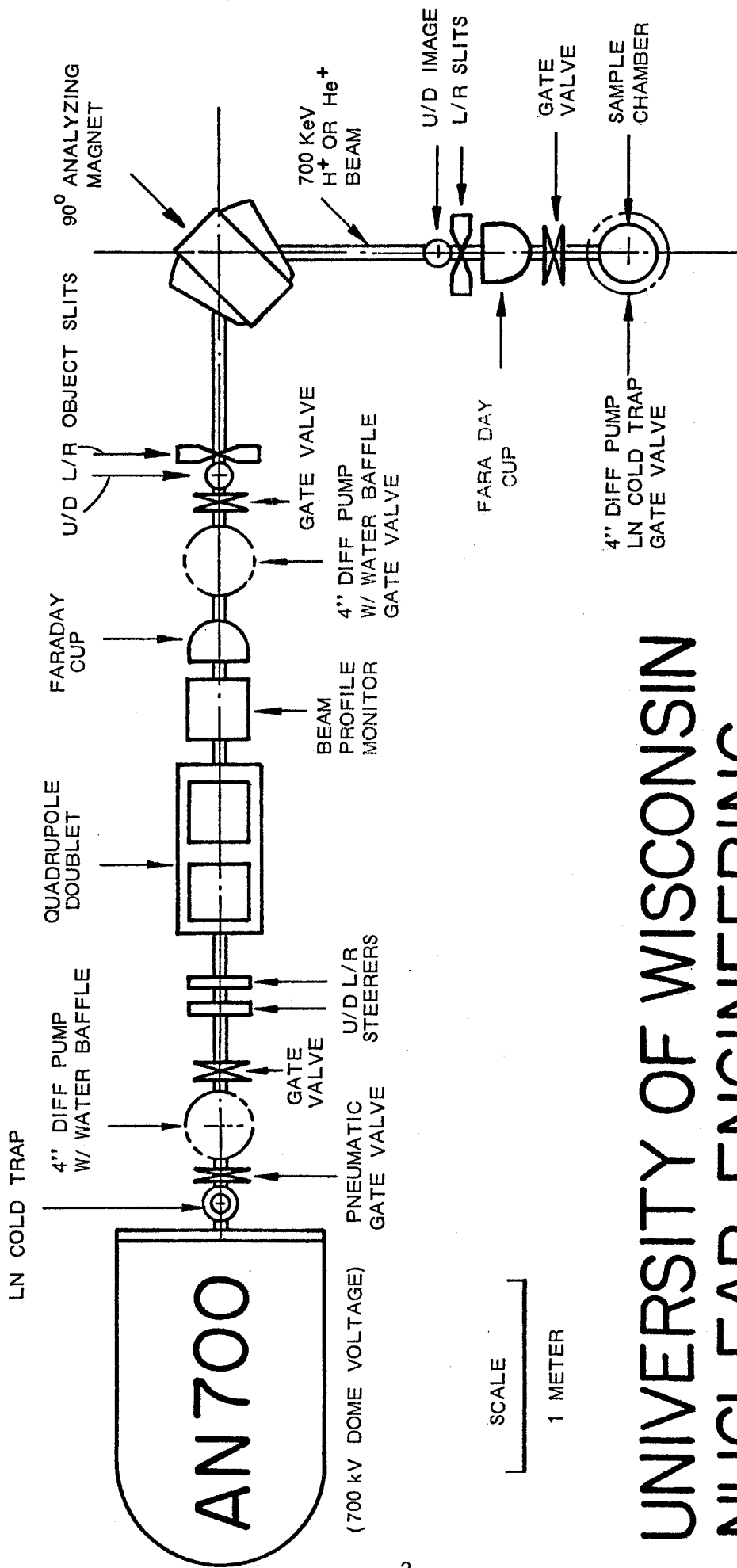
FACILITY DESCRIPTION

The accelerator facility consists of a 700 kV electrostatic accelerator, beam focusing and analyzing equipment, a vacuum system, and a specimen holder-heater. See Fig. 1 for a schematic of the facility.

A. AN-700 Accelerator

The AN-700 accelerator manufactured by High Voltage Engineering Corporation operates at an accelerating potential ranging from 200 to 700 kilovolts. The accelerator column has an insulating length of 0.38 m (15 in) consisting of equipotential planes (electrically insulated from each other), voltage dividing resistors, conducting bars for maintaining control of voltage gradients across the column, and the charging belt. The high voltage terminal is an aluminum plate 0.38 m (15 in) in diameter. Mounted on the high voltage terminal are a permanent-magnet alternator pulley assembly, a belt charge collector screen, a radio frequency oscillator and power supplies for operating an r.f. source, two source gas supplies (H and He) and two remotely controlled gas leaks.

The two gas leaks consist of a palladium leak used to control the flow of hydrogen from the supply cylinder to the ion source and a thermo-mechanical



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Fig. 1

leak to control the flow of helium. The palladium leak operates when power supplied to a heater warms the palladium making passage of hydrogen through the leak possible. Normal gas flow, under standard r.f. source operating conditions, is from 5 to 10 cc per hour. The thermo-mechanical leak, which operates on the principle of the differential expansion of elements to control the flow of gas with a ball valve, is used to regulate the flow of helium to the r.f. source.

The accelerator pressure vessel is a steel tank 0.55 meters (24 inches) in diameter and 1.6 meters (5.25 ft) long. The vessel is pressurized to 345 kPa (50 psig) with pure sulfur hexafluoride (SF_6) as an insulating gas. Mounted on the tank are a generating voltmeter, a capacitive pickup assembly, and a motor-driven corona control assembly. This instrumentation is used in conjunction with slit stabilization electronics to provide beam stability.

The dome voltage of the AN-700 electrostatic accelerator is stabilized against fluctuations in belt upcharging current, slight line voltage variations, etc., by means of an in-house constructed feedback circuitry system which controls the corona point current. By controlling the current to the points, more/less charge is bled off the dome thereby stabilizing its voltage.

The feedback signal originates from the current incident upon the left and right image slits. From here, each left/right current signal is independently logarithmically amplified and fed into a difference amplifier which puts out a signal proportional to the difference of the left/right inputs. Finally, this output is integrated, modified, and differentiated to produce a series of positive or negative pulses (depending on whether more or less beam current is incident upon the left slit compared to the right) which then are superimposed on a -5 V bias potential. This final voltage is connected to the

grid of a Sylvania Type 6BK4 High Voltage Regulator which is a triode vacuum tube that controls the corona current.

The above circuits were adapted and modified from circuits (used on the EN Tandem Van de Graaf accelerator at the University of Wisconsin-Madison) which were designed by Mike Murray of the UW-Physics Department.

Pumping for the accelerator system is provided by three Varian Model VHS-4 diffusion pumps. These pumps are located near the high energy end of the accelerator, just prior to the object slits of the 90° analyzing magnet, and directly below the sample chamber and will hereafter be referred to as the accelerator diffusion pump, magnet diffusion pump, and sample chamber diffusion pump, respectively.

The accelerator diffusion pump is equipped with an optically opaque water-cooled baffle to prevent diffusion pump oil from backstreaming into the beam tube. Pressure at the accelerator is monitored by a Penning Discharge Vacuum Gauge which is connected via a feedback circuit to the accelerator control panel. This feedback loop will automatically shut down the machine should the accelerator diffusion pump backing pressure exceed approximately 10^{-2} Pa (10^{-4} torr). Ultimate achievable pressure with this system is roughly 10^{-5} Pa (10^{-7} torr), with a nominal accelerator operating pressure of 10^{-3} Pa (10^{-5} torr). The ultimate pressure is monitored by a Bayard-Alpert ionization gauge controlled by an ionization gauge controller mounted in the target room.

The magnet diffusion pump is also equipped with an optically opaque water-cooled baffle for suppression of backstreaming. An aluminum solid-body slide valve is mounted just above the pump and baffle to allow pump isolation should access to the beam line be required. Pressure near the magnet diffusion pump is monitored by a Bayard-Alpert ionization gauge mounted on the

beam tube above the Faraday cup adjacent to the magnet diffusion pump. Ultimate pressure near the magnet is roughly 10^{-5} Pa (10^{-7} torr) with a nominal operating pressure of 10^{-4} Pa (10^{-6} torr).

The sample chamber diffusion pump, mounted directly beneath the sample holder, is equipped with a Varian Model NRC 316-4 Cryotrap. This liquid nitrogen trap completely suppresses diffusion pump oil backstreaming and subsequent sample contamination. Mounted directly above the cryotrap is another aluminum solid-body slide valve which allows the sample chamber diffusion pump to be isolated and facilitates quick sample changes. A Bayard-Alpert gauge monitors sample chamber pressure.

Initial irradiations with sample chamber pressures of approximately 2×10^{-6} torr yielded carbon deposition in the irradiated area. This was due to breakdown of residual hydrocarbon molecules present in the vacuum system at this pressure. To alleviate this problem, a liquid nitrogen cooled pumping impedance was designed and built. The geometry of the impedance reduces the conductance of this section of the vacuum system by a factor of 20. The liquid nitrogen cooling helps to limit hydrocarbon streaming from areas of higher pressure up the beam line from the sample chamber. The pumping impedance and liquid nitrogen cooling should yield sample chamber pressures of about $2-4 \times 10^{-7}$ torr during irradiation thus eliminating the carbon contamination problem.

Four gate valves are mounted at various locations along the beam line to allow isolation of various beam tube sections. A pneumatic gate valve is mounted just outside of the machine and is actuated when a pressure rise occurs in the accelerator diffusion pump backing line. This backing pressure is monitored by a Varian model 810 single set-point thermocouple gauge con-

troller which can activate relays to close the gate valve and turn off the accelerator diffusion pump when the set-point pressure is exceeded.

B. Beam Handling/Monitoring

There are three major beam handling components situated along the beam line, including up-down, left-right steerers, a quadrupole doublet and a 90° analyzing magnet. The steerers are an in-house design and construction, while the quadrupole doublet and analyzing magnet are manufactured by Magnion, Inc. and ANAC, Inc. respectively.

The steerers are mounted approximately one meter from the end of the accelerator and are capable of steering the beam in up-down and/or left-right directions. Each set of steerers consists of two magnet coils with 2600 turns of number 22 magnet wire around a 0.0254 meter (1 inch) core. The pole pieces consist of Armco iron mounted between the coils having dimensions of 0.064 m x 0.064 m x 0.051 m (2-1/2 in x 2-1/2 in x 2 in). The power supply, capable of producing ± 2 amps for each set of steerers, is constructed from two Model 440C 50 watt Operational Power Amplifiers and one Model 526 Power Supply purchased from OPAMP Labs, Inc.

The quadrupole doublet, mounted approximately 1.5 meters from the end of the machine, is a Magnion Model QD 200. The coils of the quadrupole have 100 turns and are capable of carrying 30 amps. Power is supplied by two Varian Model 6021 current regulated power supplies capable of producing from 0-30 amps each. Each set of coils is water-cooled to dissipate the 900 watts produced at full power operation.

The 90° analyzing magnet, located 6 meters from the end of the accelerator, is an ANAC Model 3938. It has a maximum mass-energy product of 3.4 ($\text{amu} \cdot \text{MeV}/Z^2$) at 90° with a gap field of 1.2 tesla and a bending radius of

0.224 meters (8.8 in). The magnet power supply is a Hewlett-Packard Model 6269B, which provides 50 amps with current regulation of 0.02%. A power control center is also included in the magnet system. The center includes a breaker box and an interlock trip to switch off the power supply if the magnet exceeds maximum operating temperature or if the cooling water flow drops below a minimum required level. Object and image slits are used in conjunction with the analyzing magnet. These slits, manufactured by HVEC, are water-cooled and capable of dissipating 100 watts each.

Beam characteristics are monitored along the beam line by a beam profile monitor, two Faraday cups and beam current integration electronics associated with the specimen holder. The beam profile monitor is a National Electrostatics Corporation Model BPM-45. The monitor is located directly beyond the quadrupole doublet so that the beam shape may be evaluated after this focusing element. Two Faraday cups are located along the beam line. The cups, mounted between the quadrupole and the magnet and between the magnet and the sample chamber, are pneumatically operated and electrically suppressed to give accurate beam current readings.

The beam current integration electronics include an Ortec Model 439 Digital Current Integrator, a Mechtronics Nuclear Model 420 Scaler and a Mechtronics Nuclear Model 419 Counter. These components are all NIM bin modules mounted in the control panel. The integrator can handle beam currents ranging from 10^{-9} ampere to 10^{-2} ampere while the scaler-counter records the integrated current at a rate of up to 100 MHz. The integration electronics are accurate to within 0.10% as shown by tests with a constant current power supply.

C. Sample Holder and Heater

The sample holder, shown schematically in Fig. 2, consists of a stainless steel holder upon which is mounted a specimen holder capable of accommodating three 3 mm discs and/or three 0.5 cm x 1.0 cm foils. The sample holder maintains electrical isolation of the sample while it masks the irradiated area to allow for accurate measurement of the current density. The holder is heated by electron bombardment from a biased filament. The isolated sample is radiatively heated with the temperature measured with thermocouples attached behind each sample position. The temperature range of operation of this sample holder is roughly 100°C to 800°C.

The heater power supply is an Alpha Scientific Model 3000 current regulated 0-10 amp supply. The heater filament is biased to -10 kV with a Universal Voltronics high voltage power supply.

RECENT EXPERIMENTS

Blistering is an important erosion process for various parts (including the first wall, limiter, divertor openings) of a thermonuclear fusion reactor. Not only will this limit the lifetime of these parts, but it also is a factor in impurity contamination in the plasma [1,2].

Blistering on metallic surfaces is the formation of gas-filled dome-like protrusions with the subsequent decohesion of the top surface layer. A review on the description and mechanisms has been given by Das and Kaminsky [3].

There have been two basic mechanisms proposed for the occurrence of inert-gas-induced blistering of metals. The first model promotes a gas pressure-driven model [4] whereas the second model suggests a lateral stress-driven cause for blistering [5,6]. Wolfer [7], using a recently developed equation of state that extends to high densities of He atoms [8], purports a

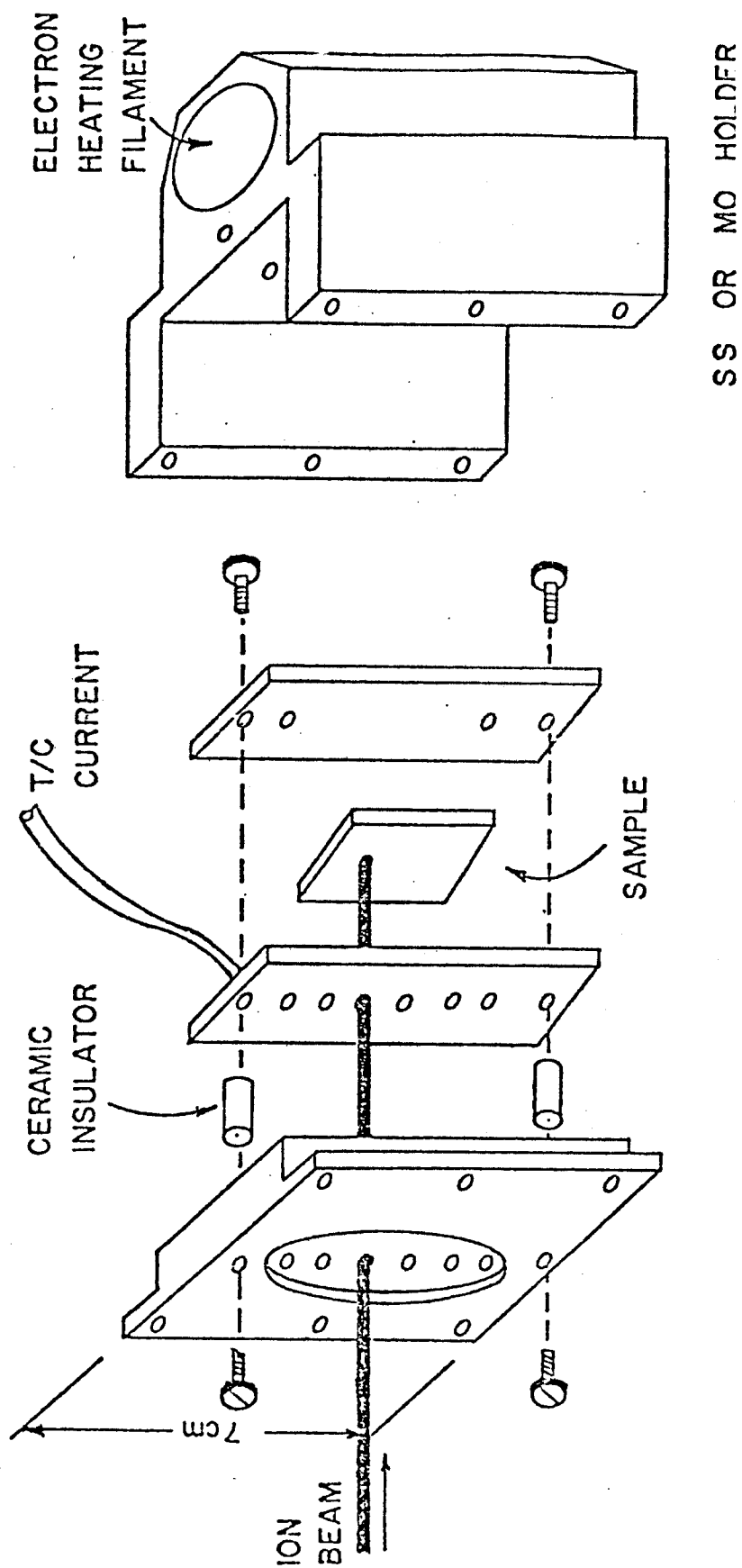


Fig. 2

scenario in which both the gas-pressure-in-bubbles stresses and the lateral stresses from swelling play a significant role in the blister dome formation. Pressure from the gas bubbles generate microstresses which eventually cause interconnection of the bubbles, thus creating penny-shaped cracks parallel to the metal surface. These cracks then extend to a diameter dictated by the lateral stresses.

We are initiating a study to test the accelerator facility by investigating the blistering phenomenon and comparing it to previous results [9]. Figures 3 and 4 show scanning electron micrographs of annealed nickel and 20% cold-worked 316 SS that have been blistered.

FUTURE EXPERIMENTS

In a recent review article, Farrell [10] testifies to the dramatic effect that the inert gas helium has on cavity nucleation, and to the effects of helium on radiation-induced phase instability. We will study these effects by pre-implanting helium uniformly in nickel and 316 stainless steel samples from 1 to 1000 appm. Subsequent heavy ion irradiations using 14 MeV Ni^{3+} ions will be performed using the UW Tandem Van de Graaf accelerator. This last step simulates the displacement damage effects of the 14 MeV neutrons from the D-T fusion reaction.

Microstructural analysis will be performed using a JEOL 200CX Transmission Electron Microscope utilizing a cross-sectioning technique as described by Whitley [11].

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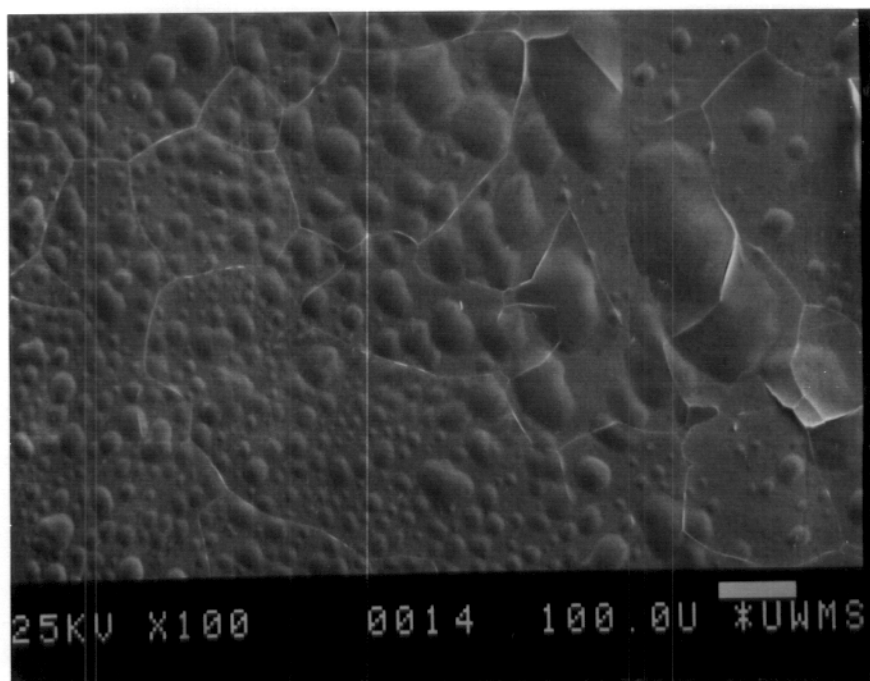


Fig. 3. Annealed Ni irradiated at 5.2×10^{14} He/cm²/sec to 2×10^{18} He/cm³.
Temp. of irr. = 275°C.

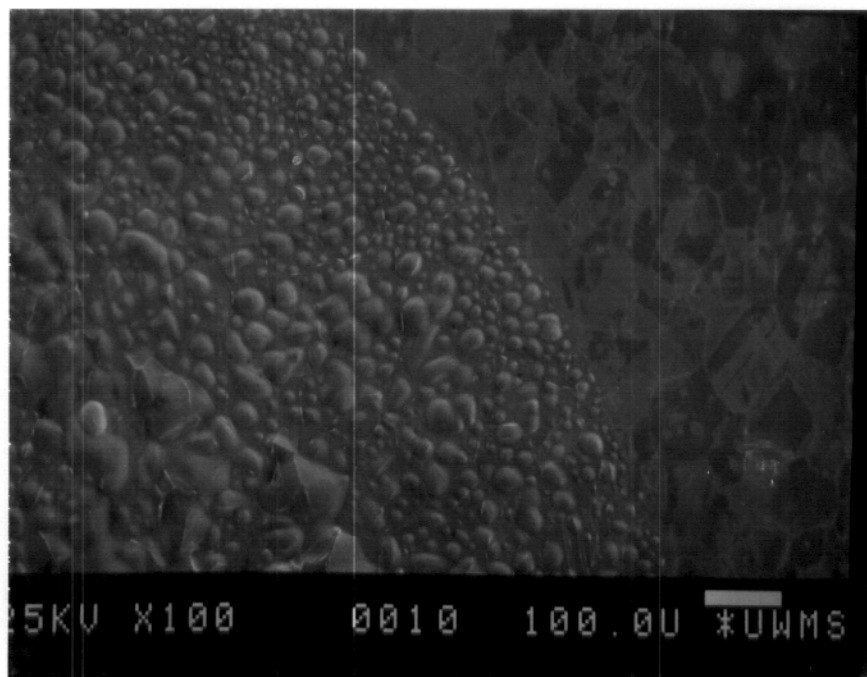


Fig. 4. Cold worked 316 SS irradiated at 4.9×10^{14} He/cm²/sec to 2×10^{18} He/cm². Temp. of irr. = 550°C.

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